LOWER REPUBLICAN STREAM-AQUIFER PROJECT:

FINAL REPORT

by

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Kansas Geological Survey
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TABLE OF CONTENTS

Appendices

LIST OF FIGURES

LIST OF TABLES

LOWER REPUBLICAN STREAM-AQUIFER PROJECT: FINAL REPORT

Vol. 1. Combined watershed/stream-aquifer model conceptualization and application

1. INTRODUCTION AND STUDY PURPOSE

During 1988-1991, streamflows in the Republican River were low relative to historic levels. Low-flow conditions were especially pronounced in the reach between Concordia and Clay Center, thus affecting the inflows into Milford reservoir. This reach is in an area where large ground-water appropriations exist, necessitating an assessment of the impact of ground-water pumpage on streamflow. Because various interests compete for the water, and there are only finite amounts of that resource, decisions balancing water rights for irrigation and maintaining minimum streamflow standards and desired inflows to the Milford Reservoir must be made.

The purpose of this project is to evaluate the water budget for the Lower Republican River basin and to evaluate the impact of water rights, various land uses, and irrigation alternatives on streamflows in the reach between Concordia and Clay Center. The goal is to develop a comprehensive numerical simulation model capable of assessing the impact on streamflows that would result from the selective administration of water rights and other management alternatives within the study area.

The hydrologic setting of our study area is reviewed in Section 2. Our model of the Lower Republican River basin is based on hydrologic data that were obtained from a variety of sources outlined in Section 3. An overview of the modeling process, model description, and model input are discussed in Sections 4, 5, and 6, respectively. Sources of error are also discussed in Section 6. Hydrologic data from Section 3 provide observations against which results from the watershed-aquifer model simulations are compared for the calibration period 1980-1990 (Section 7), and for the verification period 1991-1994 (Section 8). Sensitivity of the calibrated model to watershed, stream, and aquifer parameters is examined in Section 9. The resulting model is then used to predict the effect of changes in water use on stream yield by examining a range of scenarios (Section 10). The report concludes with Section 11 summarizing the major work elements, our conclusions and recommendations.

2. OVERVIEW OF THE HYDROLOGIC SETTING

The Lower Republican River basin (or Unit) is a 2,600 square-mile area in north-central Kansas which comprises about 10 percent of the Republican River basin (KWRB, 1961). The Republican River enters the Lower Republican Unit near Superior, Nebraska, flows southeastward, and joins the Smoky Hill River near Junction City to form the Kansas River. The site of Milford Reservoir, which was completed in 1967 by the Corps of Engineers, is near the downstream end of the Republican River.

The generalized surface features of the Lower Republican River basin are illustrated in Fig. 2.1, which shows the major physiographic areas, geologic formations that crop out, and major soil areas. The rocks that crop out at the surface are mostly shale, sandstone, and limestone formations of Cretaceous and Permian age. The central and major portion of the Unit lies in the Dissected High Plains physiographic area, whereas the southeastern portion of the Unit lies in the Flint Hills Upland. The major stream valleys in the Unit are underlain by Quaternary alluvium and terrace deposits. Sand and gravel aquifers within these deposits provide a major source of water for most uses in a large part of the Republican River basin.

The climate of the Lower Republican River basin is classified as subhumid. The average annual temperature is about 55°F but varies widely. The average annual precipitation also varies widely generally increasing from west to east; it averages about 27 in/yr in Concordia and 31 in/yr in Clay Center. About 75 percent of the annual precipitation occurs in the crop-growing season, April to September. The basin has a high evaporation potential. Annual lake evaporation ranges from about 55 in/yr along the southern central part of the basin and gradually decreases to about 49 in/yr along the west, north, and east edges of the basin (Koelliker, 1984). This results in a large annual moisture deficit (lake evaporation-precipitation) in all parts of the basin.

The predominant land use in the basin has historically been agricultural. Water requirements for row crops under irrigation averages about 13.8 in/yr across the basin. Irrigation development from ground-water sources has increased significantly. Wheat is the dominant crop, but corn and grain sorghum are also important cash crops.

Average annual streamflow at Concordia is about 480,000 acre-ft/yr, whereas at Clay Center the average annual streamflow is about 689,000 acre-ft/yr. This increase of 209,000 acre-ft/yr corresponds to approximately 3.9 inches per year (applied over the watershed area between Concordia and Clay Center, which is approximately 992 square miles.)

3. BASIN HYDROLOGIC DATA

A.) Geographic Information System (GIS) Database

The modeling effort was supported by data organized in a geographic information system (GIS) database. This database was developed primarily for the purpose of preparing input parameters for the hydrologic model SWAT. Because SWAT allows subdivision of the basin into numerous subbasins, it is critical to have spatially distributed data, and more important, the analytical functions to manipulate these data in order to extract desired parameters to characterize each subbasin. GIS has provided data and capabilities for detailed modeling of spatial variability of hydrologic processes.

GIS data were gathered for most of the spatial parameters of the SWAT model. These data provide spatial distribution of climate, channel morphology, ground-water table, and basin conditions such as basin topography, land use, soils, hydrography, and geology (bedrock elevation). Other necessary data included township and range and administrative boundaries. The specific GIS data files are listed and briefly explained in Appendix 3A. All GIS data were processed in Arc/Info (workstation version 7.0 or higher) format, which is compatible with the statewide GIS database. All the final coverages are in Albers projection. Besides GIS data coverages, there are also several Arc/Info Macro Language (AML) and other files in the database, which were developed particularly for generating maps to display different data themes.

The model parameters were extracted through various GIS procedures, depending upon the nature of the parameters. In this study, length and areal measurements were frequently needed, such as stream lengths and sizes of subbasin, land-use, and soil polygons. These values were calculated automatically and stored as part of attributes when a GIS coverage was created. GIS overlay functions were used to obtain composite parameters as needed, such as soil properties in a subbasin, where a soil coverage was overlaid with a basin-boundary coverage. With appropriate areal weights calculated by GIS procedures, spatial averages of soil parameters can be estimated for each subbasin and used as input for the hydrologic model. Using relational database functions, attributes from different data sources were linked and manipulated to derive required parameters for the model. For spatial data that were only available at point locations, such as precipitation and temperature, spatial interpolation based on the Thiessen polygon technique was initially used to extend point data to polygons, so that areal weights could be extracted. A listing and brief description of the Lower Republican River basin database is given in Appendix 3A.

B.) Water Use, Irrigated Acreage, and Ground-water Levels

Ground-water and surface-water use are estimated on the basis of data provided by the Division of Water Resources (DWR) of the Kansas Department of Agriculture. These data consist of two sets: water rights (appropriations) and water use. The water- rights data specify the annual volume of ground water or surface water that may be drawn from each point of diversion. Annual water-use data, available for the years 1980-1993, give the volume of water withdrawn from each point of diversion reported by water-rights holders. We use these two data sources to estimate annual ground- and surface-water use within the gridded rectangular region defined for the watershed-aquifer model. Water is used predominantly for irrigation, and most irrigation-use reports specify the area irrigated, from which we can estimate the total area irrigated by all water rights. A large fraction of water users also report depth to water (dtw) and the date of its measurement. In addition to these reported dtw measurements for 1980-1993, we measured water levels in November 1994 at 80 wells, most of which were for irrigation and were screened in the alluvial aquifer. (For further information on the 1994 ground-water-level survey, see section B3 at the end of this unit.) The combined dtw measurements from the DWR use reports and our survey constitute one of the two key data sets we have available to compare with our watershed-aquifer model simulations for the years 1980-1994; daily streamflow data at Concordia and Clay Center constitute the other key data set. Appendix 3B1 shows water-table elevations based on depth to water (dtw) measurements and 1:24000-quadrangle maps for topographic elevations; and water-table contour maps based on these elevations for selected years. Fig. 3.1 and Table 3.1 show, for both ground and surface water, the number of water rights and annual water-use reports within the Lower Republican River basin study area, and the number of dtw measurements included in the ground-water-use reports.

Approximately 90 percent of the Lower Republican River basin lies within a rectangular grid covering 897 square miles extending 39 miles east-west and 23 miles north-south. This area is subdivided by 39 columns east to west and 23 rows north to south into a regular grid of 1-square-mile cells that correspond closely to sections, which are numbered from the northwest corner at T5S-R4W-S6. Within this grid, 85 percent of surface-water rights and 73 percent of ground-water rights are located along the Republican River alluvial valley, along which 125 sections (or square miles) are defined as "active nodes" (the solution space) for MODFLOW. Appendix 3B2 tabulates the ground-water and surface-water rights data obtained from DWR files.

Both water-rights and water-use data sets identify each point of diversion by its associated application number, legal location, and a DWR code. Application numbers are chronological and are associated with the first year of the establishment of the water right. The legal location is mapped onto both geographical and model grid coordinates, and the DWR code distinguishes each point of diversion for a given water right. These three items are combined to provide an identifier that is used to match water-use reports to water rights. Each point of diversion is associated with either surface or ground water as its source.

Two companion programs, WRREPUB and WUREPUB, were used to process the water-rights and water-use data, respectively. (For a detailed description of these programs the reader is referred to Volume 2 of this report.) WRREPUB was used to select diversion points from the DWR water rights data lying within the ground-water model's solution space of 125 sections, and to write separate lists for surface- and ground-water rights. For each year for which DWR water-use data were available (1980-1993), WUREPUB was used to select those water-use reports with matching water-rights descriptions in the lists selected by WRREPUB and to write separate input files describing annual ground- and surface-water use for MODFLOW as reported for each point of diversion. Water-use reports were matched successfully to water rights in most cases. For non-reporting water rights, water use is approximated by the point of diversion's appropriated right times the average water-use fraction for all reporting ground or surface points of diversion lying within the active model area (see reported water-use estimates, below). In years for which water-use data were not available in the study period (1977-1994), water-use models based

Table 3.1. Number of water rights and water use reports

	Number of water rights				Number of water use reports					
year (1)	gwnon (2)	gwirr (3)	gwtot (4)	srfirr (5)	gwnon (6)	gwirr (7)	gwtot (8)	srfirr (9)	acres (10)	dtw (11)
1977	15	231	246	31	0	0	0	0	0	0
1978	15	241	256	31	0	0	0	0	0	0
1979	15	249	264	31	0	0	0	0	0	0
1980	15	252	267	31	1	64	65	2	63	3
1981	15	262	277	32	4	143	147	6	134	104
1982	16	262	278	32	5	145	150	8	138	83
1983	17	267	284	32	7	154	161	7	151	102
1984	17	268	285	33	7	177	184	10	174	107
1985	17	268	285	33	8	162	170	11	155	94
1986	17	273	290	33	7	137	144	9	128	101
1987	17	279	296	33	11	193	204	11	188	158
1988	22	288	310	35	3	161	164	10	151	138
1989	22	296	318	37	11	238	249	13	238	185
1990	22	314	336	39	15	245	260	13	245	176
1991	22	318	340	39	15	253	268	16	253	207
1992	23	323	346	40	15	192	207	16	192	174
1993	24	323	347	40	13	137	150	3	137	105
1994	25	323	348	40	0	0	0	0	0	0

Key to columns in Table 3.1:
1. Study year (1977-1994).
Number of water rights (points of diversion, cols. 2-5):
2. Ground water rights for uses other than irrigation, excluding domestic wells.
3. Ground water rights for irrigation (DWR use code value = 3).
4. Total ground water rights, excluding domestic wells (add cols. 2 and 3).
5. Surface water rights (all are for irrigation).
Number of water use reports to DWR:
6. Ground water reports for other than irrigation (excl. domestic wells).
7. Ground water reports for irrigation.
8. Surface water (all are for irrigation, and all provide area irrigated).
9. Ground water reports for irrigation that also provide area irrigated.
10. Ground water reports that also provide depth to water (dtw) measurement.

on precipitation were employed to estimate water use as a fraction of appropriation and as a depth of water applied as irrigation (see precipitation-based water-use estimates, below). The water-use input files written by WUREPUB for ground- and surface-water use are read, respectively, by MODFLOW's WELL and SURFACE packages, which are comparable in their handling of points of diversion. The SURFACE package, written as part of this project, represents surface points of diversion as lateral outflow from associated stream reaches and so is coordinated with a modified version of MODFLOW's STREAM package. (For additional information on these programs, the reader is referred to volume 2 of this report.)

Fig. 3.2 shows water use and appropriations for our study period, 1977-1994, converted from units of acre-ft/year to cubic ft/sec, cfs (1 cfs = 723.967 acre-ft/yr), and Fig. 3.3 shows irrigated area for both ground and surface water. Table 3.2a combines ground- and surface-water rights, and estimated (reported) use; Table 3.2b shows irrigated area in acres and as a percent of the Lower Republican River basin's gridded area (Fig. 3.4). Table 3.2b also shows May-August precipitation (in), and both surface- and ground-water components of water-use fraction and irrigation expressed as depth of water applied (in).

Annual water use, irrigated area, and corresponding depths were estimated for both ground and surface water, first based on water-use reports for years 1980-1993, and then based on precipitation models for other years of our study period, 1977-1994. Terms used in this water-use analysis are defined in Table 3.3.

B1.) Report-based estimates of water use and irrigated area

Annual water-use data, available for the Lower Republican River basin from DWR for years 1980-1993, give the reported annual volume of water withdrawn by individual water-rights holders. Appropriated water rights are also described by data from DWR. These two data sources were analyzed to estimate annual water use, U by all water rights with total appropriation, R. The total reported use in a given year, U_r, is expressed as a fraction of the total appropriation, R_r by $u = U_r/R_r$, shown in Fig 3.5 for both ground and surface water. Assuming that water-use reports are representative of water use by all water-rights holders, U is estimated by $U = (U_r/R_r)\ R$, written as $U = uR$ or $U = U_r/r$, where $r = R_r/R$, the reporting fraction. Alternatively, it could be assumed that no water was used by non-reporting water-rights holders, implying that $U \approx U_r$, which can serve as a lower limit on water-use estimates.

Assuming that irrigation water-rights holders reporting irrigated area, A_a and water use, U_a, which correspond to water rights, R_a, are representative of those who do not report, total irrigated area is estimated by $A = A_a(R/R_a)$. Irrigation-water use as a depth is given by $d = 12U_a/A_a$ [in], shown in Fig. 3.6 for both ground and surface water. The procedure followed for report-based estimates is summarized in Table 3.3. Figs. 3.1-3.6 provide estimates based directly on water-use reports only for 1980-1993, for which water-use reports are available.

Table 3.2a. Appropriations and water use

	Appropriations (cfs)					Water use (cfs)				
year	gw.non	gw.irr	srf.irr	tot.irr	tot.app	gw.non	gw.irr	srf.irr	tot.irr	tot.use
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
1977	1.72	34.46	1.64	36.10	37.81	0.50	10.10	0.86	10.96	11.46
1978	1.72	35.71	1.64	37.35	39.06	0.89	18.58	1.71	20.29	21.18
1979	1.72	36.82	1.64	38.46	40.17	0.96	20.63	1.87	22.50	23.46
1980	1.72	37.15	1.64	38.79	40.50	1.77	37.13	4.04	41.17	42.93
1981	1.72	38.98	1.76	40.74	42.45	0.96	13.54	1.62	15.16	16.12
1982	2.22	38.98	1.76	40.74	42.96	1.36	13.06	1.07	14.13	15.49
1983	2.29	39.91	1.76	41.67	43.97	2.50	31.27	4.23	35.50	37.99
1984	2.29	40.04	1.90	41.93	44.23	2.55	31.34	4.05	35.39	37.94
1985	2.29	40.04	1.90	41.93	44.23	2.03	17.08	1.80	18.88	20.91
1986	2.29	40.53	1.90	42.43	44.72	1.51	15.51	1.18	16.69	18.19
1987	2.29	41.54	1.90	43.43	45.72	1.64	20.04	1.75	21.79	23.43
1988	4.23	43.42	2.22	45.64	49.87	4.22	40.68	4.03	44.71	48.93
1989	4.23	44.60	2.93	47.52	51.75	3.20	32.18	5.12	37.30	40.50
1990	4.23	47.09	3.30	50.39	54.61	3.44	31.98	4.48	36.46	39.91
1991	4.23	47.62	3.30	50.91	55.14	4.77	45.47	3.85	49.32	54.08
1992	4.25	48.01	3.40	51.41	55.67	3.37	13.06	0.99	14.05	17.42
1993	4.26	48.01	3.40	51.41	55.67	3.41	9.19	0.72	9.92	13.32
1994	4.48	48.01	3.40	51.41	55.89	2.64	28.32	4.14	32.46	35.10

Key to columns in Table 3.2a (symbols defined in Table 3.3 and in Sections 3B1 and 3B2):

1. Study year (1977-1994). Water use was estimated on the basis of water use reports for years 1980-1993 (Section 3B1); estimates for the remaining years were based on precipitation models derived from analysis of the water use reports (Section 3B2); for a summary of the water use estimate procedure, see Table 3.3 (below).

Appropriations, cfs (columns 2-6):

2. Groundwater appropriations for uses other than irrigation. Domestic water use, which is not reported to DWR, is neglected.
3. Groundwater appropriations for irrigation.
4. Surface water appropriations, all of which are for irrigation.
5. Total ground and surface water appropriations for irrigation, R_{irr} (add cols. 3 and 4). Irrigation points of diversion are identified by DWR use code value of 3.
6. Total surface and ground water appropriations for all uses, R (add cols. 2, 3, and 4).

Estimated water use, cfs(columns 7-11):

7. Non-irrigation groundwater use (excluding domestic use).
8. Irrigation groundwater use
9. Surface water use, all for irrigation.
10. Total ground and surface water use for irrigation, U_{irr} (sum of cols. 8 and 9).
11. Total ground and surface water use, U (sum of cols. 7, 8, and 9).

Table 3.2b. Water use and report ratios, irrigated area and depth, and precipitation

year	Ratios of		Report fract.		Irrigated area			Irrigation		Precipitation	
	use/approp.		of approp's.		acres	acres	pct	(in)	(in)	(in)	(in)
	gw	surf	gw	surf	gw	surf	gw+srf	gw	surf	may-aug	annual
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
1977	0.29	0.53	0.00	0.00	18277	1561	3.13	4.8	4.8	23.9	38.1
1978	0.52	1.05	0.00	0.00	19298	1778	3.32	8.3	8.3	16.9	29.9
1979	0.56	1.14	0.00	0.00	19945	1808	3.42	9.0	9.0	16.0	32.3
1980	1.00	2.47	0.26	0.05	23952	2590	4.18	13.5	13.5	9.2	22.4
1981	0.35	0.92	0.57	0.24	23206	2624	4.06	5.2	5.4	22.2	33.4
1982	0.34	0.61	0.57	0.38	20638	1832	3.54	5.4	5.1	22.5	34.7
1983	0.78	2.40	0.59	0.25	20358	2531	3.61	13.1	14.5	10.3	27.6
1984	0.78	2.14	0.66	0.37	21067	2167	3.66	12.8	16.2	11.4	30.9
1985	0.43	0.95	0.67	0.39	20477	1824	3.51	7.0	8.5	17.4	31.9
1986	0.38	0.62	0.54	0.40	21354	1221	3.55	6.0	8.4	23.0	41.2
1987	0.48	0.92	0.74	0.45	21380	2488	3.76	8.0	6.1	16.9	34.2
1988	0.94	1.82	0.51	0.31	24572	2608	4.28	14.3	13.4	9.6	16.1
1989	0.72	1.75	0.81	0.45	23554	3165	4.21	11.9	14.1	16.5	25.3
1990	0.68	1.36	0.81	0.43	24355	2993	4.31	11.4	13.0	16.8	27.2
1991	0.96	1.17	0.83	0.53	25970	2759	4.52	15.2	12.1	11.4	23.5
1992	0.27	0.29	0.69	0.43	25443	2600	4.42	4.1	3.3	20.2	37.9
1993	0.19	0.21	0.50	0.06	25410	4910	4.77	2.2	1.3	33.5	47.8
1994	0.59	1.22	0.00	0.00	26051	3808	4.70	9.4	9.4	15.4	24.4

Key to columns (symbols are defined in Table. 3.3 and in Sections 3B1 and 3B2):

1. Study year (1977-1994).

2, 3. Ratios of annual water use to appropriation for ground and surface water, respectively; $u = U/R$.

4, 5. fraction of appropriated rights that report water use for ground and surface water, respectively; $r = R_r/R$.

6, 7. Irrigated area of basin, A_{irr} (acres) for ground and surface water, respectively.

8. Irrigated area as a percent of basin, combining both ground and surface water.

9. Ground water irrigation as a depth (in), $d_{gw} = 12cU_{irr}/A_{irr}$, given ground water use for irrigation U_{irr} (cfs, Table 3.2a, col. 8), A_{irr} (acres, col. 6), and $c = 723.97$, conversion from cfs to acre-ft/yr.

10. Surface water irrigation as a depth (in), $d_{srf} = 12cU_{irr}/A_{irr}$, given surface water use for irrigation U_{irr} (cfs; Table 3.2a, col. 9), A_{irr} (acres, col. 7), and c as above (9).

Note that columns (9) and (10) are similar because they represent annual water use per unit irrigated area from ground-water and surface-water sources, respectively.

11. Precipitation (in) for May through August, which is the basis for water use estimates for years without water use reports according to (3B-1).

12. Annual spatial average precipitation (in).

Table 3.3. Definition of terms and relationships for water use analysis

n_{wr} = number of appropriated points of diversion;

n_{use} = number of water use reports for points of diversion within active grid cells;

n_r = number of reports corresponding to water rights;

n_a = number of irrigation water-use reports that also provide area irrigated;

n_{dtw} = number of water-use reports providing depth to water-level measurements;

R = total water rights (acre-ft);

R_{irr} , U_{irr}: irrigation water rights and corresponding water use (acre-ft);

U_r = reported use (acre-ft);

R_r = water rights corresponding to reported use U_r (acre-ft);

U_a = irrigation use by those rights also reporting irrigated area (acre-ft)

R_a = irrigation water rights corresponding to reported use, U_a (acre-ft);

A_a = reported area irrigated (acres)

Summary of procedure for making report-based water use estimates:

$r = R_r/R$, reporting fraction for all reported types of use;

$u = U_r/R_r$, water use as a fraction of appropriation for all reported uses, and for either ground (u_g) or surface water (u_s).

$r_a = R_a/R$, reporting fraction for irrigation in which area irrigated is given;

$u_a = U_a/R_a$, water use as fraction of appropriation for irrigation;

$U = R\ (U_a/R_a)$, estimated total water use;

$U_{irr} = R_{irr}\ (U_a/R_a)$, estimated irrigation water use (acre-ft)

$A_{irr} = A_a(R/R_a)$, estimated area irrigated (acres)

$d = 12U_a/A_a$, applied irrigation depth (in)

Summary of procedure for making precipitation based water use estimates:

$P_{m\text{-}a}$ = total precipitation (in) for May through August;

u_g = groundwater use fraction, (3B-1a) based on $P_{m\text{-}a}$;

u_s = surface water use fraction, (3B-1b) based on $P_{m\text{-}a}$;

d = irrigation depth (in) for both ground and surface water (3B-1c);

$U = u\ R$ = estimated total water use

$U_{irr} = u\ R_{irr}$ = estimated irrigation water use (acre-ft)

$A_{irr} = 12U_{irr}/\ d$ = estimated area irrigated (acres)

The arithmetic average of water-use fraction, *u*, for 1980-1993 is 1.2 for surface water and 0.60 for ground water; however, the annual variation in use fraction is large, ranging from 0.2 to 2.4 for surface water and from 0.2 to 1.0 for ground water (Table 3.2b). The data also indicate that the fraction, *r* of reporting water users varies from 0.05 to 0.53 for surface water and from 0.26 to 0.83 for ground water. The reporting fraction is higher in later years but low in wet years such as 1993.

B2.) Precipitation-based estimates of water use and irrigated area

The relationship between water use and weather was examined using regression analysis to determine whether water use can be predicted by a combination of monthly temperature and precipitation variables in years for which use data are not available. Using weather data from the National Weather Service (NWS) stations within the Lower Republican River basin, various combinations of monthly precipitation and temperature were tested as independent variables for regression models to explain water use. The exponential form

$$f(P) = a\exp(bP) \qquad (3B\text{-}1)$$

was found to be a simple and effective predictive model for both water use fraction, u(P) (ground-water use fraction u_g(P) and surface-water use fraction u_s(P)), and irrigation depth, d [P], as functions of total May-August precipitation, denoted by P. Three versions of this form are used to estimated both surface- and ground-water use and irrigated depth, given respectively by

$$u_g(P) = 2.07\ \exp(-0.0819P),\ R^2 = 0.89,\quad \text{d.f.} = 12,\quad \text{s.e.} = 0.10 \qquad (3B\text{-}1a)$$

$$u_s(P) = 5.46\ \exp(-0.0978P),\ R^2 = 0.78,\quad \text{d.f.} = 12,\quad \text{s.e.} = 0.35 \qquad (3B\text{-}1b)$$

$$d(P) = 0.81\ \exp(-0.0794P),\ R^2 = 0.89,\quad \text{d.f.} = 26,\quad \text{s.e.} = 1.7\text{ in.} \qquad (3B\text{-}1c)$$

where s.e. = standard error of estimate, d.f. = degrees of freedom, and R^2 = coefficient of determination. These relationships are significant at level $\alpha<0.01$, where α = the probability that the computed relationship is not significant. Figs. 3.2 and 3.5 show that ground-water use lies within appropriation limits for all years except 1980, whereas surface-water use exceeds appropriations in half the years 1980-1993, and so are represented separately by (3B-1a) and (3B-1b), respectively. On the other hand, Fig. 3.6 shows that surface- and ground-water irrigation depth, i.e., use per unit area irrigated, are similar in their response to May-August precipitation, and so were combined to form the basis of (3B-1c).

The water use models based on (3B-1a to 3B-1c) are useful for comparison with data from 1980 to 1993 and for projecting total water use, U, and area of irrigation, A, to the years in this study, 1977-1979 and 1994, for which water-use reports were not available. Total water is given by U = u·R as before, but the use fraction, u, is obtained from (3B-1a) or (3B-1b) rather than from the water-use data. Total irrigated area is estimated by $A = 0.3048 \cdot U_a/d$, where $U_a = u \cdot R_a$, u is given by (3B-1a) for ground water or (3B-1b) for surface water, and d is given by (3B-1c).

Fig. 3.7 compares ground-water-use fractions based on use reports for years 1980-1993 with (3B-1a), and Fig. 3.8 compares surface-water-use fractions with (3B-1b). Similarly, Fig. 3.9 compares irrigation depth based on combined ground- and surface-water-use reports with (3B-1c). As shown in Fig. 3.6, irrigation practices are similar for ground and surface irrigation; and are largely determined by May-August precipitation.

B3.) Ground-water-level survey

Recognizing the lack of water-level data, we organized and carried out a water level survey in the Lower Republican River basin between Concordia and Clay Center during the week of November 7-11, 1994. We measured 80 alluvial wells distributed throughout the valley as shown in Fig. 3.10, and the results are plotted and contoured in Fig. 3.11. A table of the measured data is presented in Appendix 3B3. During the water- level-measurement survey, we encountered Mr. Wilber Taddiken of Clay Center, who collected and made available to us monthly water levels of his wells in the Republican River valley near Clifton since 1991. We plotted these data in Fig. 3.12, where the impact of the 1993 flood on ground-water levels is clearly visible.

C.) Land Use and Soils

Table 3.4 shows estimates (Kansas Farm Facts Reports) for total cropland planted in Clay and Cloud counties, which together enclose most of the Lower Republican River basin. The cropland in each county is subdivided into areal fractions of nonirrigated crops, consisting principally of wheat, sorghum, soybeans, and hay; and irrigated crops, consisting predominantly of corn and alfalfa hay. The counties are combined into average nonirrigated and irrigated components, shown at the right of Table 3.4. The means of these components, also shown in Table 3.4, are 90.7 percent for nonirrigated crops and 9.3 percent for irrigated crops, each with a standard deviation of 1.1 percent; i.e., they are approximately constant for the period 1977-1994 according to the Farm Facts Reports. Table 3.4 is based on a more detailed version shown in Appendix 3C.

Table 3.5 shows, for each subbasin, the principal land uses as areal percents of grassland, woodland, and cropland, based on LANDSAT Thematic Mapper data. Grassland, woodland, and other minor uses (in terms of area occupied) are combined as noncropland, which is subdivided into 90.7 percent nonirrigated and 9.3 percent irrigated components according to the Farm Facts Reports analysis shown in Table 3.4. This subdivision, however, is only nominal and is superseded by a subdivision that is based on the water-use analysis described above and shown in Table 3.2; this subdivision is the irrigated area as a percent of gridded area (Fig. 3.4), which is assumed to be a representative sample of the basin's area.

Table 3.4. Summary of Cropland Uses for Clay and Cloud counties, 1977-1994 [based on *Kansas Farm Facts* Reports].

	Total cropland planted (acres)		Wheat+sorghum+soybeans+other hay (nonirrigated crops) fraction		Corn+alfalfa hay (irrigated crops) fraction		Average Non-irrigated fraction	Average Irrigated fraction
Year	CLAY	CLOUD	CLAY	CLOUD	CLAY	CLOUD		
1977	235700	261400	0.903	0.924	0.097	0.076	0.914	0.086
1978	217100	232400	0.883	0.904	0.117	0.096	0.893	0.107
1979	203300	232500	0.895	0.892	0.105	0.108	0.894	0.106
1980	221500	257700	0.893	0.896	0.107	0.104	0.895	0.105
1981	205700	249500	0.912	0.906	0.088	0.094	0.909	0.091
1982	218500	259600	0.897	0.912	0.103	0.088	0.905	0.095
1983	205000	248100	0.904	0.906	0.096	0.094	0.906	0.094
1984	210900	238700	0.908	0.911	0.092	0.089	0.910	0.090
1985	196300	236300	0.891	0.903	0.109	0.097	0.897	0.103
1986	175000	225900	0.946	0.922	0.054	0.078	0.932	0.068
1987	180000	209600	0.907	0.925	0.093	0.075	0.917	0.083
1988	178800	202500	0.920	0.911	0.080	0.089	0.915	0.085
1989	215200	227400	0.934	0.920	0.066	0.080	0.927	0.073
1990	210800	231300	0.912	0.898	0.088	0.102	0.905	0.095
1991	202900	222500	0.906	0.893	0.094	0.107	0.900	0.100
1992	212000	228700	0.910	0.896	0.090	0.104	0.903	0.097
1993	229300	244300	0.911	0.890	0.089	0.110	0.900	0.100
1994	231000	257800	0.911	0.896	0.089	0.104	0.903	0.097
		Average	0.908	0.906	0.092	0.094	0.907	0.093
		Standard Deviation	0.015	0.011	0.015	0.011	0.011	0.011
Range:								
		Minimum	0.883	0.890	0.054	0.075		
		Maximum	0.946	0.925	0.117	0.110		
Combined Cropland in Clay and Cloud Counties								
		Average	0.907		0.093			
		Standard Deviation	0.013		0.013			

Table 3.5. Summary of land uses by modified HUC-11 subbasins based on 1990 LANDSAT Thematic Mapper Data Analysis.

	Land Use				Cropland Classes[1]	
Subbasin	Grassland Percent	Woodland Percent	Cropland Percent	100-cropland r/p[2]	Dryland: 90.7% 3-wsf[3]	Irrigated: 9.3% irc[4]
1	34.67	4.73	59.62	40.38	54.08	5.54
2	35.47	7.01	54.63	45.37	49.55	5.08
3	31.44	4.79	62.81	37.19	56.97	5.84
4	35.73	5.84	57.37	42.63	52.03	5.34
5	23.66	3.3	71.64	28.36	64.98	6.66
6	34.48	4.21	61.13	38.87	55.44	5.69
7	28.34	3.46	67.53	32.47	61.25	6.28
8	43.82	2.61	53.16	46.84	48.22	4.94
9	24.21	3.09	69.91	30.09	6.50	

[1] Irrigated/Dryland percentages from Table 4.

[2] r/p=range and pasture (grassland+woodland).

[3] wsf=nonirrigated crops: wheat+sorghum+soybeans+other hay;
(index crop: 3-yr rotation of wheat, sorghum, fallow).

[4] irc=irrigated crops: corn+alfalfa hay (index crop: corn).

Land use, then, is described by three components, namely grassland, nonirrigated crops, and irrigated crops, which are represented in SWAT by the following management schemes. Grassland is represented as pasture with a growing season from March 1 through October 31 (designated as"r/p" for range and pasture). Nonirrigated cropland is represented by a three-year crop rotation of wheat, sorghum and fallow (designated as "3-wsf") as follows. Wheat is growing at the beginning of the three-year cycle, having been planted at the end of the previous cycle, and is harvested June 25 of the first year. The land remains fallow until the spring of the second year: sorghum is planted May 1 and is harvested October 10. The land again remains fallow until the end of the third summer: wheat is planted on September 20 and grows for the remainder of the year, completing the three-year cycle. Irrigated cropland is represented by corn (designated as "irc"), which is planted May 7 and harvested September 7 every year.

Table 3.6 shows the areal fractions for each of the six soil types present in the Lower Republican River basin; within each subbasin, the sum of areal fractions over the soil types adds to 1, as shown in the right-hand column. The six soil types are combinations of associations whose designations are listed below each of the six corresponding columns of Table 3.6. Figures 3.13 and 3.14 are maps of these soil associations for the Lower Republican basin, and identify the main soil series in each association, whose designations are given by the National Resource Conservation Commission (NRCR), formerly Soil Conservation Service (SCS). Both maps are overlaid by the subbasin boundaries and the numbering scheme used to identify them; Fig. 3.14 shows only the area gridded for the purpose of the aquifer model, and overlays the grid used for that model with the row and column indices and the corresponding township coordinates.

The categorization of the soil associations shown in Table 3.6 allows the soils of the basin to be represented by the characteristics of these six soil types as defined for the STATSGO soils data base. Each soil type is characterized by three or four layers in terms of depth; bulk density; available water content; permeability; content of silt, sand, and clay; and organic carbon content. In addition, Table 3.6 shows the texture associated with each of these soil types: Carr is identified as fine sandy loam, Crete and Hastings as silty clay loam, Hedville as stony loam, and Kipson and Muir as silty loam.

The irrigated land percent (Table 3.2), land-use percents (Table 3.5), and soil fractions (Table 3.6) are read and summarized by our WEIGHTS program (see section 5E1, and also volume 2 for details) for each year as shown in Table 3.7; note that the irrigated-crop percent is that shown in Table 3.2 based on water-use reports for 1980-1993, superseding the values shown in Table 3.4 based on Farm Facts Reports, and is subtracted from the cropland percent to obtain the nonirrigated-crop percent in Table 3.7.

D.) Climate and Streamflows

Fig. 3.15 displays the precipitation and temperature climate stations employed in the Lower Republican River basin. Initially both precipitation and temperature Thiessen

Table 3.6. Modified HUC-11 subbasin areal fractions for each soil type.

	Predominant Soil Series in Soil Associations						
Subbasin	Carr	Crete	Hastings	Hedville	Kipson	Muir	Sum
1	0.092	0.471	0.099	0	0.338	0	1
2	0.191	0.064	0.402	0	0.342	0	0.999
3	0.098	0.637	0.125	0.007	0.052	0.081	1
4	0.126	0.543	0.054	0	0.274	0.004	1.001
5	0.043	0.745	0	0	0.086	0.126	1
6	0	0.741	0	0.176	0.059	0.024	1
7	0	0.869	0	0.022	0	0.108	0.999
8	0	0.697	0	0.279	0	0.024	1
9	0	0.63	0	0.021	0	0.348	0.999
Max Fraction	0.191	0.869	0.402	0.279	0.342	0.348	
STATSGO Soil Association Designations	KS374	KS301 KS307 KS327	KS345	KS302	KS304 KS314	KS372	
Soil Texture	Fine Sandy Loam	Silty Clay Loam	Silty Clay Loam	Stony Loam	Silty Loam	Silty Loam	

Table 3.7. Land use and soils.

	Land use (percent subbasin area)				Predominant soil series (percent subbasin area)					
Sub-basin	cropland	nonirrig.[1]	irrigated[2]	grasses[3]	Carr	Crete	Hastings	Hedville	Kipson	Muir
1	59.62	55.59	4.03	40.38	9.2	47.1	9.9	0	33.8	0
2	54.63	50.60	4.03	45.37	19.1	6.4	40.2	0	34.2	0
3	62.81	58.78	4.03	37.19	9.8	63.7	12.5	0.7	5.2	8.1
4	57.37	53.34	4.03	42.63	12.6	54.3	5.4	0	27.4	0.4
5	71.64	67.61	4.03	28.36	4.3	74.5	0	0	8.6	12.6
6	61.13	57.10	4.03	38.87	0	74.1	0	17.6	5.9	2.4
7	67.53	63.50	4.03	32.47	0	86.9	0	2.2	0	10.8
8	53.16	49.13	4.03	46.84	0	69.7	0	27.9	0	2.4
9	49.91	45.88	4.03	50.09	0	63.0	0	2.1	0	34.8

[1] (total cropland - irrigated land); represented by rotation of wheat, sorghum, and fallow.

[2] Average value for 1980-1993, represented by irrigated corn; based on Table 3.2b (DWR), superseding values in Table 3.4.

[3] (100-total cropland); represented by range and pasture.

polygons were constructed to spatially distribute precipitation and temperature throughout the basin. However, we realized that this averaging process tends to smooth out climatic variations which in turn impacts runoff calculations. Therefore, we decided not to Thiessen-average climatic-station data. Instead, we chose the closest climatic station to each subbasin as typical of the climatic characteristics of that subbasin. Thus, for each of the nine subbasins employed, the following precipitation and temperature stations were used.

Subbasin	Precipitation Station	Temperature Station
1	Bellville	Bellville
2	Concordia Airport	Concordia Airport
3	Miltonvale	Concordia Airport
4	Clifton	Concordia Airport
5	Clifton	Washington
6	Clifton	Washington
7	Clifton	Washington
8	Clay Center	Clay Center
9	Clay Center	Clay Center

Some stations had only precipitation or only temperature records for the period of interest (1977-1994), thus explaining why some subbasins had different climatic stations for precipitation and temperature, respectively. These data were obtained from the National Climatic Data Center (NCDC), Asheville, NC, and sorted in a CD-ROM storage medium by EarthInfo, Inc.

Streamflow data were available on a daily basis from two USGS streamgaging stations near Concordia and Clay Center, respectively. These data were electronically retrieved from the USGS ADAPS database and are displayed on an annual basis in Fig. 3.16. The baseflow separation program HYSEP2 (White and Sloto, 1990) was employed to determine baseflows in Figs. 3.16a and b using the local minimum technique.

Figures 3.16d and e display the established monthly minimum desirable streamflows (MDS) for the Republican River at Concordia and Clay Center, respectively, together with the monthly streamflows at the same locations for the period January 1977 to December 1994. We see that during the late 80's and beginning 90's, MDS were repeatedly violated.

E.) Farm Ponds

SWAT has the capability to account for the effects of farm ponds on water yield. For this purpose we identified all major water bodies within all subbasins in the study area using the ARC-INFO GIS database. We also used the GIS to identify the areas of each pond plus the drainage areas which contribute runoff to the ponds. The existing digital elevation model (DEM) for the Lower Republican River basin was too coarse for delineating drainage areas (the existing DEM corresponded to a scale of 1:250,000). However, we had available a digital line graph (DLG) GIS coverage of our area with elevation contours corresponding to 1:100,000 scale. Using the ARC-INFO TOPOGRID command, we converted this DLG coverage to a DEM coverage, and this allowed us to use the WATERSHED command to identify the drainage areas for each pond in a satisfactory manner. Figure 3.17 outlines these pond-drainage areas for each subbasin and identifies each water body with a code number. Tables 3.8 and 3.9 list the pond and contributing watershed areas for all ponds in each subbasin plus additional information.

F.) Hydrogeologic Properties of Lower Republican River Valley Alluvial Aquifer

Hydrogeologic-parameter data (i.e. hydraulic conductivity and storativity) are very limited, thus causing problems in establishing an areal distribution of these parameters in a two-dimensional areal model, and also in obtaining representative average values of these parameters. Fader (1968) listed a number of hydraulic-conductivity values in the Republican River area for Republic and Cloud counties, based predominantly on specific capacity and step-drawdown tests. The average hydraulic conductivity for Cloud County based on 31 such tests (Fader, 1968) is 422 ft/day, which indicates that the Republican River alluvium in Cloud County is highly permeable. Walters and Bayne (1959) reported the results of one pump test in the Republican River valley of Clay County resulting in a hydraulic conductivity of 300 ft/day, which also confirms that the Republican River alluvial aquifer is highly permeable. Storativity values, however, are generally lacking. A Kansas Geological Survey map of saturated thickness and specific yield of Cenozoic deposits in Kansas (Bayne and Ward, 1969) indicates a value of 0.20 for the specific yield of the Lower Republican River alluvial aquifer.

The ARC/INFO GIS database developed for this study proved to be extremely useful in our numerical simulations. By superimposing the MODFLOW grid (1 mi x 1 mi square mesh, shown in Fig. 3.18) on the various data coverages, we were able to extract most MODFLOW required data quickly, accurately, and efficiently. A utility module named REGRID was programmed to read the GIS output files containing the grid-cell indices, location (latitude and longitude), and elevations (water level, bedrock, ground surface) and set up appropriate MODFLOW input files. Figs. 3.19 through 3.22 depict the grid values extracted through the GIS system for bedrock elevations, 1977 water-table elevations, spring 1977 aquifer saturated thickness, and land-surface elevations, respectively. The saturated thickness is higher in the valley west/northwest of Concordia with thicknesses on the order of 70-100 ft, and thins as one moves east/southeastward down to the order of 15 to 30 ft near Clay Center.

Fig. 3.18 also displays GIS-derived stream lengths and slopes. Stream lengths within each grid cell were also obtained from the GIS, and employed to calculate streambed conductance. Streambed conductance, C, is defined as $\left[C=\frac{k'}{b'}(L*W)\right]$, where $\left(\frac{k'}{b'}\right)$ is the ratio of streambed hydraulic conductivity to streambed thickness, L is the actual stream length within the grid cell, and W is the average stream width within the grid cell. The

Table 3.8. Individual ponds and contributing areas.

subbasin no.	pond no.	pond area (acres)	pond-contributing area (acres)	subbasin area (acres)	pond area / contributing area	contributing area / subbasin area
1	2	4.77	6.00	139781.77	0.7937	0.00004
1	3	4.55	80.06	139781.77	0.0568	0.00057
1	4	7.21	242.69	139781.77	0.0297	0.00174
1	8	7.43	32.02	139781.77	0.2320	0.00023
1	9	8.72	111.31	139781.77	0.0784	0.00080
1	11	26.45	1595.20	139781.77	0.0166	0.01141
1	12	8.89	6.00	139781.77	1.4798	0.00004
1	14	4.23	34.03	139781.77	0.1244	0.00024
1	23	5.47	108.08	139781.77	0.0506	0.00077
1	29	4.69	360.27	139781.77	0.0130	0.00258
1	31	6.13	242.18	139781.77	0.0253	0.00173
1	35	6.51	120.09	139781.77	0.0542	0.00086
1	38	5.35	104.08	139781.77	0.0514	0.00074
1	41	5.12	124.09	139781.77	0.0413	0.00089
1	42	7.68	469.64	139781.77	0.0164	0.00336
1	45	6.12	136.10	139781.77	0.0450	0.00097
1	48	6.58	202.15	139781.77	0.0326	0.00145
1	60	5.28	152.38	139781.77	0.0347	0.00109
1	65	7.04	56.04	139781.77	0.1257	0.00040
1	68	8.32	594.70	139781.77	0.0140	0.00425
1	69	4.38	16.01	139781.77	0.2735	0.00011
2	72	22.70	64.05	31168.49	0.3544	0.00205
2	73	19.67	32.02	31168.49	0.6143	0.00103
3	78	4.92	36.03	129754.38	0.1366	0.00028
3	79	5.22	70.05	129754.38	0.0745	0.00054
3	83	5.69	260.20	129754.38	0.0219	0.00201
3	86	6.44	204.15	129754.38	0.0316	0.00157
3	87	12.34	230.34	129754.38	0.0536	0.00178
3	88	21.79	32.02	129754.38	0.6805	0.00025
4	30	10.29	154.12	55427.19	0.0668	0.00278
4	33	8.59	364.27	55427.19	0.0236	0.00657
4	34	7.88	300.45	55427.19	0.0262	0.00542
4	39	5.55	244.18	55427.19	0.0227	0.00441
4	43	4.65	38.03	55427.19	0.1224	0.00069
4	47	4.78	358.27	55427.19	0.0134	0.00646
4	61	4.50	26.02	55427.19	0.1728	0.00047
5	55	13.12	60.11	33536.62	0.2182	0.00179
5	76	10.76	10.01	33536.62	1.0749	0.00030
7	74	2.13	347.45	69498.07	0.0061	0.00500
7	75	4.12	146.11	69498.07	0.0282	0.00210
7	77	6.96	194.15	69498.07	0.0359	0.00279
7	81	3.90	162.12	69498.07	0.0240	0.00233
7	82	2.82	58.06	69498.07	0.0485	0.00084
8	100	5.83	868.58	74849.09	0.0067	0.01160
8	104	9.04	70.05	74849.09	0.1291	0.00094
8	106	25.51	378.14	74849.09	0.0675	0.00505
8	113	8.50	96.07	74849.09	0.0885	0.00128
8	115	9.18	84.06	74849.09	0.1093	0.00112
8	301	14.95	230.17	74849.09	0.0650	0.00308
8	302	24.81	134.10	74849.09	0.1850	0.00179
8	303	14.73	140.11	74849.09	0.1052	0.00187
8	304	13.42	422.32	74849.09	0.0318	0.00564
8	305	4.87	38.03	74849.09	0.1280	0.00051

8	306	5.90	62.05	74849.09	0.0951	0.00083
8	307	22.28	230.17	74849.09	0.0968	0.00308
8	308	10.87	54.04	74849.09	0.2012	0.00072
8	309	16.16	192.14	74849.09	0.0841	0.00257
8	311	9.74	98.07	74849.09	0.0993	0.00131
9	80	9.31	303.62	48567.82	0.0307	0.00625
9	84	24.33	914.22	48567.82	0.0266	0.01882
9	85	7.52	16.01	48567.82	0.4694	0.00033
9	92	33.78	139.22	48567.82	0.2426	0.00287
	sum	610.49	12656.58			

Lower Republican River streambed conductance varied from 0.9 to 7.6 ft^2/sec depending on actual stream length (L) within the grid cell, and the ratio of streambed hydraulic conductivity to streambed thickness $\left(\frac{k'}{b'}\right)$; the range of this ratio was estimated from 0.17 to 0.33 ft/day/ft, using NRCS soil-property data to estimate streambed hydraulic conductivity; average stream width (W) for the Lower Republican River was approximated at 150 ft. The average streambed conductance was 2.85 ft^2/sec.

Another utility module (WRBASIN) was programmed to read legal locations of water-rights appropriations and convert them to the appropriate locations on the grid as required for MODFLOW's WELL module input file.

4. OVERVIEW OF THE MODELING PROCESS

Numerical modeling is the most commonly used form of ground-water/surface-water modeling analysis. The strength of numerical models is their ability to tie together data and physical principles into a coherent and useful picture of an area. Numerical models are a tool to solve problems but not the solution itself. Numerical models do not give accurate answers to insufficiently defined problems. In designing a ground-water/surface-water model, the model user combines numerous modeling components. These components are:

- Natural system for which the model is designed.
- Conceptual model as an idealized representation of the natural system.
- Mathematical model representing controlling mechanisms in mathematical terms.
- Solution of the mathematical model.
- Calibration of the solution by adjusting simulated to observed responses of the natural system.
- Verification or validation of the accuracy of the model predictions.
- Simulations based on the calibrated solution of the conceptual model.

This section explains the steps usually required to prepare a realistic area-specific model (Figure 4.1).

The first step of a model study consists of collecting and evaluating relevant data on the flow system under investigation. These data are used for

- Problem definition (material properties and geometry of hydraulic units).
- Numerical requirements (initial conditions, boundary conditions, time-stepping conditions, and spatial discretization).
- Modeling requirements (calibration targets, validation targets, and definition of alternate hypotheses and scenarios).

Field data are essential to understand the natural system, to specify the investigated water problem, to facilitate selection of computer code, and to derive model input data. The quality of the simulations depends in large part on the validity of the model physics and on the quality of the input data.

The second step in a modeling study is developing a conceptual model. A conceptual model is an idealization of the real world that summarizes the current understanding of area conditions and how the flow system works. It embodies all of the important features of the flow system, while incorporating simplifying assumptions. The three purposes of developing a conceptual model are

- Develop a better understanding of field conditions and be able to communicate this understanding.
- Define the water problem for development of a numerical model.
- Aid in selecting a suitable numerical model.

Transfering the real world into an equivalent model system, which can then be solved using existing program codes, is a crucial step in modeling. Errors in the conceptual model cannot be corrected during the model calibration or at any later stage of the modeling project without major revisions. The three steps in developing a conceptual model are (1) explore and summarize the key mechanisms governing water flow at the site, (2) develop the assumptions and simplifications required to make the real situation tractable to analysis, and (3) establish the framework of the model (number of dimensions, type of model).

The conceptual model itself may take various forms. Different approaches are suited to different flow systems and model objectives. Figure 5.2 illustrates one type of a conceptual model consisting of a pictorial representation of the flow system in the form of a block diagram.

The third step in the modeling process is to select a model code. General considerations in the selection process include defining model objectives, selecting a model based on appropriate technical criteria to match area characteristics with a model of appropriate capabilities, and using implemention on criteria to narrow the choices.

The model technical and implementation criteria can be summarized as four key questions:

- Can the model adequately simulate area conditions?
- Can the model satisfy the objectives of the study?
- Is the model verified and reasonably well field-tested?
- Is the model well-documented, peer-reviewed, and available?

Model setup is the fourth step in the modeling process. Model setup and calibration often constitute 50 to 70 percent of the total modeling effort. Model setup entails selecting the model domain, discretizing data in space and time, defining boundary and initial conditions, and assembling and preparing model input data. Choice of the domain and discretization affect the physical and numerical resolution and level of effort (cost) of the modeling study.

Selection of the optimum model domain involves balancing the following factors:

- The domain should cover the entire area of interest.
- The boundaries of the domain should take advantage of natural ground-water boundaries such as rivers, lakes, drains, ground-water divides, edge of aquifer, boundary between adjacent pumping centers, ground-water recharge/discharge area or boundary location distance (in hydrologic terms) from the area of interest. Note that rivers, lakes, and drains are not always ground-water boundaries and that ground-water divides may move over time or with depth.
- The model domain should be oriented parallel to the primary ground-water-flow direction to reduce numerical dispersion.
- Available data should adequately define conditions throughout the domain selected.
- Domain size should be minimized to reduce computational effort.

In discretizing a model, the orientation of the model, space discretization, and time discretization must be considered. The following factors affect model mesh orientation:

- Hydrologic, hydrogeologic, and geologic features at the site. Representation of key features such as rivers, streams, impoundments, faults, and other natural boundaries can be simplified through appropriate orientation of the mesh.
- Predominant ground-water-flow direction. Numerical dispersion due to the ground-water velocity being split into components parallel to the calculation-mesh axes is minimized if the mesh is oriented along the direction of predominant ground-water flow. If the flow direction varies within the model domain, alignment of the calculation mesh with the flow direction in the primary area of interest is optimum.
- Anisotropy of hydraulic properties. Since the hydraulic conductivity is expressed in the model as components aligned with the axes of the calculation mesh, inaccuracies are reduced by choosing a mesh oriented coincident with the conductivity tensor.

Selecting the model grid-cell size is comparable to selecting a net for fishing; the openings in the net must match the size of the "fish" (heterogeneities and predictive details) to be captured. The following factors are considered when choosing a model grid:

- Degree of heterogeneity in hydraulic parameters and boundary conditions.
- Model domain size.
- Predicted resolution required to meet modeling objectives.
- Restrictions imposed by computational resources.

In general, the accuracy of the predicted results improves with finer calculation meshes, but computational time and space requirements increase correspondingly.

Two kinds of time intervals are used in models: stress periods (during which boundary conditions are constant and between which boundary conditions vary) and time steps (during which model calculations are made). This section discusses time-step selection. Time steps are required for transient calculations. Factors affecting choice of time step include numerical stability considerations, time variation of boundary conditions, and time-related modeling objectives. In general, the smaller the time step, the more accurate are the predicted results. Too small a time step results in excessive computation time, while too large a time step results in an excessive number of iterations required to reach a mass-balanced solution and possibly numerical dispersion or instability.

A model boundary is the interface between the model-calculation domain and the surrounding environment. Boundaries occur at the edges of the model domain and at other points where external influences are represented, such as rivers, wells, leaky impoundments, or chemical spills and so forth. Boundary conditions are expressions of the effect of the external world on the model domain, and they are required to complete the description of a flow or transport problem. The mathematical expression of the boundary condition is required for a well-posed problem. There are three major types of boundary conditions, all of which may vary with time (Table 4.1). These boundary conditions each have differing degrees of constraint upon the model solution and implications to the ease of developing a balanced model solution.

The initial conditions describe the distribution of heads throughout the model domain at the start of the simulation. Errors in initial conditions will propogate through a transient solution, causing unrealistic predictions especially in the early time steps. However, the impact of initial conditions diminishes with time in the simulation. The initial conditions supplied to a transient run should be the result of a steady-state flow, which will give a mass-balanced starting point.

Field data provide local estimates of conditions, whereas a model requires input of data distributed over the entire model domain. Either model input data are zoned (with homogeneous values within each zone) or they have a continuum of input values. Overall model realism reflects the methods used to estimate model input data from field, laboratory, and literature data. Estimation methods range from use of parameter estimation or inverse models to trial and error methods.

In an inverse method, the objective is to determine values of the parameters and hydrologic stresses from information about heads, whereas in the forward problem, system parameters such as hydraulic conductivity, storativity, and hydrologic stresses (such as recharge rate) are specified, and the model calculates heads. The advantages of inverse methods are:

- Results include the mean value and the parameter variance.

Table 4.1. Model-boundary conditions.

Boundary Type	Boundary Name	Common Applications	Constraints on Solution	Effects of Boundary Condition on Solution
First kind, or Dirichlet boundary	Prescribed or constant pressure, hydraulic head, or concentration	Lakes, rivers, springs, constant-head wells, seepage faces	Most constrained	Easiest to solve
Second kind, or Neumann boundary	Prescribed flux of head or concentration; no flow	Impermeable boundary, water divide, streamline, infiltration, evaporation, sinks, and sources	Moderately constrained	Moderately difficult to solve
Third kind, or Cauchy boundary	Semipermeable or head-dependent flux	Leaky rivers, drains, seepage faces	Least constrained	Most difficult to solve

- Subjectivity is removed from the calibration process.
- All of the field data are honored.

The disadvantages of inverse methods are

- Extensive time and computational effort are involved.
- Intuition based on training, experience, and knowledge of the site and other soft data are neglected.
- The model output may be erroneous, unstable, or nonunique if the input data are sparse or of differing quality.

The trial-and-error method involves variation of uncertain input data, taking into account observed data, intuition, and analogies with other sites. The trial-and-error approach is the most widely used approach in practical applications. The advantages of this method are

- Data of varying accuracy may be used appropriately.
- Soft data, such as inferences based on site-specific data, may be reflected in the input data.
- Less effort is required to understand results.

The disadvantages of the trial and error method are

- The resulting model reflects, in part, the experience (or inexperience) of the modeler.
- No simple criterion can assess satisfactory completion of this task.
- The uncertainty in the input data, and its reflection in accuracy of predictions, is not quantitatively defined.

A range of methods fall between the inverse and trial-and-error methods and can be used to augment trial-and-error and parameter estimation. These techniques include, for example, geostatistics, and equivalent-media approximations.

Model calibration, step 5 of preparing the model (Fig. 4.1), is the process of varying uncertain model input data over likely ranges of values until a satisfactory match between simulated and observed data is obtained. Calibration is needed to account for unmeasured, unknown, or unrepresented conditions or processes and uncertainty in measured input data. If an inverse model is used for parameter estimation, then this step of the modeling process is partially automated. However, if data need to be extrapolated, or the field data are unsuited to automatic calibration, then the more traditional approach of trial-and-error calibration is needed. Model testing prior to application in predictive mode is often split into two processes: calibration and verification or validation. The field data are split into two data sets, often for different time periods at one area: one data set is used for calibration and the other for verification or validation.

The model-calibration step requires the greatest effort. The calibrated model may evolve in a variety of ways. For example, the modeling analysis might begin with incomplete field data, and the model may be refined as additional data become available.

Alternatively, the model input data could contain some well-defined parameters and some highly uncertain data. Varying these uncertain data is the starting point for the calibration process. Typically parameters should only be varied within measured or likely ranges, parameter distributions should be limited to geologically feasible hypotheses, and parameter values in areas beyond the extent of field data can be varied the most.

Model calibration usually involves most of the following steps:

- Establish calibration criteria. Calibration criteria compare model-prediction errors with key components of the model mass balance. That is, a discrepancy between predicted and observed heads is compared to a key hydraulic gradient, as described below. Model performance criteria might be:

  Paired-data testing (i.e., comparing predicted and observed values for corresponding locations in time and space). Common examples of such testing are *variance* between predicted and observed data should be less than about 10 percent of the range of observations, *standard deviation* between predicted and observed data should lie in the range 0.7 to 1.0 depending on the number and quality of data points, and *bias* between predictions and observations should be random rather than systematic.

  Averaged paired-data testing (i.e., the predicted and observed values are averaged over space and/or time and then compared).

  Frequency distribution testing (i.e., predicted and observed cumulative-frequency distributions are compared).

- Modify model assumptions and/or uncertain input data, within reasonable bounds, to obtain a realistic simulation. Specify model input data in ranges of values. Note the accuracy of these data so that changes made during the calibration procedure will concentrate on the most uncertain data while remaining within realistic bounds.

- Predict transient-flow conditions for the period of development up to the present (this process is also known as *history matching*). Ideally the transient-calibration period should be as long as, or longer than, the period of future predictions to which the calibrated model will be applied.

- Evaluate the model predictions versus historical observations. The model evaluation should use as many pieces of information as possible.

The objectives of <u>model error analysis</u> are to quantify how well the model simulates the physical system and to identify problem areas in the model. The method typically used to quantify model error is to compute the difference between predicted and observed values (residual) at a point (e.g., monitoring location) and evaluate these differences. The residuals may be illustrated as scatter diagrams of predicted values versus observed values or histograms of residuals or spatially displayed. Ideally a histogram of residuals should be normally distributed around zero, and the residuals should be randomly distributed in space.

Model errors occur from five general sources:

- Mathematical-model errors. These errors involve the physical and mathematical basis of the computer code and its numerical framework. This framework should be appropriate to the situation to be simulated, with inherent assumptions honored.
- Conceptual errors. Among these are misconceptions about the governing mechanisms, boundary conditions, sources, and dimensionality of the problem.
- Input data errors. Input errors include mistakes in data entry, sets of assumptions about data that in combination do not make sense, measurement error (see Section 6D for errors in ground-water data), and levels of heterogeneity that either have not been identified and characterized in the field or cannot be represented in the model. The last two sources of error are unavoidable and should be taken into account when interpreting the model predictions.
- Numerical errors. Examples include truncation errors due to truncation of the Taylor series expansion of the finite-difference or finite-element formulation of the governing equations, roundoff errors due to the precision of numbers stored by the computer, and numerical dispersion due to discretization.
- Interpretation errors. These can take the form of misunderstanding of the predicted results, misconception of the expected results (e.g., prediction of contaminant migration at an angle to ground-water flow), and comparison of spatially and temporally averaged model predictions with point observations.

Model-sensitivity analysis (see next) may also provide feedback on model error predictive uncertainty due to uncertainty in model inputs.

Model-sensitivity analysis is the seventh step (Fig. 4.1) in the modeling process, and is also considered part of the calibration and error-analysis procedures. The purpose of sensitivity analyses is to demonstrate the model responses to variations in uncertain input parameters. The model response to these variations is of interest because the range in the resulting predictions illustrates the level of model-prediction uncertainty and, given a sensitivity case with results as statistically valid as the calibrated model, it demonstrates the nonuniqueness of the calibrated input data set. A systematic sensitivity analysis provides sufficient data to rank the input parameters in terms of their influence on the predicted results. The results of a sensitivity analysis can be used to

- Identify sensitive input parameters for the purpose of guiding additional field data collection and, perhaps, focusing calibration efforts.
- Define parameters to be used in uncertainty analysis.

A typical sensitivity analysis involves rerunning the calibrated model with each of the input parameters individually varied to their maximum values. An ad hoc sensitivity analysis will have been undertaken during the calibration process, but a more rigorous sensitivity analysis is based on the calibrated model. Sensitivity analysis is typically performed by changing one parameter value at a time.

Model verification or validation, the eighth step, is the process of demonstrating that the calibrated model is an adequate representation of the physical system. Model validation is a shortcut to gaining greater confidence in model predictions in the absence of uncertainty analyses. Validation is more common in hydrologic modeling for which time-history data are often available. One approach to model validation would be to successfully predict existing conditions. In this method model validation uses comparison data not employed in the calibration process. This method is the most useful but can only be used if there are sufficient data to describe the entire domain satisfactorily using half (or a fraction) of the available data.

Step nine in the model process (Fig. 4.1) is conducting the model predictive simulations. The model predictions are often considered the main purpose of the modeling exercise, although there may be many more purposes to a model than straightforward prediction. The assumptions to be used in the predictive analyses should be well defined. As model predictions extrapolate over time, the time period of model predictions should be comparable to the period of model calibration.

Two major pitfalls are involved in making predictions: uncertainty in the calibrated model and uncertainty about future hydrologic stresses. Each of these requires a different type of sensitivity analysis. Even though the set of calibrated parameters may give close agreement during calibration and verification, the model may not accurately reflect system behavior when the model is stressed in some new way. Therefore, a sensitivity analysis should be performed to quantify the effect of uncertainty in parameter values on the prediction.

Furthermore, many predictive simulations require guesses about the likelihood and magnitude of future hydrologic or human-regulated events such as future recharge events or pumping rates. Because such information is known only with uncertainty, new errors are introduced into the simulation. In the predictive sensitivity analysis, several variations of a particular scenario are simulated. For example, several different pumping rates may be simulated or the response of the system to different assumed recharge rates may be tested. The resulting heads and drawdowns for each scenario are reported.

5. MODEL DESCRIPTION

A). Overview of Conceptual Model

The Lower Republican River valley aquifer consists of Quaternary alluvium and terrace deposits overlying shale and limestone bedrock formations of Cretaceous and Permian age. This valley aquifer is therefore modelled as a single-layer, unconfined aquifer system. This aquifer unit is only a small portion of the Lower Republican River basin, the remainder being soil-covered bedrock outcrops, representing non-aquifer material. Recharge to the system is primarily a function of precipitation, soil and vegetation cover, land use, depth to water table, and irrigation return flow. The Lower Republican River is both recharging and draining the alluvial aquifer at different river segments. Ground-water and surface-water-based irrigation in the valley may be impacting streamflows, especially during drought years. The Republican River is gaining surface runoff from a number of tributaries draining the upland subbasins. Because the interest in this study is the Republican River valley from Concordia to Clay Center, only that portion of the watershed which drains into this stretch of the Republican River is numerically simulated. A constant specified head across the river valley just west of Concordia is thus considered as a boundary condition in the model. The contributions of the Republican River basin upstream of Concordia are represented in the model by the Republican River incoming streamflows at the Concordia streamgaging station. Water percolating beyond the root zone over the Republican River valley is considered as recharge to the alluvial aquifer. Our conceptual model of the combined surface and ground-water-flow system is pictorially represented as a block diagram in fig. 5.2.

B.) Model Selection and Design

Because the primary purpose of the modeling study was to construct a comprehensive model of the Lower Republican River basin, an extensive review of existing stream-aquifer and watershed models was undertaken to identify potential candidates. It was critical that the chosen model adequately handle the hydraulic interaction between the surface and subsurface bodies of water, especially along the Republican River. Additionally, all the key hydrologic processes within the surface and subsurface water systems should be simulated in sufficient detail and accuracy. For example, the surface-water component of the model should be capable of handling land use, evapotranspiration, surface runoff, climatological impacts, etc., adequately. In the subsurface, it is important to represent the system on a distributed rather than a lumped scale, so that irrigation pumpage could be represented in detail. Therefore, it was neccesssary that the ground-water component of the model permit at least semi-continuous representation of the hydrogeologic properties, a variety of different types of boundary conditions, and also adequate accounting of agricultural and other withdrawals.

In accordance with the objectives of the Lower Republican River basin study, several alternative models could be used in our study. Objective methods of choosing the best model have not yet been developed, so this choice remains a part of the art of hydrologic modeling. Four general criteria that can be used to choose between alternative models are (a) accuracy of prediction, (b) simplicity of the model, (c) consistency of parameter estimates, and (d) sensitivity of results to changes in parameter values.

Accuracy of prediction of system outputs is obviously very important. It is desirable that models developed by research groups be tested in such a manner that error statistics are known. All other factors being equal, the model with minimum bias and error variance would be superior. Simplicity refers to the number of parameters that must be estimated and the ease with which the model can be explained to clients or public bodies. Again, all other factors being equal, one should choose the simplest model. Consistency of parameter estimates is an important consideration in developing conceptual models using parameters estimated by optimization techniques. If the optimal parameters are very sensitive to the particular period of record used, or if they vary widely between similar watersheds, the model will probably be unreliable. Finally, models should not be too sensitive to input variables that are difficult to measure.

Measured streamflow from a watershed is the sum of surface runoff, lateral flow from the root zone, and return flow from the shallow aquifer (Figure 5.1). Few models attempt to simulate all these components. Ground-water models simulate the aquifer system and usually include stream-aquifer interaction processes. Several watershed-scale models have been developed to simulate the surface and root zone, but usually ignore ground-water aspects.

In order to accomplish the objectives of this study, based on the above-mentioned general and also on other specific criteria, the selected model should be (1) distributed at the watershed scale, allowing the basin to be subdivided; (2) physically based as much as possible; (3) designed to accept readily available inputs to allow general use over large regions; (4) continuous in time to allow simulation of land-management factors such as crop rotations, tillage, reservoir operation, etc.; (5) computationally efficient to allow simulation of a variety of management strategies without excessive cost; (6) capable of simulating long periods for use in frequency analysis; and (7) "verified" over a wide range of hydrologic regimes.

We examined a number of candidate models, some of which are briefly described in Appendix 5B. We put emphasis on physically based, continuous simulation, distributed, and agriculturally oriented models. Thus we exclude from the descriptions single-event models, as well as rangeland-oriented models.

From the evaluation process we concluded that none of the well-established and technically supported models currently available was capable of independently representing the key hydrologic and hydrogeologic processes adequately in the basin. We therefore recommended developing a model by combining the stream-aquifer model MODFLOW with the watershed model SWAT. Both models are well established, provide a wide range of modeling options and flexibility, can represent field conditions adequately, incorporate robust numerical schemes, are GIS-capable, are public domain software, and finally have a long history of successful use in the field. Therefore, the MODFLOW and SWAT models were linked into a comprehensive surface- and ground-water-modeling tool. Extensive coding was implemented for linking the two models into a single combined model. The details of this linkage are reported in Appendix 5B.

A brief description of the individual model components (SWAT and MODFLOW) and the combined model (referred to in this report as SWATMOD) is provided below.

C.) SWAT Description

SWAT (Soil and Water Assessment Tool, Arnold et al., 1993) is a mostly physically based, linked surface-subsurface watershed model. The objective in model development was to predict the effect of management decisions (climate, vegetative, and land-use changes; ground-water withdrawals; reservoir management; and water transfer) on water, sediment, and chemical yields with reasonable accuracy for river basins.

The system simulated by the SWAT model consists of four control volumes that include (1) the surface, (2) the soil profile or root zone, (3) a shallow aquifer, and (4) a deep aquifer, if present, as shown in Figure 5.1. Contributions to streamflow are surface runoff, lateral flow from the soil profile, and return flow from the shallow aquifer. The percolation from the soil profile is assumed to recharge the shallow aquifer. Once the water percolates to the deep aquifer, it is lost from the simulated system and cannot return.

A brief description of the major components of the model is presented here. Those processes, such as sedimentation, nutrients, and pesticides, that are not used in this project are omitted. Detailed descriptions of the processes are presented in the SWRRB documentation reference by Arnold et al. (1990) and the SWAT documentation manual (Arnold et al., 1994.)

C1.) Hydrologic Processes

1. Surface Runoff

Runoff volume is estimated using a modification of the NRCS curve number method (U.S. Department of Agriculture, Soil Conservation Service, 1972). The curve number varies non-linearly from condition 1 (dry) at wilting point to condition 3 (wet) at field capacity. The SWAT model also includes a provision for estimating runoff from frozen soil.

Peak runoff-rate predictions are based on a modification of the Rational Formula. The runoff coefficient is calculated as the ratio of runoff volume to rainfall. The rainfall intensity during the watershed time of concentration is estimated for each storm as a function of total rainfall using a stochastic technique. The watershed time of concentration is estimated using Manning's formula, considering both overland and channel flow.

2. Percolation

The percolation component of SWAT uses a storage-routing technique to predict flow through each soil layer in the root zone. Downward flow occurs when field capacity of a soil layer is exceeded if the layer below is not saturated. Upward flow may occur when a lower layer exceeds field capacity. Movement from a lower layer to an adjoining upper layer is regulated by the soil water to field capacity ratios of the two layers. Percolation is also affected by soil temperature. If the temperature in a particular layer is 0°C or below, no percolation is allowed from that layer.

3. Lateral Subsurface Flow

Lateral subsurface flow is calculated simultaneously with percolation. A non-linear function of lateral-flow travel time is used to simulate the horizontal component of subsurface flow. The magnitudes of the vertical and horizontal components are determined by simultaneous solution of the two governing equations.

4. Evapotranspiration

Depending on the level of detailed information available (daily maximum and minimum air temperature, wind speed, relative humidity, solar radiation), three different options for estimating potential evapotranspiration are available in SWAT. The model computes soil and plant evaporation separately.

5. Snowmelt

If snow is present, it is melted on days when the maximum temperature exceeds 0°C, using a linear function of temperature. Melted snow is treated in the same way as rainfall for runoff and percolation estimation, but rainfall energy is set to 0.0 and peak runoff rate is estimated assuming uniformly distributed rainfall for a 24-hr duration.

6. Transmission Losses

Many semiarid watersheds have alluvial channels that abstract large volumes of streamflow. The abstraction, or transmission losses, reduce runoff volumes as the flood wave travels downstream. SWAT uses Lane's method, described in Chapter 19 of the Soil Conservation Service (SCS) Hydrology Handbook (USDA Soil Conservation Service, 1972), to estimate transmission losses. Channel losses are a function of channel width and length and flow duration. Both runoff volume and peak rate are adjusted when transmission losses occur.

7. Ponds and Reservoirs

Farm-pond storage is estimated as a function of pond capacity, daily inflows and outflows, seepage, and evaporation. Ponds are assumed to have only emergency spillways. Required inputs are capacity and surface area. Surface area below capacity is estimated as a non-linear function of storage. Reservoirs are treated similarly except they have emergency and principal spillways. Thus, required inputs include volume and surface area at both spillway elevations and the principal spillway release rate.

8. Flood Routing

The flood routing structure of SWAT routes and adds flow down through the watershed through reaches and reservoirs. A set of commands are used to control routing and adding the flows down through the watershed. The basic commands are subbasin, route, routres, transfer, add, routsub, recall, save, and finish.

C2.) Weather

The weather variables necessary for driving SWAT are precipitation, air temperature, and solar radiation. If daily precipitation data are available, they can be input directly to SWAT. If not, the weather generator can simulate daily rainfall and temperature. Solar radiation is always simulated in SWAT. (This was modified by KGS to directly read solar radiation data if available). One set of weather variables may be simulated for the entire basin, or different weather may be simulated for each subbasin.

1. Precipitation

SWAT requires daily precipitation data. SWAT can also generate precipitation data based on a first-order Markov chain precipitation model. Input to the precipitation model include monthly probabilities of receiving if the previous day was dry or if the previous day was wet. Given the wet-dry state, the model determines stochastically whether precipitation occurs or not. When a precipitation event occurs, the amount is determined by generating from a skewed normal daily-precipitation distribution. The amount of daily precipitation is partitioned between rainfall and snowfall using average daily air temperature.

2. Air Temperature and Solar Radiation

SWAT requires daily minimum and maximum air temperatures. However, daily maximum and minimum air temperature and solar radiation can be generated from a normal distribution model corrected for wet-dry probability state. The correction factor is used to provide more deviation in temperatures and radiation when weather changes and for rainy days. Conversely, deviations are smaller on dry days. The correction factors are calculated to insure that long-term standard deviations of daily variables are maintained. Monthly values of daily standard deviations of maximum and minimum temperature are input.

Monthly values of daily standard deviations (SDs) of solar radiation are estimated by assuming that the difference between mean and maximum daily radiation is 4SDs.

3. Soil Temperature

Daily average soil temperature is simulated at the center of each soil layer. Because air temperature is provided by the weather component of SWAT, the soil-temperature model is capable of using these air temperatures as drivers for generating soil temperatures. A linear relationship is used to relate the bare-soil-surface temperature, the maximum and the minimum daily air temperature, and a damping factor to vary the temperature as soil depth changes.

The soil-surface temperature is also affected by residue and snow cover. This effect is simulated by lagging the predicted bare-surface temperature using a weighting factor.

C3.) Crop Growth

SWAT uses concepts of phenological crop development based on daily accumulated heat units, harvest index for partitioning grain yield, Monteith's approach for potential biomass, and water and temperature stress adjustments. A single model is used for simulating all the crops considered. SWAT is capable of simulating crop growth for both annual and perennial plants. Annual crops grow from planting date to harvest date or until the accumulated heat units equal the potential heat units for the crop. Perennial crops maintain their root systems throughout the year, although the plant may become dormant after frost.

C4.) Agricultural Management

1. Irrigation

The SWAT user has the option to simulate dryland or irrigated agricultural areas. If irrigation is indicated, one must also specify the runoff ratio (volume of water leaving the field/volume applied) and a plant water stress level to start irrigation. The plant-water stress factor ranges from 0.0 to 1.0 (1.0 means no stress and 0.0 means no growth).

2. Tillage and Residue

The SWAT tillage component was designed to partition the above-ground biomass at harvest. A portion of the biomass is incorporated into the soil while the remainder is left on the soil surface as residue. Once the residue is incorporated, it has no impact on the model. Also no change is made in bulk density due to tillage. The residue is set at harvest according to the tillage practices chosen. The residue decays throughout the remainder of the year (harvest to next harvest) as a function of soil-water content and soil temperature. Inputs include dates, tillage, crop, and pesticide codes (relating to the numbers in the CROP.DAT, TILL.DAT, and PEST.DAT files), and application amounts.

C5.) Ground-water Model Component

The main objective of the linked model developed in SWAT is to predict the impact of management changes on total water supplies. The model is intended for general use where extensive field-work to obtain inputs is not feasible. Thus, the ground-water component must use readily available inputs. Thus, a relatively simple ground-water model was developed in SWAT. Such a model, however, cannot handle spatially distributed ground-water rights, and therefore this SWAT component was replaced in this study with the more sophisticated MODFLOW ground-water simulator.

D.) MODFLOW Description

Because MODFLOW (McDonald and Harbaugh, 1988) is a well-known and widely used code, only a short description will be presented here. MODFLOW is primarily a physically based model, developed by combining the well-known Darcy's law governing fluid movement through saturated porous media, and the mass balance or continuity equation for subsurface flow. It is a modular three-dimensional block-centered finite difference code for layered aquifer systems.

MODFLOW can represent a number of aquifer conditions including confined, unconfined, leaky, delayed yield, and variably confined/unconfined conditions. Isotropic as well as anisotropic medium can be represented in either homogeneous or heterogeneous settings. Both steady-state and transient conditions can be simulated for laminar flow. The option for deactivating regions within the domain permits the modeler to model complex irregular systems with ease. All the common boundary conditions generally encountered in practice can be accounted for by the model, including fixed heads or pressures, variable or constant fluxes, time-dependent head or fluxes, ground-water recharge/discharge, point withdrawals, and drains. Several surface-subsurface interactive processes such as evapotranspiration and stream-aquifer interactions can be also be adequately simulated by MODFLOW.

The choice of a number of equation-solving techniques equips MODFLOW with powerful tools for solving even the most intransigent problem encountered in the field. Numerical solvers based on the Line Successive Over Relaxation, Strongly Implicit Procedure, Slice Successive Over Relaxation, and the Conjugate Gradient methods are included. Its modular structure permits ease in integrating it with other surface-water models as well as Geographical Information Systems.

E.) Linking SWAT and MODFLOW (SWATMOD)

KGS undertook the task of linking the watershed model SWAT with the ground-water model MODFLOW. The resulting combined model is known as SWATMOD.

SWAT is a linked model consisting of an existing basin-scale surface-water and root-zone model (SWRRB) to which a reach-routing structure and a ground-water component, among others, were added. This ground-water component, however, is not detailed enough and is too simplistic for handling distributed parameters and variable pumping. As a result, SWAT cannot predict ground-water levels accurately. Therefore, it was deemed necessary to replace the ground-water component of SWAT with the more detailed and sophisticated ground-water MODFLOW simulator.

The linkage between the two programs is shown schematically in Fig. 5.2 and is intended to represent the significant interactions among a watershed and its stream network and the associated aquifer. Surface runoff (SRO) resulting from precipitation (PCP) becomes lateral inflow to a stream or pond. Infiltration (INF) that percolates downward beyond the root zone (PERC), along with pond seepage (POND SEEP), channel-transmission losses(TL), and subsurface lateral flow (SLF) that does not flow into the pond-contributing areas, are the sources of recharge (R) to the aquifer. Ground water pumped from the aquifer (Q) is applied as irrigation (IRR) at the surface. Water in the pond evaporates (E), and water in the soil zone within reach of plant roots evapotranspires (ET). The stream and aquifer interact via leakage driven by a hydraulic gradient across the streambed.

Both SWAT and MODFLOW have been modified to implement the linkage shown in Fig. 5.2. A detailed exposition of the SWAT-MODFLOW (SWATMOD) model structure and documentation is provided in Volume 2. Interaction of the two programs can occur indirectly via data files or directly by calls from SWAT to MODFLOW according to one of several options added to SWAT which are accessible through SWAT's *.cod input file (see also section 6). Program modules to handle interactions between SWAT and MODFLOW are referred to as HYDBAL called by SWAT, and MODSWB, called by MODFLOW.

HYDBAL passes hydrologic fluxes calculated by SWAT (surface runoff, lateral-subsurface flow, pond seepage, transmission losses, percolation from root zone, irrigation, and surface evaporation) to MODFLOW, and retrieves fluxes calculated by MODFLOW (baseflow, irrigation reported pumpage, and optionally ground-water evapotranspiration). HYDBAL also retrieves annual constraints on fluxes set by MODFLOW (appropriation or use limits on irrigation), and evaluates a hydrologic balance at each time step (daily, monthly, or annual) for which fluxes are retrieved from MODFLOW.

On the other hand, MODSWB associates the SWAT subbasins with aquifer-grid domains and subbasin outflows with the stream network defined in MODFLOW, evaluates water-rights appropriations for each subbasin at the beginning of each stress period, maps hydrologic fluxes calculated by SWAT onto the aquifer grid, and summarizes for each subbasin the fluxes relevant to SWAT's hydrologic balance. Specifically, the MODSWB module consists of four subroutines.

a) SWB1AL: Allocate memory requirements for the module in a manner consistent with the standard MODFLOW modules.

b) SWB1RP: Read the input required to associate the morphology of the watershed, stream network, and aquifer. Specifically, this subroutine defines outflow locations from the watershed subbasins onto locations in the stream network specified by MODFLOW's STREAM package, and correspondences of watershed-subbasin domain to aquifer-grid cells.

c) SWB1FM: For each aquifer time step, this subroutine transforms hydrologic fluxes for each subbasin as computed and written by SWAT into ground-water-model fluxes as follows:

    i) lateral inflow to a stream network due to overland flow;
    ii) ground-water recharge from percolation, transmission losses and pond seepage; and
    iii) ground-water pumping for irrigation.

d) SWB1BD: This subroutine summarizes results from MODFLOW's solution in each aquifer time step for inclusion in SWAT's hydrologic summary, including baseflow due to streambed leakage.

For further details on HYDBAL and MODSWB, and the linking process, the reader is referred to Volume 2.

E1.) Heterogeneity within subbasins

Because of the lump-model nature of SWAT (in contrast to the distributed-model nature of MODFLOW), heterogeneous conditions within the watershed subbasins cannot be directly represented in a single combined run of SWAT and MODFLOW. Instead, SWAT is run for 18 separate homogeneous cases (i.e., hydrologic response units, or HRUs) representing the combinations of three land uses (grassland, irrigated cropland, and non-irrigated cropland) and six soil types. For each of these 18 HRUs, a hydrologic summary of results is written for each hydrologic component and subbasin in each aquifer time step, which can be annual, monthly, or daily. A composite of these 18 HRUs is produced by program SWBAVG, which calculates an areally weighted average of the HRUs for each hydrologic flux within each subbasin. Input to SWBAVG is described in Section 6, and SWBAVG is explained below and further documented in Volume 2.

The heterogeneity existing within each subbasin of a watershed was represented by computing a weighted average of several cases run with the watershed model SWAT into one composite case to be used as input for MODSWB as follows. For each component of the watershed heterogeneity, a separate case of SWAT was run in which the entire watershed was assumed to be homogeneous in the characteristics of that component. Land use and soil type are the main features whose heterogeneity within the subbasins is expected to have significant hydrologic impact. Then for each subbasin and time step, the areal fractions corresponding to each of these components were calculated. These areal fractions were then used by program SWBAVG as weight functions for each subbasin and time step to calculate a weighted average of the component cases for each hydrologic flux. All subbasins within the basin are characterized by six dominant soil types (Carr, Crete, Hastings, Hedville, Kipson, Muir) with corresponding areal fractions for each subbasin, and three land uses/management schemes summarized as irrigated cropland (represented by corn), nonirrigated cropland (represented by rotation of wheat, sorghum, and fallow), and pasture/rangeland, with corresponding areal fractions for each subbasin. For each of the resulting 18 soil-land-use combinations, which define 18 hydrologic-response units, HRUs, a model of the watershed was run with SWAT in which all subbasins were assumed to have that particular soil-land-use combination (HRU). Then, program SWBAVG produced a weighted average of these 18 cases for each hydrologic flux and subbasin based on a weight function given by the areal fraction of each soil-land-use combination within each subbasin for each year of the simulation. The weight functions were calculated by program WEIGHTS; see section 6 for a summary of input to WEIGHTS and SWBAVG, and the resulting weighted average fluxes. This weighted average was then used as input to MODFLOW to represent the hydrologic fluxes for the heterogeneous watershed. A consequence of this approach is that SWAT, SWBAVG, and MODFLOW must be run sequentially.

E2.) Coordination of water-use data with model components

Water-use data and model components are coordinated as follows to maintain mass balance according to the following equation:

$$cQ_{irr}\Delta t = d_{irr} f_{irr} A, \qquad (5E\text{-}1)$$

where Q_{irr} (cfs) is the sum of ground and surface water use for irrigation, $f_{irr} = A_{irr}/A$, the irrigated fraction of the basin area; A = basin area (2,570 km^2), d_{irr} = annual irrigation depth (mm); Δt (s) is the time step for one year ($\approx$ 86,400.365 s), and c is a units conversion factor; $A/(c\Delta t) = 2.8775$ for a 365-day year. As described previously, estimates of Q_{irr} and A_{irr} are based on water-use data from DWR for 1980-1993; d_{irr} is derived from these data, i.e. $d_{irr} = c\Delta t Q_{irr}/A_{irr}$. These estimates are used to associate data for d_{irr} with SWAT, f_{irr} with SWBAVG, and Q_{irr} with MODFLOW as described below in order to represent irrigation-water use. Results based on this method are discussed in terms of the calibrated model (base case) in Section 8D.

For each year, total ground- and surface-water diversions are specified as input to MODFLOW's Well and Surface packages, respectively. Total irrigation use $Q_{irr} = U_{gi} + U_s$; where U_{gi} is the irrigation component of total ground-water use U_i, and U_s is total surface-water diversions, all of which are for irrigation. These totals represent the sums $U_g = \Sigma q_{gk}$ and $U_s = \Sigma q_{sk}$ of individual ground-water and surface-water points of diversion q_{gk} and q_{sk}, respectively.

Annual irrigation depth, d_{irr} is specified by SWAT's *.cod input file (see section 6A) as an annual limit on irrigation, which is simulated in SWAT on a daily basis, and is applied either on the basis of time schedules (*.mgt files) or according to a threshold based on soil moisture or plant-stress factor (*.mco files). SWAT, as modified for this project, applies irrigation at a maximum rate of 0.5 in/day (12.7 mm/day) during the growing season whenever total soil water as a fraction of available field capacity falls below a threshold of 0.70. The daily maximum irrigation rate and soil-water threshold that triggers irrigation are also specified in SWAT's *.cod file and were chosen to obtain an approximate match between the annual irrigation depth assigned by SWAT and that estimated from DWR data as described above.

Annual estimates of irrigated fractions of the basin area, f_{irr} are incorporated by program WEIGHTS into weight functions. These weights are applied by program SWBAVG to compute a weighted average of the balance files written by SWAT for the 18 combinations of homogeneous soil-type and land-use conditions (hydrologic-response units, or HRUs) representing the basin heterogeneity. The resulting depths for each hydrologic component are read by MODFLOW's soil-water balance (MODSWB) package and converted to flow rates, Q_i over the appropriate areas, f_iA according to $Q_i c\Delta t = d_i f_i A$. The areal basin fractions, f_i are summarized as follows:

hydrologic connection	relevant areal fraction, $f_i = A_i/A$	
tributary flow (runoff to streams)	contributing area	$f_{con} = 0.98$
recharge and baseflow	aquifer area	$f_{aqf} = 0.126$
irrigation	irrigated area	$f_{irr} = 0.039$ (avg annual)

Contributing and aquifer areas vary over the subbasins but are constant over time. Irrigated area is constant over all subbasins but varies slightly over time with a range from 3.13 to 4.77 percent, according to our estimate based on water-use reports. For a 365-day year, the constant $A/(c\Delta t) = 2.5775$ as mentioned previously, so that depth, d_i corresponds to a flow rate given by $Q_i = 2.8775 d_i f_i$.

For monthly aquifer-solution time steps, the irrigation depths calculated by SWAT and SWBAVG are read by MODFLOW's MODSWB package from the balance file, and converted to a total pumping rate Q_i for the entire basin. This irrigation-flow rate for the month is divided by the annual average pumping rate Q_A for the basin specified by MODFLOW's input, resulting in a scaling factor $s = Q_i/Q_A$. This is multiplied by the annual average rate of irrigation use specified by input to MODFLOW's Well and Surface packages for each individual point of ground-water and surface-water diversion as $s \cdot q_{gk}$ and $s \cdot q_{sk}$, respectively. During peak irrigation months, this scaling factor may increase the average annual rates significantly; in months without irrigation, $s = 0$.

The annual water use assigned in MODFLOW should match the annual estimated water use Q_A specified by MODFLOW's input, allowing for discrepancies introduced by simulation conditions in SWAT and MODFLOW as follows. In SWAT, automatic application of daily irrigation based on soil-moisture (or plant-stress factor) threshold may result in either using less than the annual limit or running into the annual limit part way through the growing season. In MODFLOW, irrigation-pumping rates are subject to two constraints which we have introduced into the Well package. First, a well's pumping rate q is decreased from its assigned range q_r if the aquifer's saturated thickness y declines too much (Sophocleous, 1981): a saturated thickness between $y_0 = 5$ ft and $y_1 = 10$ ft results in a linear scaling of the pumping rate by a factor of from 0 to 1 according to $q = q_r(y-y_0)/(y_1-y_0)$, and $q = 0$ for $y < y_0$. Second, irrigation pumping-rates are limited to a maximum value set at 4 cfs (approximately 1800 gpm), which limits the scaling factor s based on irrigation assigned by SWAT as described above.

6. MODEL INPUT AND SOURCES OF ERROR

The combined SWATMOD model requires input data for its three main component programs: SWAT, SWBAVG, and MODFLOW. Data are required for SWAT that describe the 18 homogeneous components (HRUs) corresponding to six soil types and three land-use management schemes. For each of these HRUs, a daily simulation of SWAT is run for 18 years (1977-1994), and a "soil-water balance" file is written that summarizes the HRU's results for each aquifer time step, subbasin, and hydrologic flux. Program SWBAVG calculates a weighted average based on the balance files for these HRU's and a weight function (calculated by program WEIGHTS), and writes an average balance file that is read as part of MODFLOW's input to specify primarily recharge, tributary flow, and irrigation. The data for each of these three components are summarized as follows.

A.) SWAT Input

SWAT input files are grouped as general input files and subbasin input files. The first group of files consists of input data for the entire basin, and the second group consists of input data for each of the subbasins. The hydrologic unit code HUC-11 official subbasins were employed to subdivide the Lower Republican River basin, except that two HUC-11 subbasins were further subdivided so as to better define the contributing areas to the Republican River stem from Concordia to Clay Center, as shown by the darker lines in fig. 3.15. There are two types of data files in the general input files: User-provided files and database files.

For user-provided files, the file names can be defined by users but the file extension must be maintained. The names of most input and output data files associated with a run of SWAT are summarized on a file which must be named FILE.CIO at the time of SWAT's execution. Such a file corresponding to each HRU is named according to a combination of prefixes corresponding to soil type and land-use management represented by the HRU, and then is renamed to the mandatory FILE.CIO just prior to executing SWAT. Soils and corresponding prefixes are Carr (CARR), Crete (CRET), Hastings (HAST), Hedville (HEDV), Kipson (KIPS), and Muir (MUIR). Land-use management schemes and corresponding prefixes for annual and monthly aquifer time steps, respectively, are as follows: (1) wheat, sorghum, and fallow rotations without irrigation (WSF, WSM); (2) irrigated corn (IRC, IRM); and (3) range and pasture (PAS, PAM). For example, the annual versions for HRUs with Carr soils have the prefixes CARR-WSF, CARR-IRC, and CARR-PAS. Certain additional file names are specified in the *.COD file, whose name is given in the *.CIO file corresponding to a particular HRU, and which specifies most of the standard, modified, and added options for SWAT execution. Standard SWAT output is to file *.STD, named by the *.CIO file. A special output file *.BAL summarizes the hydrologic fluxes calculated by SWAT for each subbasin and for each aquifer time step. This file is written in a format that is to be read by both programs SWBAVG and MODFLOW. Names identifying HRUs for the base case, listed below, are used as prefixes for *.CIO and *.COD input files, and for *.STD and *.BAL output files. Separate runs are made, with names shown below, to distinguish annual and monthly summaries written to soil-water-balance (*.BAL) files, corresponding to annual and monthly aquifer time steps in MODFLOW.

The following is a brief description of the SWAT input files.

A1.) General Input Files

I. Database Files

1. CROP.DAT

This is the crop database input file. It contains crop-specific parameters that are input to the model. When a crop is specified to be planted in the management (*.mgt) file, the crop parameters for that crop are taken from CROP.DAT. The crop parameters include biomass conversion factor, harvest index, optimum and base temperatures, maximum leaf area, maximum root depth, and several others.

2. TILL.DAT

This is the tillage-database input file. It contains mixing efficiencies for over 70 tillage operations that can be selected in the management (*.mgt) file.

3. PEST.DAT

This is the pesticide-database input file. It contains pesticide parameters for over 80 pesticides that can be selected in the management (*.mgt) file. The pesticide parameters include the soil-partition coefficient, washoff fraction, foliar and ground pesticide half-lifes, and water solubilities.

II. User-provided Files

4. *.COD

This is the input-control code file. It contains the number of years of simulation, beginning year, number of subbasins, print codes, weather-generation-control codes, and several others. All the input are common to the entire basin and are not subbasin-dependent.

5. *.BSN

This is the general basin input file. It contains inputs that are relevant to the entire basin that include drainage area, baseflow factors, and initial soil-water content.

6. *.WGN

This is the weather-generator input file. It contains monthly parameters that are required for generating daily amounts of precipitation, maximum and minimum temperatures, and solar radiation. Many of the parameters are required by the model even if measured precipitation and temperature data are used.

7. *.LWQ

This is the lake-water-quality input file. It contains parameters for the lake toxic balance and for the lake phosphorus balance.

8. *.FIG

This is the watershed-configuration input file. It contains the routing commands SWAT uses to route and add flows through a watershed.

9. *.STA

This is the measured-data input file from a gaged station. It contains monthly measured flow and sediment-yield data. The model reads in the data and compares to simulated model output.

10. *.RES

This is the reservoir input file. This file contains reservoir input data including surface area and storages for emergency and principal spillways, release rates, and normal sediment concentration.

A2. Subbasin Input Files

1. *.SUB

This is the general subbasin input file. This file contains general inputs specific to each subbasin that include area, curve number, land and channel slopes and lengths, Manning's coefficients, USLE erosion control practice factor P, and initial residue cover.

2. *.RTE

This is the subbasin routing input file. This file contains information on channel dimensions (length, slope, width, depth, etc.) for the main channel through the subbasin.

3. *.PND

This is the pond input file. This file contains pond input data including surface area and storages, conductivity of the pond bottoms, and normal sediment concentrations.

4. *.CHM

This is the chemical input file. This file contains data on initial pesticide concentration in the soil and on the foliage along with initial nutrient concentrations in the soil.

5. *.SOL

This is the soils input file. This file contains soil data including bulk density, available water capacity, saturated conductivity, particle sizes, organic carbon, and maximum rooting depth. Each soil can have a maximum of 10 soil layers.

6. *.MGT

This is the management input file. This file contains input data for management operations for planting, harvest, irrigation applications, nutrient applications, pesticide applications, and tillage operations. Users can schedule the operations by month and day or by heat units. Inputs include dates, tillage, crop, and pesticides codes (relating to the numbers in the CROP.DAT, TILL.DAT, and PEST.DAT database files), and application amounts. The maximum number of years of rotation is currently set at 40 and can be easily increased.

7. *.MCO

This is the management-code input file. This file contains input data for automatic management operations for irrigation and fertilization. The user can input stress level to trigger irrigation or fertilization, and SWAT will automatically boost water levels to specified amounts.

8. *.GW

This is the ground-water input file. This file contains aquifer data including a recession parameter, specific yield, a "revap" coefficient, and a deep-aquifer percolation coefficient.

9. *.PCP

This is the measured precipitation input file. There are four choices for rainfall input: 1) Read in a single rain gage for the entire basin, in which case there is only one precipitation input file for the entire basin. 2) Read in one rain gage for each subbasin, in which case each of the subbasins must have one measured-precipitation input data file; each of these files contain daily rainfall values in mm and each day is stored on one line. 3) Simulated single rain gage for the entire basin. 4) Simulated multiple rain gages; in the last two cases, no precipitation input file is necessary to run the simulation.

10. *.TMP

This is the measured temperature input file. There are also four choices for temperature input: 1) Read in single maximum and minumum temperature for the entire basin, in which case there is only one temperature input file for the entire basin. 2) Read in maximum and minimum temperature for each subbasin, in which case each of the subbasins must have one measured-temperature input data file; these files contain daily maximum and minimum temperature values in Celsius, and each day's maximum and minimum temperature are stored on one line. 3) Simulated single maximum and minimum temperature for the entire basin. 4) Same simulated items for each subbasin; in the last two cases, no temperature input file is necessary to run the simulation.

As mentioned earlier, one file is named FILE.CIO and contains all the names of the input and output files for an application. It must always be called FILE.CIO and must always be present in every SWAT application.

B.) SWBAVG Input

Program SWBAVG reads the balance files written by SWAT for each HRU, and calculates an areally weighted average over the HRUs for each hydrologic flux and each subbasin. The weights are computed by program WEIGHTS for each year based on the areal fractions of soil and land use within each subbasin, and on the irrigated areal fraction for the entire basin. SWBAVG writes its results to an average balance file in the same format with which the component-balance files were written for each HRU.

B1.) WEIGHTS input file

Table 6.1a shows the input file for program WEIGHTS. For each subbasin, areal fractions are specified for cropland and for each of six soil types. Areal fractions for cropland and for soil types are taken to be constant over the study period. In addition, the irrigated cropland as a fraction of the entire basin is given for each year (last two rows). Program WEIGHTS uses these to calculate a weight function for each year and for each subbasin.

Table 6.1a. Input to program WEIGHTS to calculate weight functions for SWBAVG[1]

file wrpbase.inp (base case)									
9,6,18,1977,nsubs,nsoils,numver,ibgnyr (1)									
subbasin	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
subfrc	0.22105	0.04909	0.20435	0.08729	0.05282	0.08247	0.10945	0.11788	0.07649
aqffrc	0.0733	0.2053	0.2368	0.0924	0.2099	0.0122	0.0829	0.0257	0.2504
crop pct	59.62	54.63	62.81	57.37	71.64	61.13	67.53	53.16	49.91
Soils:									
Carr	0.092	0.191	0.098	0.126	0.043	0	0	0	0
Crete	0.471	0.064	0.637	0.543	0.745	0.741	0.869	0.697	0.63
Hasting	0.099	0.402	0.125	0.054	0	0	0	0	0
Hedville	0	0	0.007	0	0	0.176	0.022	0.279	0.021
Kipson	0.338	0.342	0.052	0.274	0.086	0.059	0	0	0
Muir	0	0	0.081	0.004	0.126	0.024	0.108	0.024	0.348
pctirr:									
	3.13	3.32	3.42	4.18	4.06	3.54	3.61	3.66	3.51
	3.55	3.76	4.28	4.21	4.31	4.52	4.42	4.77	4.7

[1] Key to Table 6.1a (see also Table 3.7):
Row definitions (cols. 1-9 identify corresponding subbasins except for last two rows):
subfrc: area as fraction of total basin;
aqffrc: aquifer area as fraction of subbasin;
crop pct: cropland area as percent of subbasin (from Table 3.5).
Soils: for each predominant soil series, area as fraction of subbasin.
pctirr: percent irrigated area for each year of the 1977-1994 period

B2.) SWBAVG input file

This input file contains the names of the balance files summarizing the HRUs calculated by SWAT, and the weight functions calculated by WEIGHTS. SWBAVG applies these weights to calculate averages of the HRUs, and writes the averages for each hydrologic flux, subbasin, and time step for which MODFLOW is to be run. The balance file is read as part of the input to the Soil Water Balance (MODSWB) package added to MODFLOW.

Table 6.1b shows part of the input file for the averaging program, SWBAVG. Table 6.1b identifies the eighteen combinations of land use and soil type and the corresponding hydrologic balance file written by SWAT for each case. Below this, it shows the first year's matrix of normalized weights as percents that are to be used to calculate the weighted means of the hydrologic components corresponding to the eighteen cases. The rows of the matrix correspond to the nine subbasins, and the columns correspond to the eighteen cases

Table 6.1b. Input to averaging program SWBAVG, including weight functions for first year (1977) of simulation.

```
     9    18   217    17     1   'rpbase nwshed,ncond,nper,nrevis,iopsub,outfil,swbavg.inp
1978,1979,1980,1981,1982,1983,1984,1985,1986,1987,1988,1989,1990,1991,1992,1993,1994, yrs to update weight functions
Carr-wsm        carr-wsm.bal  soil 1 (wheat/sorghum/fallow rot.) (case, file name)
Carr-irm        carr-irm.bal     (irrigated corn)
Carr-pam        carr-pam.bal     (grass:  range and pasture)
Crete-wsm       cret-wsm.bal
Crete-irm       cret-irm.bal
Crete-pam       cret-pam.bal
Hasting-wsm     hast-wsm.bal
Hasting-irm     hast-irm.bal
Hasting-pam     hast-pam.bal
Hedville-wsm    hedv-wsm.bal
Hedville-irm    hedv-irm.bal
Hedville-pam    hedv-pam.bal
Kipson-wsm      kips-wsm.bal
Kipson-irm      kips-irm.bal
Kipson-pam      kips-pam.bal
Muir-wsm        muir-wsm.bal
Muir-irm        muir-irm.bal
Muir-pam        muir-pam.bal
normalized weights beginning year 1977 3.13 pct basin irrigated
sub\HRU:     1     2     3     4     5     6     7     8     9    10    11    12    13    14    15    16    17    18
        1  5.2  0.29  3.71  26.6  1.47    19  5.59  0.31     4     0     0     0  19.1  1.06  13.7     0     0     0
        2 9.85   0.6  8.67   3.3   0.2  2.91  20.7  1.26  18.3     0     0     0  17.6  1.07  15.5     0     0     0
        3 5.85  0.31  3.64    38  1.99  23.7  7.46  0.39  4.65  0.42  0.02  0.26   3.1  0.16  1.93  4.83  0.25  3.01
        4 6.83  0.39  5.37  29.4   1.7  23.1  2.93  0.17   2.3     0     0     0  14.9  0.86  11.7  0.22  0.01  0.17
        5 2.95  0.13  1.22    51  2.33  21.1     0     0     0     0     0     0  5.89  0.27  2.44  8.63  0.39  3.57
        6    0     0     0    43  2.32  28.8     0     0     0  10.2  0.55  6.84  3.42  0.18  2.29  1.39  0.08  0.93
        7    0     0     0    56  2.72  28.2     0     0     0  1.42  0.07  0.72     0     0     0  6.96  0.34  3.51
        8    0     0     0  34.9  2.18  32.7     0     0     0    14  0.87  13.1     0     0     0   1.2  0.08  1.12
        9    0     0     0  29.5  1.97  31.6     0     0     0  0.98  0.07  1.05     0     0     0  16.3  1.09  17.5
```

of land use and soil type, whose sequence corresponds to the order in which the case names were read. For example, the mean of each hydrologic balance component for subbasin 1 (row 1) includes 4.9 percent of case 1 (Carr-wsf; Carr soil-wheat/sorghum/fallow rotation), 25 percent of case 2 (Carr-irc; Carr soil-irrigated corn), 5.2 percent of case 3 (Carr-r/p; Carr soil-rangeland/pasture), and so on, through 13.6 percent of case 17 (Muir-irc; Muir soil-irrigated corn).

Table 6.2 shows intermediate 1977 results for case 2 (Carr-irc; Carr soil-irrigated corn) as written by SWATMOD to the hydrologic balance file carr-irc.bal (as listed in the first line of Table 6.2). Table 6.2 lists the hydrologic fluxes, which are precipitation (PREC) through potential evapotranspiration (ETPOT) under the "component" columns, that constitute the components of case 2 in the weighted means calculated by program SWBAVG.

C.) MODFLOW Input and Related Model Assumptions

Data are referenced in MODFLOW with respect to the model grid cells. The model domain is discretized into square grid cells, each one square mile in area (Fig. 3.18). The initial MODFLOW grid consisted of 23 rows and 39 columns starting approximately 8 miles west of Concordia. However, in order to make the basin areas contributing flow to the region between the Concordia and Clay Center streamgaging stations compatible with the basin subwatersheds employed in the SWAT module, the cell nodes west of Concordia were assigned specified head values. Thus, the number of remaining active nodes in the ground-water model from Concordia to Clay Center was 125, representing an alluvial aquifer area of 125 square miles.

One of the attractive features of MODFLOW is the modular composition of the package, whereby necessary boundary conditions, aquifer parameters, grid data, and other relevant information are input through separate data files. A summary of the input data required for the Lower Republican River subbasin model is presented in Table 6.3. All the data items required for each key package of MODFLOW are listed therein.

Unlike SWAT, which is mostly a lumped-parameter model, MODFLOW is a distributed-parameter model. Therefore hydrogeologic and other input parameter values need to be specified for each grid cell. Each of the key MODFLOW data modules is discussed below along with the modeling assumptions and implications on the Lower Republican River basin model.

Program MODFLOW is run only once for a particular case of the Lower Republican River model. For convenience, a "response" file (with extension RSP, which is named for the case and analogous to the *.CIO file for SWAT) identifies most of the input and output files associated with MODFLOW. Input files specified by the response file correspond to MODFLOW packages, some of which have been added or modified for the purpose of this integrated watershed model.

Table 6.2. SWAT results for 1977, case CARR-IRC, to be passed to SWBAVG or MODSWB.

```
  18 1977    9    0 file carr-irc.bal
(25x,i3,a,2f7.1,10f8.2/,(t53,10f8.2))
 balttl = 1977 initialize subr HYDBAL
 basttl = annual
           365. (days)   1977 annual hydrologic balance:
 id So Va Aq St To Sb Bas Sh component   mean  std d       1       2       3       4       5       6       7       8       9
       2569.600 km**2 area  fractions:               0.22015 0.04909 0.20435 0.08729 0.05282 0.08247 0.10945 0.11788 0.07649
 ponds (areal fractions):              0.01994       0.03430 0.00310 0.00640 0.02680 0.00210 0.00000 0.01310 0.04139 0.02827
 active gridded fraction:              0.00000       0.00000 0.00000 0.00000 0.00000 0.00000 0.00000 0.00000 0.00000 0.00000
  1  1  0  0  0  1  1   1 10   PREC MM  985.5   71.0 1035.10  895.30  895.30  895.30  991.70  991.70  991.70 1079.60 1079.60
  2  1  0 -1  0  0 22   0 11    IRR MM  241.8   22.5  215.90  215.90  228.60  228.60  254.00  266.70  268.13  269.80  266.70
  3 -1  0  0  0 -1 12   7 12     ET MM  873.2   25.3  874.95  824.85  843.96  845.84  883.72  889.14  892.23  909.73  901.00
  4 -1  0  0  1  0  4   3 13   SURQ MM  268.4   46.9  308.57  210.15  209.37  208.57  272.97  267.12  267.30  325.10  328.62
  5  0  0  1  0  1 13  38 14  TLOSS MM    8.3    3.0    6.25   12.94   12.51    9.91    6.18    4.24    9.53    5.15    6.78
  6 -1  0  0  c  0  5   4 15   LATQ MM    0.2    0.1    0.23    0.12    0.14    0.34    0.32    0.22    0.17    0.27    0.17
  7 -1  1  0  0  0 11   5 16   PERC MM  129.9   17.5  106.95  128.97  123.12  116.23  131.03  139.06  148.85  152.80  157.43
  8  0 -1  1  0  0  9 107 17   GWRE MM  129.9   17.5  106.95  128.97  123.12  116.23  131.03  139.06  148.85  152.80  157.43
  9  0  0 -1  0 -1  7 105 18    REV MM    0.0    0.0    0.00    0.00    0.00    0.00    0.00    0.00    0.00    0.00    0.00
 10  0  0 -1  1  0  6 104 19   GW Q MM    0.0    0.0    0.00    0.00    0.00    0.00    0.00    0.00    0.00    0.00    0.00
 11  0  0  1  0  1 16  20 20   PSEP MM    4.6    4.3    7.24    1.35    1.47    4.32    0.75    0.00    0.00   13.22    8.50
 12  0  0  0  0  0 25 108 21  ETPOT MM 1373.6   37.0 1371.68 1306.71 1334.48 1326.75 1419.68 1386.65 1402.33 1423.39 1416.16
 Balances:
  1                         soil        -44.5    5.9  -39.69  -52.89  -52.69  -47.07  -42.34  -37.15  -48.71  -38.50  -40.93
  2                         vadose        0.0    0.0    0.00    0.00    0.00    0.00    0.00    0.00    0.00    0.00    0.00
  3                         aquifer    -103.6   11.0 -102.70  -73.99  -92.96 -102.46 -116.79 -123.39 -109.75 -111.85 -102.48
  4                         stream      263.3   43.3  298.21  209.61  208.16  203.30  272.72  267.34  263.97  311.90  319.50
  5                         combined    125.1   50.5  173.64   84.74   65.31   63.69  114.91  106.80  109.01  188.24  193.88
 water yield:
  1                10   6      WYLD MM  256.1   48.7  301.88  197.27  196.29  195.47  273.52  270.07  264.71  311.41  317.69
 Combined Swat fluxes for Modflow: jkkopt=0
 GWRE = Qtrans_loss + Qperc_rz + Qpond_seep;
 subbasin outflow to streams = c*(Qlat + Qsurf)
 GW recharge:                             0.00          0.00    0.00    0.00    0.00    0.00    0.00    0.00    0.00    0.00
 Tributary flow:                          0.00          0.00    0.00    0.00    0.00    0.00    0.00    0.00    0.00    0.00
 1977 avg temperature, C:                 12.8   0.5    12.5    12.5    12.5    12.5    13.1    13.1    13.1    13.7    13.7
    1977appropriation (mm):                           260.00  260.00  260.00  260.00  260.00  260.00  260.00  260.00  260.00
    1977GW pumped (mm):                               215.90  215.90  228.60  228.60  254.00  266.70  268.13  269.80  266.70
    1977GW applications:                 19.3             17      17      18      18      20      21      22      23      21
```

Table 6.3. Summary of input data required in applying MODFLOW model to Lower Republican River basin (numerical solution-related data excluded).

BASic Module
- Number of layers, rows, and columns
- Number of "stress periods" within which all external stresses are constant
- For each stress period: the length of the period and the number of time steps
- Active, inactive, and constant head-boundary nodes
- Initial head for each layer

Output Control Module
- Options for printing/saving head/drawdown
- Specification of time intervals for printing/saving head/drawdown

Block Center Flow Module

For each layer specify:
- Steady-state or transient simulation
- Layer type code: confined (0), unconfined (1), combination (2 or 3)
- Transmissivity or hydraulic conductivity depending on layer type
- Storage coefficient or specific yield depending on layer type for transient simulations
- Layer bottom elevation for certain layer types
- Leakance (vertical hydraulic conductivity divided by the thickness from a layer to a layer beneath it) if layer is not the bottom layer
- Layer top elevation for certain layer types
- Anisotropy ratio
- Grid spacing along rows and columns

ReCHarge Module

For each stress period specify spatial distribution (row, column, layer) and amount of recharge.

WEL1 Module

For each stress period specify layer, row, column, and withdrawal rate.

STReam Module
- Number of stream segments (in which streamflow from surface sources are added at the beginning of the segment or subtracted (in the case of a diversion) at the end of the segment), stream reaches (parts of segments that correspond to individual grid cells), and tributary segments
- Layer, row, column of each segment and reach
- Streamflow entering the first reach of each segment
- Stream stage for each reach in a segment
- Streambed hydraulic conductance for each reach in a segment
- Elevation of top and bottom of the streambed for each reach in a segment
- Stream channel width, slope, and Manning's roughness coefficient for each reach in a segment
- Tributaries and diversions for each segment.

RIVer Module
- For each stress period specify layer, row, and column of river/pond.
- For each stress period specify stage, vertical conductance, and bottom of river/pond.

GHB Module
- For each stress period specify layer, row, column, hydraulic head, and hydraulic conductance of river/pond.

C1.) Input for Standard MODFLOW Modules

BASic Module

The initial heads, boundary types, and the temporal discretization is specified in MODFLOW via this package. The boundaries were represented by a combination of no-flow and specified head-boundary conditions.

A time-step size of one month was implemented for the simulations. The initial head distribution specified to MODFLOW corresponds to the simulated 1977 water-level surface.

Block-Center Flow Module

The hydrogeologic parameters, aquifer type, and the discretized domain are specified in MODFLOW through this package. As mentioned earlier, the domain has been dicretized by a uniform 1 mile by 1 mile mesh.

Vertically, the domain is being represented by a single layer, in which flow is assumed to be predominantly horizontal in accordance with the Dupuit-Forchheimer assumptions (Bear, 1972). The vertical-flow components are not totally neglected as the water-balance equations used in the model do take into account the effects of vertical flow such as vertical recharge, well pumping, and vertical flow through confining beds. The Dupuit-Forchheimer assumptions are justified and routinely used in ground-water investigations where the geometry of the aquifer simulated is such that it is thin relative to its horizontal dimensions as is the case in the Lower Republican River alluvial aquifer (where thickness is in the order of tens of feet compared to tens of miles in areal extent). Thus, for regional modeling of single-aquifer subsurface systems, this is a reasonable assumption and is expected to provide results similar to those obtained by a more complex and computationally intensive three-dimensional model. All aquifer parameters were therefore specified in a vertically averaged sense. Another point worth noting is that the hydrologic parameters in MODFLOW can vary in space but remain constant within each cell. This is adequate for our purposes because the exact distribution of the parameters can only be approximated with the limited data available.

The hydraulic conductivities, storativities, and the bedrock surface were specified through this package. The spatial distribution of the bedrock surface is presented in Fig. 3.19.

ReCHarge Module

The net effective recharge to the system is specified through this package. The specified recharge is the amount of percolation reaching the water table through the vadose zone. In the combined model, the amount of recharge to the subsurface model is a function of deep percolation below the root zone, pond seepage, and transmission losses calculated by the surface-water component (SWAT). For each time step, the total recharge in the subbasins was determined as follows:

RECHARGE=PERCOLATION + POND SEEPAGE + TRANSMISSION LOSSES.

These subbasin recharge values were then uniformly distributed to each MODFLOW cell corresponding to the specific subbasin.

WEL1 Module

Ground-water use in the basin was specified through this package. Since reliable estimates of water use exist only for recent years, an estimate of the actual water used for years prior to 1980 was made based on the average reported use (as fraction of the annual appropriation) for the 1980 to 1992 period. (An analysis of water use and appropriations is reported in section 3 of this report.)

MODFLOW cannot account for the exact spatial location of a well within a grid cell. Therefore, several wells may be lumped and specified at the cell-center location. The drawdown in cells near the pumping wells therefore may not match the actual drawdown very closely. Another limitation is that MODFLOW assumes that wells fully penetrate the entire thickness of the aquifer. As a consequence, drawdowns close to a well that do not penetrate the entire saturated thickness may not be calculated accurately at the well site by the model. This however is not expected to be critical because the impact of withdrawals is of interest at a regional rather than a local scale.

STReam Module

Stream-aquifer interaction between the alluvial aquifer and the Republican River was simulated via this module. Unlike other numerical models in which the stream stage is specified as a constant, the stream module in MODFLOW simulates dynamic response in the stream by permitting the stage to fluctuate in response to losses or gains to or from the aquifer. The model however neglects storage within the river bed. The impact of this is expected to be minor as streambed thicknesses are normally relatively small.

The stream module calculates stream stage from Manning's equation (Prudic, 1989) for rectangular channels, in which the stream width is assumed to be much larger than the depth (stage). These conditions also exist in the Lower Republican River basin. Streamflow is calculated by specifying flow for the first reach (grid cell) in each stream segment that enters the model area, and then computing streamflow in the adjacent downstream cells by adding/subtracting the amount of water exchanged between the aquifer and the stream. MODFLOW assumes that streamflow entering the model layer is instantly available to the downstream reach. This assumption is reasonable because of the much faster flow rate of surface water relative to the slow rate of ground-water flow.

For each model cell through which the stream traversed, the stream slope, width, stream-bed conductance, stream-bed elevation, and the roughness coefficient were specified. An average stream width of 150 feet, and a Manning's roughness coefficient of 0.03 were assigned to the Republican River. The slope and length of each stream reach in the model cell were obtained from the KGS ARC-INFO database.

The riverbed hydraulic conductivity was estimated from NRCS soil reports as 0.5 ft/day and used to calculate streambed conductance. Discussion on the sensitivity of stream-module parameters such as streambed conductance is provided under Sensitivity Analysis (Section 9).

C2.) Input for added or modified MODFLOW modules

WELL Package (WEL1RP) changes:

1. Additional data that are read for each well at the beginning of a stress period are listed below.
   layer, row, column;
   annual estimated use for year of interest (cfs);
   code to distinguish wells used to specify derivative (Neumann) boundary conditions;
   annual appropriation (cfs): multiplied by annual water-use fraction to estimate water use for scenarios;
   grid coordinates to precision of .01 as fraction of cell width;
   distance to nearest stream reach (mi): used to select wells for scenarios;
   application number for the appropriated diversion point: criterion for well selection in scenarios;
   index to nearest stream reach;
   DWR use code (3 indicates irrigation);
   index to list of water rights;
   no. measurements of depth to water (dtw) reported at this well;
   year and month of dtw report, and depth to water from land surface (ft): used to calculate solution error (residuals);
   reported depth to bottom of well: used to select residuals based on alluvial wells;
   land-surface elevation at well;
   measured water-table elevation at well.
2. Well data as annual estimated use can be varied in each time step (month) under the control of irrigation assigned by SWAT.
3. Both annual estimated use and appropriation are specified; appropriations from previous stress period multiplied by a water use fraction for the current stress period can be used to represent estimated use for individual wells; this is used for the management scenarios (section 10).
4. Well-pumping rates are scaled and selected according to management scenarios 1-11 (see section 10); these are specified by input to the MODSWB package, and implemented in WEL1RP by calls to subr USEMGT, described in Appendix 10A.

Well-package additions:

i) WEL1F0

For each time step (just prior to entering loop to solve for aquifer heads), reduce pumping rates of wells in grid cells with a saturated thickness within a range from satlo = 5 ft to sathi = 10 ft; and limit irrigation wells to a maximum pumping rate pmpmax = 4 cfs. These parameters are specified by the first record of the WELL package input file.

ii) WEL1WR

For each time step just after solving for aquifer heads, the solution is compared with any available water-level measurements made during the time step within the corresponding grid nodes. Included are dtw measurements from DWR water-use reports (1980-1993) and from the water-level survey of November 1994 (Appendix 3B3). Annual results are summarized, including estimated water use, water yield, and residual error statistics.

SURFACE package

This package was written to represent surface-water diversions similarly to ground-water diversions. Irrigation calculated by SWAT is assigned in MODFLOW to both ground- and surface-water points of diversions, whose estimated annual water use as average flow rates are scaled on a monthly basis. Surface-water diversions are represented as lateral outflow from stream reaches with which they are associated. This is similar to the way runoff from the watershed is represented in MODSWB (see section 5E) as tributary flow, which is associated with a particular stream reach as lateral inflow for each subbasin. The net lateral inflow due to tributary flow and surface water diversions is incorporated into streamflow by a modified version of the stream routing procedure in the STREAM package.

At the beginning of each stress period (year), the following data are read for each surface-water diversion.

layer, row, column;
annual estimated use for the year of interest (cfs);
annual appropriation (cfs): multiplied by annual water-use fraction to estimate
    water use for scenarios;
grid coordinates to precision of .01 as fraction of cell width;
distance to nearest stream reach (mi): used to select wells for scenarios;
application number for the appropriated diversion point: criterion for well selection
    in scenarios;
index to nearest stream reach;
DWR use code (3: indicates irrigation);
index to list of water rights.

Water-use scenarios (section 10) are applied in the same way to both ground- and surface-water diversions: either estimated annual use is increased or decreased, and diversion points are selected on the basis of application number and distance from the river.

STREAM package input-data changes

1) The Stream package was modified to allow inflow data to be specified for each time step within a stress period without having to specify a complete set of data as described for the standard options.

2) The standard package requires streambed conductance C to be read for each reach based on an assumed rectangular-channel geometry with steady flow. Alternatively, streambed hydraulic conductivity k' and reach length L_s can be read instead of C, which is then calculated by the program using $C = k' \cdot L_s \cdot P/b'$, where:

   k' = streambed saturated hydraulic conductivity;
   L_s = stream-reach length;
   P = wetted perimeter;
   b' = streambed thickness.

3) Stream-channel geometry can be specified as trapezoidal (icalc=2), in which case reciprocal side slope is read, or as natural channel (icalc=3). In either case, a modified version of Prudic's stream-routing procedure (subr STR1DW) is used. The natural channel option is used for the Republican River model, in which data from USGS gaging stations at Concordia and Clay Center are used to approximate stream depth, width, and cross sectional area as functions of flow rate.

D.) Sources of error in ground-water and other hydrologic data

Numerous problems involving ground-water flow modeling of real field systems exist because the data necessary for the direct or inverse solutions are usually lacking. Head distribution is never known exactly because measurements do not exist at all points and because, where the measurements do exist, they are not exact. Estimates of the parameters either are completely unknown or have been obtained by spot measurements, few of which are directly useful for constructing appropriate effective values for use in a regional ground-water-flow model. It should be clear that modeling problems in ground-water hydrology involve an incomplete combination of several types of data in which error and error propagation are important considerations.

Some major potential sources of random error in head data with respect to the ground-water-model component are the following:

1. Areal ground-water models assume that the head used is the average over the vertical, but wells may not be open over the entire interval modeled, and, if they are, they may not measure the average.

2. Hydraulic conductivity varies from point to point, which causes water levels to vary from values they would have if hydraulic conductivity were uniform. However, models usually do not take this detailed variation into account. In addition, isotropy is usually assumed because of lack of data to characterize anisotropy.

3. Water levels measured in wells in use may contain unknown amounts of residual drawdown. In addition, unused wells may be near wells that are in use, with resulting unknown drawdown in the unused well.

4. Measurement of well-head elevation may be in error. This error may be significant (in the order of several feet) because most often these elevations are not benchmark-surveyed but interpolated from topographic maps (usually USGS 7.5-minute quadrangle maps).

5. Measurement of depth to water levels may be in error, although usually of the order of 0.1-0.2 ft.

Actual total error from the listed sources is highly problem-dependent, but it is easy to imagine errors of several feet. In addition, interpolation errors are also of the order of several feet (Sophocleous, 1983). Major model errors in ground-water/surface- water flow and its associated boundary conditions can be detected and eliminated by analysis of model results.

Because several different parameters are considered and because each parameter can be estimated or measured in several different ways, numerous sources of error exist in the parameter data. Some examples of errors in parameter data are as follows:

1. Too few estimates of parameters are available to compute stable estimates of statistics such as mean and variance.

2. Results of point sampling are often biased because a large amount of data does not necessarily allow computation of nearly true or effective values of a parameter and its variance. For example, permeability values from core analyses often are not representative of regional values because flow through large fractures is not reproduced by core analyses.

3. Transmissivities estimated from specific-capacity data collected by drillers are subject to numerous sources of error. Common sources include mismeasured water levels or pumping rates, recovery of water level after bailing, clogging the slots or screen, and inaccurate reporting. A persistent source of bias results because drillers drill wells in favorable locations and screen only the most productive zones.

4. Transmissivities and storativities estimated from pumping-test analyses are subject to many of the same errors in item 3, but the more carefully controlled tests should reduce their frequency and magnitude. In addition, a single test may not be representative of an entire hydrostratigraphic unit.

5. Transmissivities and storativities estimated from lithologic data are biased to an unknown extent.

Ground-water and streamflow model assumptions and limitations, which constitute another source of error, are outlined previously, as related to MODFLOW input.

In addition to ground-water-related errors, uncertainties and errors in surface hydrologic components are also pronounced. Precipitation, weather-related, and streamflow measurements are subject to relatively large errors under variable circumstances. Numerous variables related to surface runoff, transmission losses, subsurface lateral flows, pond-related variables, and evapotranspiration-related variables are uncertain, containing appreciable and generally unquantifiable errors. These uncertainties need to be considered in analyzing and evaluating model results. Simulation results should only be considered order-of-magnitude, area-average estimates as opposed to locally specific estimates. Perfectly accurate models do not exist. Therefore, the model purpose should be considered in reviewing a model study. The purpose of the model defines the required accuracy, and hence reality, of the model predictions. For example, a model, such as ours, used to compare the effectiveness of alternate actions may not need to be as accurate as a model used to predict influent concentrations for a water treatment plant. Model results should also be viewed in a relative sense rather than in an absolute sense. In other words, models such as this one are more suitable for comparing various considered scenarios than for making localized predictions.

Finally, it should be realized that distances of water rights locations from the Republican River are approximate, based on conversion of legal-description locations to approximate geographic coordinates within the model grid.

7. MODEL CALIBRATION

A.) Overview

One of the most important steps in setting up a ground-water model is model calibration. In model calibration, simulated values, like hydraulic head, are compared with field measurements. The model input data are altered, within observed ranges, until the simulated and observed values are fitted within a chosen tolerance. Input data and comparison of simulated and measured values can be altered either manually (trial-and-error adjustment) or automatically (inverse or parameter estimation models). Model calibration is time-consuming and can easily take up half of the time required for the whole study.

Development of a computer model as a predictive tool is based on the premise that if historic hydrologic phenomena can be satisfactorily approximated by the model, then so should future conditions. Calibration involves determining the magnitude and spatial distribution of the model parameters that reproduce the observed system states (hydraulic heads, streamflows) with time. For the ground-water model, primary calibration parameters were the hydraulic conductivity and the storage coefficient of the aquifer. Recharge and runoff were common calibration parameters of the combined ground-water and surface-water models. Calibration targets were the observed water levels and streamflows in the Lower Republican River basin over the course of the past two decades.

In trial-and-error calibration (Fig. 7.1), parameter values are initially assigned to each node or element in the grid. During calibration, parameter values are adjusted (over likely ranges of values) in sequential model runs to match simulated heads and flows to the calibration targets.

Some parameters may be known with a high degree of certainty and therefore should be modified only slightly or not at all during calibration. The results of each model execution are compared to the calibration targets. If the error in the simulated results is acceptable, the model is considered calibrated; if the level of error is unacceptable, parameter values are adjusted and the model is run again until acceptable results are achieved (Fig. 7.1). Numerous model runs are typically needed to achieve calibration.

B.) Calibration Implementation Procedure and Results

The combined SWAT-MODFLOW (SWATMOD) model was run in a sequential mode. The relevant output from the SWAT module constituted input to the MODFLOW model module. A daily time-step size was implemented for the SWAT model, while a monthly time-step size was utilized for the MODFLOW simulations. The calibration period spanned from 1977 to 1990. The data for the post-1990 period were reserved for verifying the calibrated model. The overall calibration procedure involved adjusting the SWAT parameters by trial and error such that the resulting recharge and runoff produced relatively low errors in streamflows and water levels in the ground-water model. The hydraulic conductivity was then finalized for that particular distribution of recharge and runoff by minimizing the water-level residuals (i.e. the differences between the observed and simulated water levels) for the initial 1977 state.

DWR use reports served as the basis for estimates of annual water use and irrigated area, which correspond to an annual irrigation depth that provides a target for the daily simulation of irrigation by SWAT. Depth to water (dtw) measurements from the DWR use reports and from our November 1994 survey are used together with USGS topographic maps to provide observed water table elevations which are compared with hydraulic heads calculated by SWATMOD. Measurements of daily streamflow in the Republican River taken at Concordia and Clay Center by USGS define stream yield, to be compared with that calculated by SWATMOD.

Calibration Results

Since SWATMOD simulates a continuous space-time process, it requires specification of the system initial conditions. It is important that the initial conditions be equilibrium conditions, otherwise the simulated results may not be reliable. Therefore the system was conceptualized as being in a steady equilibrium state prior to major development, with withdrawals due to development disturbing this initial equilibrium state. The system was assumed to exist in a near equilibrium condition in 1977, the earliest recent-period year for which data were available. This assumption was confirmed by running the ground-water-model component in steady-state mode and satisfactorily reproducing the observed water levels. The near-equilibrium stresses (recharge and runoff) to MODFLOW were estimated by running SWAT for the year 1977 with the irrigation conditions prevailing at that time.

Figs. 7.1-7.4 show the corresponding residuals (observed minus simulated water levels) at the observation wells for 1982, 1985, 1988, and 1990. A reasonable match can be inferred from these plots. The statistics of these residuals are presented in Table 7.1 and their mean ranges from 1.5 to 3 ft with standard errors ranging from 0.6 to 1.0 ft. Given the uncertainties in water-level data (outlined in section 6D), the model results are satisfactory. A comparison of a measured well hydrograph reported in Munson (1991), with the model-simulated hydrograph also shows a satisfactory match (Fig. 7.5). The measured depth-to-water-level data were converted to water-level elevations for comparison with model results using two estimates of the land-surface elevation at the well locality. It should be noted that the water used (pumped) for irrigation during the 1977-79 period (for which no reported use was available) was assumed equal to the average (reported use/appropriated amount) ratio during the 1980-1992 period multiplied by the appropriated amounts during each of the 1977-79 years. This procedure resulted in smaller ground-water residuals during the 1977-79 period than alternative options.

Table 7.1. Statistics of ground-water-level residuals (i.e. differences between measured and model-simulated water levels in ft) during the calibration period.

Year	1982	1985	1988	1990
Mean	2.260	3.066	1.465	2.230
Standard Error	0.981	1.027	0.733	0.596
Standard Deviation	7.077	6.815	7.618	6.945
Count	52	44	108	136

The monthly average streamflows recorded at the Clay Center gaging station are shown in Fig. 7.6 along with the simulated values. A satisfactory match can be noted from these figures.

The simulated and recorded cumulative streamflow yields at the Clay Center gaging station (shown in Fig. 7.7) also indicate a satisfactory match. The cumulative water volume recorded at the gaging stations is reproduced satisfactorily by the model.

Stream-leakage losses and gains (baseflow) for different years (1985 and 1990) are shown in Figs. 7.8 and 7.9, together with the lateral inflows to the Republican River from the various subbasins considered. Figure 7.10 displays the Republican River reach numbers employed in the model for locational purposes. Clearly the Republican River is gaining flow as it moves downstream due to these subwatershed contributions. Baseflow gains and stream-seepage losses are relatively insignificant, on the order of less than 3 cfs, compared to tens to over a hundred cfs in lateral inflows.

8. MODEL VERIFICATION

A.) Overview and Results

Owing to uncertainties in the calibration, the set of parameter values used in the calibrated model may not accurately represent field values. Consequently, the calibrated parameters may not accurately represent the system under a different set of boundary conditions or hydrologic stresses. Model verification will help establish greater confidence in the calibration.

The process of model verification involves comparing model- simulated results with observed data for a period other than the calibration period. This permits an independent verification of the model. The calibration period spanned from 1977 to 1990. For validation purposes, the calibrated model was run from 1991 to 1994, and the simulated results compared with the observed data.

The spatial distribution of water-level residuals (measured minus simulated ground-water levels) for 1992 and 1994 are presented in Figs. 8.1 and 8.2. The statistics of these residuals are shown in Table 8.1, where the results show a satisfactory match to the observed water levels. A comparison of simulated water levels to another well hydrograph (Fig. 8.3) at the Taddiken well, in addition to the well hydrograph reported by Munson (Fig. 8.4), shows a reasonable match. The average annual streamflows at the Clay Center gaging station for the entire calibration and validation period are shown in Fig. 8.5. The cumulative streamflows for the same period are presented in Fig. 8.6. A close agreement between the simulated and observed flows can be inferred from these figures.

Table 8.1. Statistics of ground-water residuals (i.e. differences between measured and model-simulated water levels in ft) during the verification period.

Year	1992	1994
Mean	-0.232	0.846
Standard Error	0.536	0.483
Standard Deviation	6.207	3.615
Count	134	56

B.) Water Budget

A summary of all inflows and outflows to a region is generally called a water budget. The overall volumetric water budget for the Lower Republican River valley during the 1991-1994 period, representing a transition from extreme dryness to extremely wet conditions, is shown in Fig. 8.7 The convention followed in the stream-aquifer portion of the combined SWATMOD model is that flow into or out of aquifer storage is considered part of the overall budget in as much as accumulation in storage ('uptake to storage' in Fig. 8.7) effectively removes water from the flow system, and storage release effectively adds water to the flow ('release from storage' in Fig. 8.7), even though neither process in itself involves the transfer of water into or out of the ground-water regime (McDonald and Harbaugh, 1988). The present-day dominant outflow component from the aquifer is ground-water pumpage and ground-water contributions to streamflow (baseflow), whereas the dominant inflows consists of, in order of decreasing importance, stream leakage losses to the aquifer, recharge, and lateral inflows to the alluvial aquifer underlying the Republican River valley west of Concordia.

The time distribution of the water-balance components during the 1977-1994 period is shown in Fig. 8.8 (as annual volumetric rates) and in Fig. 8.9 (as cumulative monthly volumes since 1977). In these figures, "net stream leakage gain" is the difference between stream-leakage gain (baseflow) and stream-leakage loss, and "net storage gain" is the difference between aquifer-storage accumulation and storage depletion. It is evident from Figs. 8.8-8.9 that since the 1980's, aquifer-storage depletion has been taking place in the basin. This storage depletion coincides with higher levels of ground-water pumpage and decreasing baseflows to streams. The 'troughs' in well-pumpage components and the 'peaks' in aquifer-storage gains during the wet years of 1982, 1988, and 1992-1993 indicate the remarkable increase in aquifer recharge and storage gains during those flooding years. The opposite is evident during the recent droughts of 1988 and 1991.

As can be noted from Fig. 8.9, the pumping intensity varies inversely with the rate of recharge, which is to be expected since recharge is primarily a function of precipitation. A net decrease in the streamflow gain and an increase in the storage-depletion rate is very noticeable since the mid-eighties. From the plot of the cumulative water balance (Fig. 8.8), the net stream leakage gain was positive until the early 1980's, indicating that the

Republican River was gaining more baseflow contributions than losing water to the aquifer. Note that the 1993 flood was not enough to conterbalance the cumulative streamflow (baseflow) losses taking place since the early 1980's, but it was enough to counterbalance the cumulative aquifer storage losses since 1987.

The basin hydrologic components for the period 1987-1992, which includes the drought years of 1988 and 1991, for the calibrated model (base case) are shown in Fig. 8.10. Clearly the stream yield is dominated by tributary inflow, which is supplied by surface runoff from upland areas of the basin. Only in drought years, particularly in 1988, do baseflow and water-use withdrawals appear to noticeably affect yield (Fig. 8.10). Land-use impacts that may affect runoff consequently affect basin yield.

C.) Indirect confirmation of tributary flow

Unfortunately, tributary flow calculated by our model is not directly verifiable with data because tributary flows to the Republican River are not gaged. However, we compared our model results with runoff from neighboring watersheds that drain into gaged streams, assuming that streamflow from these watersheds is all surface runoff, i.e. without a baseflow component, and that the amount of surface runoff in these watersheds is approximately the same as that of the Lower Republican basin because of similar topographic and climatic conditions. To the north lies an area $A_m = 344$ mi^2 contributing to Mill Creek with streamflow Q_m, gaged at Washington, KS, which flows to the Blue River. To the south lies an area $A_c = 300$ mi^2 contributing to Chapman Creek with streamflow Q_c, gaged near Chapman, KS, flowing to the Smoky Hill River (Fig. 8.11). For our model contributing area $A_r = 972$ mi^2, an average depth of these data is used to approximate runoff by $Q_r = 0.87A_r(Q_m/A_m + Q_c/A_c)/2$. This approximation is applied to annual flow rates and compared in Fig. 8.12 with tributary flow calculated for the base case. In addition, tributary flow calculated for the base case can be approximated by $Q_{trib} = 0.85\ (A_r/A_m)\ Q_m$ based on Mill Creek streamflow (Fig. 8.12a), or by $Q_{trib} = 0.91\ (A_r/A_c)\ Q_c$ based on Chapman Creek streamflow (Fig. 8.12b). These estimated runoff flow rates are only slightly smaller (by factors of 0.85 and 0.91, respectively) than the tributary flow in the Lower Republican River basin. This analysis (Figs. 8.12, 8.12a, ans 8.12b) provides strong support for the magnitude of tributary flow as calculated by our model for thr Lower Republican River basin. Figure 8.12c is a similar comparison of these approximations with tributary flow, but on a monthly cumulative basis.

D.) Summary of water use for the base case (1977-1994)

Table 8.2 presents the annual, basinwide average for each hydrologic component of the composite of the 18 component SWAT cases averaged by SWBAVG. This summarizes the data contained by the balance file for the base case that is read by MODFLOW, providing these data for each subbasin in each aquifer solution time step of one month.

Table 8.2. Hydrologic summary (inches) from SWAT and SWBAVG for the base case

year	PREC	IRR	ET	SURQ	TLOSS	LATQ	PERC	GWRE	PSED	ETPOT
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
1977	38.79	0.26	33.41	6.49	0.22	0.004	2.83	2.83	0.13	54.04
1978	31.61	0.34	30.27	3.76	0.14	0.0	1.85	1.85	0.07	53.30
1979	32.25	0.33	23.02	5.06	0.17	0.0	1.57	1.57	0.10	53.33
1980	22.68	0.60	24.23	1.36	0.09	0.0	0.49	0.49	0.04	57.61
1981	32.24	0.24	30.85	1.44	0.12	0.0	0.45	0.45	0.03	54.53
1982	35.44	0.22	25.76	5.80	0.22	0.004	2.70	2.70	0.08	51.82
1983	28.21	0.51	25.94	1.62	0.09	0.0	0.36	0.36	0.04	53.61
1984	32.56	0.49	28.18	5.40	0.19	0.004	2.22	2.22	0.09	52.91
1985	33.20	0.27	25.24	4.70	0.15	0.004	2.33	2.33	0.08	52.54
1986	41.03	0.24	33.02	4.71	0.17	0.004	1.73	1.73	0.08	54.18
1987	34.94	0.34	30.38	6.90	0.20	0.004	3.74	3.74	0.08	56.35
1988	16.87	0.65	17.16	0.65	0.04	0.0	0.15	0.15	0.01	59.19
1989	26.42	0.53	21.02	2.05	0.09	0.0	0.57	0.57	0.02	55.35
1990	28.74	0.51	28.44	3.07	0.14	0.0	1.57	1.57	0.03	55.37
1991	22.87	0.72	18.75	1.57	0.05	0.0	0.27	0.27	0.02	57.76
1992	38.89	0.22	31.03	4.16	0.17	0.004	1.58	1.58	0.06	51.68
1993	47.95	0.13	33.66	11.98	0.35	0.004	6.94	6.94	0.13	47.78

Key to columns in Table 8.2; symbols shown below are used in Vol. 2, Section 2.

1. Year of study

2. Precipitation, d_{precip}

3. Irrigation depth averaged over the basin, $f_{irr}d_{irr}$, where f_{irr} = irrigated area as a fraction of basin area. The composite quantity $f_{irr}d_{irr}$ is based on the irrigation depths, d_{irr} assigned by SWAT for each of the 18 cases corresponding to six soil types and three land uses (irrigated crops, non-irrigated crops, and grassland) representing basin heterogeneities. In SWAT, irrigation is simulated for each subbasin on a daily basis using soil moisture as a fraction of available field capacity equal to 0.70 as a trigger for irrigation with imposed maximum values of 0.5 in/day and a daily maximum given by the annual estimated ground-water irrigation depth shown in Table 3.2b except for years 1977-1979. In these years, an annual limit of approximately 10 in. is used, corresponding to the average water use fraction $u_g = 0.63$ for purposes of calibration, as described in Table 8.3 below. The 18 cases were then spatially averaged by SWBAVG to produce $d_{irr}f_{irr}$.

4. Evapotranspiration, d_{et}

5. Surface runoff, d_{ro}, a component of tributary flow, below;

6. Transmission loss, d_{xm}, a component of groundwater recharge, below;

7. Lateral subsurface flow, d_{lat}, a component of tributary flow, below;

8. Percolation through the root zone, $d_{perc\text{-}rz}$

9. Percolation through the vadose zone, $d_{perc\text{-}vz}$, a component of recharge, below;

10. Pond seepage, d_{pond} , a component of groundwater recharge, below;

11. Potential evaporation, $d_{et\text{-}pot}$, to be used in MODFLOW's EVT package (if activated)

Combinations of these terms are applied as follows.

Recharge (flow from the watershed to the aquifer): $d_{rech} = d_{xm} + d_{perc\text{-}vz} + d_{pond}$.

Tributary flow (surface and subsurface runoff from contributing basin area) is given by $d_{trib} = f_{con}(d_{ro} + d_{lat})$, where f_{con} = contributing areal fraction of basin; the remainder, i.e. noncontributing fraction flows to ponds ($f_{pond} = 1 - f_{con}$).

Table 8.3 is an annual summary of the coordination of water use for the base case in SWATMOD's component programs SWAT, SWBAVG, and MODFLOW according to the methods described in Section 5E2.

Columns 2-5 of Table 8.3 show the annual water use that is specified as input to MODFLOW's WELL and SURFACE packages, and are directly comparable with columns 7-10 of Table 3.2a, which summarizes annual water use estimates for 1977-1994. These estimates are based on DWR reports for years 1980-1993; the remainder are based on the

Table 8.3. Annual summary of water use (cfs) for base case (1977-1994)

year (1)	gw.non (2)	gw.irr (3)	SrfIrr (4)	tot.irr (5)	SwatIrr (6)	gw.irr (7)	SrfIrr (8)	asg.irr (9)	discrep (10)	asg.tot (11)	%bsnIrr (12)	Irr(in) (13)
1977	1.08	21.71	0.93	22.64	19.57	18.62	0.81	19.43	-3.21	20.51	3.13	9.8
1978	1.08	22.50	1.55	24.05	24.75	22.97	1.60	24.57	0.52	25.65	3.32	9.8
1979	1.08	23.20	1.66	24.86	24.17	22.25	1.61	23.86	-1.00	24.93	3.42	9.8
1980	1.77	37.13	4.04	41.17	43.33	37.98	4.25	42.23	1.05	43.98	4.18	13.5
1981	0.97	13.54	1.62	15.16	17.55	15.33	1.88	17.21	1.79	17.91	4.06	5.2
1982	1.37	13.06	1.07	14.13	16.11	14.54	1.22	15.76	1.55	17.04	3.54	5.4
1983	2.50	31.27	4.22	35.50	37.41	32.21	4.45	36.66	1.03	39.03	3.61	13.1
1984	2.55	31.34	4.05	35.39	36.16	31.47	4.13	35.60	0.21	38.15	3.66	12.8
1985	2.03	17.08	1.80	18.88	19.85	17.61	1.89	19.50	0.62	21.53	3.51	7.0
1986	1.51	15.51	1.18	16.68	17.27	15.82	1.22	17.04	0.35	18.55	3.55	6.0
1987	1.64	20.04	1.75	21.79	24.46	22.32	1.96	24.28	2.47	25.90	3.76	8.0
1988	4.22	40.68	4.03	44.71	46.78	41.79	4.22	46.01	1.29	50.22	4.28	14.3
1989	3.21	32.18	5.12	37.30	38.56	32.52	5.29	37.81	0.44	40.95	4.21	11.9
1990	3.45	31.98	4.48	36.46	36.54	31.27	4.49	35.76	-0.75	39.16	4.31	11.4
1991	4.78	45.47	3.85	49.32	52.37	46.64	4.09	50.73	1.35	55.44	4.52	15.2
1992	3.37	13.06	0.99	14.04	16.07	14.37	1.13	15.50	1.42	18.83	4.42	4.1
1993	3.42	9.19	0.72	9.91	9.78	8.95	0.71	9.66	-0.28	13.06	4.77	2.2
1994	2.75	29.40	3.61	33.02	33.95	29.83	3.72	33.55	0.53	36.29	4.70	9.4

Key to columns in Table 8.3

1. Year of study;
2. annual ground-water use for other than irrigation purposes (neglecting domestic use);
3. annual ground-water use for irrigation (DWR use code = 3);
4. annual surface-water use (all for irrigation);
5. total water use for irrigation (add columns 3 and 4), $U_{irr} = Q_{irr}\Delta t$;
6. annual irrigation water use based on the composite results from SWAT and SWBAVG according to (5E-1);
7. annual ground water use for irrigation assigned by MODFLOW's WELL package, subject to operating constraints for individual wells based on maximum allowed pumping rate and minimum saturated thickness;
8. annual surface water use for irrigation assigned by MODFLOW's SURFACE package, subject to operating constraint of sufficient inflow at stream reach to provide demanded diversion;
9. total water use for irrigation assigned by MODFLOW (add columns 7 and 8); based on the coordination of SWAT, SWBAVG, and MODFLOW according to (5E-1);
10. discrepancy between assigned irrigation (col. 9) and that specified as input (col. 5);
11. total water use assigned by MODFLOW, including the irrigation component (col. 9) that is coordinated with SWAT and SWBAVG, and the non-irrigation ground-water component (col. 2) that is assigned as input to MODFLOW's WELL package.
12. irrigated area as a percent of basin; both ground and surface water sources are included.
13. irrigation as a depth (inches).

precipitation model for groundwater use fraction given by (3B-1a), and shown in Figs. 3.7-3.9, except as otherwise noted.

For a monthly simulation of the stream-aquifer model with MODFLOW, a hydrologic summary of the composite results of the 18 SWAT cases that were averaged by SWBAVG (Table 8.2) is read from the balance file by MODFLOW's MODSWB package. Column 6 shows the annual total for irrigation as a composite $d_{irr} f_{irr}$, which is converted to a flow rate Q_{irr} according to (5E-1) for each aquifer time step of one month. Annual water use rates for irrigation specified by input to MODFLOW's WELL and SURFACE packages for each year are scaled to match the monthly use specified by the balance file as a depth averaged over the basin.

Columns 7 and 8 show ground and surface water assigned for irrigation by MODFLOW on an average annual basis; column 9 shows their sum. These columns summarize assignment of irrigation shown in column 6 to individual ground and surface points of diversion, respectively. Groundwater irrigation assignments are subject to operating constraints based on maximum allowed pumping rate for a well (4 cfs, or approximately 1350 gpm) and a range of saturated thickness from 5 to 10 ft over which a well's pumping rate is scaled linearly by a factor ranging from 0 to 1. Surface water irrigation assignments are limited by the availability of sufficient inflow to the reach from which the diversion is to be drawn.

Column 10 shows the discrepancy between the annual water use for irrigation assigned by the coordination of SWATMOD components (col. 9) and the input to MODFLOW (col. 5), which corresponds to the annual water use estimate (Table 3.2a, col. 10). Much of the discrepancy in 1977, and similar but smaller discrepancies in 1978-1979, result from the following. Input data to MODFLOW's WELL package were not based on water use estimates summarized in Table 3.2a for the first three years of the study. Instead, the average groundwater use fraction $u_g = 0.63$ for reported years 1980-1993 was used. This was done as a part of calibration to provide a better match between simulated and observed water levels. This average water use fraction deviates most notably from the estimated use fraction in 1977, when the estimated use fraction based on the precipitation model for groundwater is only 0.29. (Table 3.2b, col. 2).

D1.) Stream yield components

Stream yield, Q_{yld} is defined as net outflow, and is given by

$$Q_{yld} = Q_{out} - Q_{in} = Q_{trib} - Q_{div} + Q_{base}$$

where Q_{out} = streamflow at Clay Center, Q_{in} = streamflow at Concordia, Q_{trib} = tributary inflow between Concordia and Clay Center, Q_{div} = streamflow diversions (Qsrfdiv in Fig. 8.13), and Q_{base} = baseflow component of streamflow between Concordia and Clay Center. Stream yield and its components for the period 1988-1991of the base case are shown in Figure 8.13, a magnified part of Fig. 8.10. It is evident from these figures that tributary flow is the predominant component of stream yield, and that baseflow is a minor component.

However, even the apparently minor components of baseflow and surface water diversion may be important during drought periods.

Figures 8.15a-c are magnified views of stream yield components for the years 1988, 1990, and 1991. They are shown to demonstrate which components appear to contribute to stream yield and drive baseflow under drought conditions. In each case, baseflow responds immediately and strongly to tributary flow as a result of the hydraulic gradient imposed by the increased stream depth across the stream bed. This is shown clearly for 1991 (Fig.8.15c) by the baseflow response to tributary flow from March through July. Note also that baseflow in July 1991 appears unaffected by the high rate of ground-water pumping, and that the negative stream yield in that month is due almost entirely to surface water diversions. Regarding the effect of ground-water pumping on baseflow, however, the baseflow in August 1990 (Fig. 8.15b) drops significantly in the absence of any significant tributary inflow, possibly as a delayed response to a high rate of ground-water pumping beginning in July. The resulting negative stream yield in August 1990 is composed mostly of (negative) baseflow, but with a significant component of surface water diversions.

Comparison of the stream yield components for the drought years of 1988 (Fig.8.15a) and 1991 (Fig.8.15c), in combination with the water balance components of Table 8.2, indicate that precipitation and the resulting tributary inflows and recharge were appreciably smaller during 1988 than during 1991. Because the drought of 1988 followed a relatively wet 1987 year, baseflow during 1988 was significantly higher than in 1991. However ground-water pumping was higher during 1991 than 1988, especially during July 1991. The combination of higher tributary inflows and higher ground-water pumping during 1991 resulted in significantly higher stream leakage losses during 1991 than during 1988.

Examination of the above-mentioned results from our model for the base case leads to the following conclusions. Stream yield is almost totally composed of tributary flow. During growing seasons, and in the absence of tributary flow, stream yield appears to be affected by ground-water pumping only weakly and with a delayed response. However, stream yield can be affected significantly and immediately by surface water diversions during drought periods. The effect of water use on stream yield is investigated further in terms of sensitivity analysis in Section 9 and water use scenarios in Section 10.

In order to test the model's baseflow response to ground-water pumping, we re-run the base case (Fig. 8.16a) under the hypothetical scenario that no tributary inflows occurred from May 1988 to December 1989, and no ground-water pumping occurred during the 1989 year (Fig. 8.16b) so that we could investigate the impact of the 1988 pumping (drought condition) on streamflow (baseflow). It should also be noted that in this scenario the incoming streamflows at Concordia were fixed at 170 cfs from May 1988 through December 1989. Indeed, as can be seen in Fig. 8.16b, ground-water pumping caused a decrease in baseflow in 1988 to such an extent as to render the Republican River into a losing stream. However in a repeat of the above scenario but with the 1988 ground-water pumping also shut off (Fig. 8.16c), one can see that the Republican River became a gaining river with appreciable baseflow during the drought year. As can be seen from Figs 8.14 and

8.15, there is a time lag in the order of months between ground-water pumping or shutdown and corresponding impact on baseflow and stream yield.

9. SENSITIVITY ANALYSIS

A.) MODFLOW-related parameters

A1.) Aquifer hydraulic conductivity and storativity

In order to assess the sensitivity of the hydraulic-conductivity parameter on simulation results, a set of two simulations were conducted in which the average baseline hydraulic conductivity of 422 ft/day was first increased to 522 and then decreased to 322 ft/day. The results were displayed as a modified root mean squared (RMS) error or a standard deviation, expressing the average difference between simulated (h_{sim}) and measured (h_{obs}) heads (residuals, e_i) as follows: $\sqrt{\sum_{i=1}^{n} e_i^2 / (n-1)} = \sqrt{\left[\sum_{i=1}^{n} (h_{obs} - h_{sim})_i^2\right] / (n-1)}$, where n is the number of wells with observed water levels. The results show that the higher hydraulic conductivity improved the average error during the 1993 flooding year (Fig. 9.1). In general, however, the hydraulic conductivity was not a highly sensitive parameter.

The impact of increasing and decreasing the aquifer storativity parameter from the baseline value of 0.20 to 0.30 and 0.15, respectively, is shown in Fig. 9.2. The results indicate that storativity is not a very sensitive parameter over the range tested; it is less sensitive than hydraulic conductivity.

A2.) Stream-related parameters

The riverbed conductance is the product of riverbed-seepage area and riverbed hydraulic conductivity divided by the riverbed thickness (riverbed leakance). The baseline riverbed hydraulic conductivity was estimated at 0.5 ft/day, indicating a heavily silted streambed. This value was increased and decreased by one order of magnitude (5 ft/day and 0.05 ft/day, respectively) and the resulting streamflows were compared in Fig. 9.3. The results indicate that this generally difficult parameter to measure is not sensitive enough to significantly impact simulated streamflows in the area, and thus order of magnitude estimates are adequate.

A refinement of the MODFLOW stream module was also evaluated to test the impact of assuming a rectangular stream cross section with an estimated average width, and using Manning's roughness coefficients, versus using the actual measured river cross section at Concordia and Clay Center (which were very similar) and using the rating curves at these stations to derive stream stage throughout the Concordia to Clay Center stretch.

The results, shown in Fig. 9.4, indicate that the MODFLOW stream-module procedures are very robust, despite their numerous simplifications.

A3.) Ground-water evapotranspiration

The impact of ground-water evapotranspiration on streamflows was simulated by activating the evapotranspiration module of the MODFLOW component of the combined model and setting up an evapotranspiration extinction depth of 6 ft. This means that if the water table is below 6 ft from the land surface (which is the typical root-zone depth of crops), no ground-water evapotranspiration takes place. The results of this sensitivity run on streamflows are shown in Fig. 9.5, where it can be seen that the ground-water evapotranspiration impact on streamflows is relatively very small compared to the base case where no ground-water evapotranspiration occurred. However, when the cumulative 1977-1994 streamflows at Clay Center were plotted with and without ground-water ET, there is a noticeable but relatively small difference, as shown in Fig. 9.6.

A4.) Specified head boundaries

Specifying heads at a boundary is essentially fixing the hydraulic head at that location.

In order to assess the impact of uncertainty in specification of the boundary heads, a set of two simulation runs were conducted. In the first case, the specified heads were raised 5 ft throughout the valley width west of Concordia from their calibrated values for the entire (1977-94) simulation period. For the second simulation run, heads were dropped uniformly west of Concordia by 5 ft.

Increasing the specified head by 5 ft west of Concordia results in increasing the lateral subsurface inflow into the model area, but the resulting increase in lateral inflow, which is the smallest component in the ground-water balance (see Fig. 8.8), did not result in any significant changes in streamflow. The impact of these boundary changes on streamflows is shown in Fig. 9.7. Only a slight increase in the streamflows at Clay Center is noted with increased boundary heads. A corresponding slight decrease was noted when boundary heads are lowered. The impact on water levels was also minimal and became negligible as one moved away (downstream) from Concordia.

The results of the sensitivity runs indicate that the simulated flux out of the model domain is not affected significantly due to any uncertainty in the western model-domain boundary heads.

A5.) Ground-water pumping

The effect of increasing and decreasing ground-water pumpage throughout the model area was investigated to analyze its impact on streamflow. Fig. 9.8 presents the changes in streamflow at Clay Center when ground-water pumpage in the Republican River valley was assumed to be 1) equal to the full appropriation amounts, 2) equal to 50 percent of the appropriated amounts, and 3) equal to 75 percent of the appropriated amounts. The simulated relative changes in streamflow are relatively small. The maximum increase in streamflow was less than 8 percent for the 50 percent of appropriations case, and the maximum decrease was less than 5 percent for the full appropriation case. A plot of cumulative changes in streamflow at Clay Center from 1977 to 1994 is shown in Fig. 9.9 which reinforces the relatively small overall impact of ground-water pumpage on streamflows.

B.) SWAT-related parameters

B1.) Irrigated area

The area irrigated in the Republican River valley is an estimated quantity based on water-use reports. The baseline case area (reported in section 3B of this report) was increased and decreased by 50 percent, respectively, for all the years of simulation, and the results are displayed as modified root mean square errors of the residuals, as explained earlier in this section. The results, displayed in fig. 9.10, indicate that the irrigated area is a very sensitive parameter, appreciably impacting the simulated results. The average residual (i.e. the average difference between observed and simulated water levels) decreased consistently with increasing irrigated area, as shown in Fig. 9.11, which implies that the reported irrigated area may be underestimated in our model.

B2.) NRCS runoff-curve number

Runoff-curve numbers (CN) were estimated based on soil type, land use, and normal antecedent moisture condition II (USDA, SCS, 1972 National Engineering Handbook, Section 4.) Since the watershed consists of several soil types and land uses, a composite CN is used. A range of 65 to 80, which is typical for the area, was employed to determine the curve number that will minimize the modified root mean square (RMS) residual-error criterion, outlined earlier in this section. The results showed that the CN parameter is a sensitive one (Fig. 9.12), with different curve numbers resulting in lower RMS errors at different years. However, since CNs predominantly affect the surface runoff component of the hydrologic balance, the impact of the various CNs employed was evaluated on the simulated 1977-1994 cumulating stream yields between Concordia and Clay Center against the measured values. The results are displayed in Fig. 9.13 and indicate that an average CN of 78 best describes the cumulative stream yield, and that indeed the CN is a very sensitive parameter in the model. The temporal variation of CNs during the 1990 and 1991 simulations for the Kipson soil (which exhibited the most extreme soil-moisture variations—see figures under "Irrigation scheduling" further below) with irrigated cropland is depicted in Figs. 9.14 and 9.15, respectively, indicating the impact of moisture conditions and vegetation conditions on CNs.

B3.) Soils, crops, and land use

A sensitivity analysis was conducted to investigate the impact of soil-water characteristics of the four predominant soil series in the Republican River valley, namely Carr (FSL), Muir (SiL), Crete (SiCL), and Hastings (SiCL), and of crop and land uses as represented by irrigated cropland, non-irrigated cropland, and grassland (pasture). Irrigated cropland is represented by corn, whereas non-irrigated cropland is represented by wheat-sorghum-fallow rotation.

Table 9.1 presents the results of this series of sensitivity analyses, using the 1990 hydrologic conditions as typical for the area. It is clear from this table that the Hastings soil series produced the highest runoff, and the Muir soil series the lowest runoff from all the series shown in the table. The Carr soil series, being the sandiest soil, induced the highest aquifer recharge, whereas the Crete soil series, being a heavy soil, induced the lowest aquifer recharge.

With regard to vegetation cover, grasslands induced the lowest runoff and recharge compared to cropland. Wheat-sorghum-fallow rotations induced the highest aquifer recharge, whereas irrigated corn produced the highest evapotranspiration and runoff losses.

B4.) Irrigation scheduling

In order to investigate the soil-moisture-based irrigation triggering procedure specifically programmed by us in SWAT as a more intuitive and stable alternative to the SWAT-employed plant-water-stress factor, a number of simulations in irrigated cropland were run for the Crete, Kipson, and Carr soil series during 1990 and 1991. Figs. 9.16-9.17, 9.18-9.19, and 9.20-9.21 show the results of these simulations. In each one of these figures, the following items were displayed: daily soil-profile moisture in mm, precipitation (mm) at the bottom of the graph, soil-water threshold to initiate irrigation during the crop-growing season (shown in dashes), and assigned ground-water-based irrigation (shown at the top of the graphs), constrained by limits based on water-use estimates. The figures show that the programmed irrigation scheduling worked as expected, with irrigation being triggered each time (during the growing season) the soil moisture dropped below the set moisture trigger (70 percent of the available moisture capacity of the soil) indicated by the horizontal dash line in the figures. The resulting irrigation amounts matched the reported estimated water use when the irrigation (moisture) trigger was set at 70 percent of maximum available soil-moisture capacity, as can be seen in Fig. 9.22.

Experiments at Scandia Experiment Field (Cooperative Extension Service, Kansas State University, Corn Production Handbook, 1994), north of Concordia, indicated that scheduling irrigation by plant conditions (stress factors) has not worked well with corn because corn shows few obvious signs of water stress; waiting for the crop to wilt prior to irrigation is too late. However, monitoring soil water is a safe routine with universal applicability (Corn Production Handbook, 1994). In the Scandia results, maintaining soil

Table 9.1. SWAT-hydrologic components for various soil, crop, and land-use combinations.

	Carr (FSL)			Muir (SiL)			Crete (SiCL)			Hasting (SiCL)		
Hydrologic Variable (in)	irr. corn	wsf	grass	irr. corn	wsf	grass	irr. corn	wsf	grass	irr. corn	wsf	grass
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Irrigation	11.7	0.0	0.0	11.5	0.0	0.0	11.5	0.0	0.0	11.6	0.0	0.0
Evapotranspiration	35.1	27.3	26.6	35.3	31.5	27.5	35.1	30.9	27.6	34.9	28.9	27.5
Surface Runoff	5.0	4.3	2.3	4.3	3.5	1.0	4.8	4.0	1.3	5.1	4.5	1.6
Transmission Losses	0.2	0.2	0.1	0.2	0.2	0.0	0.2	0.2	0.1	0.2	0.2	0.1
Subsurface Lateral Flow	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Ground-water Recharge	2.3	3.4	0.3	1.8	1.8	0.0	1.2	1.4	0.0	1.7	2.5	0.1
Pond Seepage	0.1	0.1	0.0	0.1	0.0	0.0	0.1	0.0	0.0	0.1	0.1	0.0

water above 65 percent depletion resulted in best yields. Therefore, in our modeling we used 70 percent soil water depletion before irrigation is triggered (after trial-and-error calibration), to account for non-ideal conditions and application inefficiencies. Higher percent depletion (such as 80 percent) resulted in almost identical outcomes to those of 70 percent.

10. MANAGEMENT SCENARIOS

The primary objective of the modeling effort was to develop a numerical model of the Lower Republican River basin through which the hydrologic impact of various management scenarios on water levels and streamflows in the basin can be assessed. KWO provided management scenarios as test cases for the combined model.

This section describes results of a number of test scenarios that were conducted in order to evaluate the feasibility of simulating typical scenarios of interest to KWO. The scenarios involved specifying hypothetical stresses (withdrawals) to the system and determining the change in the water-levels and streamflows from a baseline scenario. The baseline scenario represents an 18-year future simulation period (1995-2012) with 1994 initial and boundary conditions, 1994 land- and water-use conditions, and a repeat of climatic conditions of the past 18 years (1977-1994). Thus, 1977 climate data are used for the first year of the (1995-2012) simulation, 1978 for the second year, and so on. The irrigation demand in each subwatershed was determined by SWAT based on climatic conditions and 1994 land-use conditions. Appropriations for surface and ground water for years 1995-2012 were assumed to be given by the 1994 appropriations for the base case. The historical water-use fractions were repeated in the 1995-2012 simulation period, but based on the 1994 existing wells. The 1977-1994 historical simulation will be referred to as *base case* to distinguish it from the *baseline scenario*.

Table 10.1 summarizes water use for the baseline scenario (1995-2012), and is analogous to Table 8.3 that describes water use for the base case (1977-1994). Columns 2-5 summarize projected annual water use as specified by input to MODLOW's WELL and SURFACE packages. Column 6 summarizes annual irrigation based on SWAT, SWBAVG, and conversion from depth to flow rate as described in Section 8. Columns 7-9 and 11 summarize the water use assigned by MODFLOW based on column 6 and subject to constraints on saturated thickeness, individual well pumping rates, and streamflow. Column 12 denotes the irrigated area as a percentage of the Lower Republican River basin considered in this report, and column 13 represents the annual amount of irrigation (in inches) employed in the model.

The water-level hydrographs at four observation wells (index locations, Fig. 10.1) in different regions of the basin (namely, near Concordia [6,13], Clyde [4,20], Clifton [9,30], and Clay Center [19,35], where the brackets indicate model grid-cell row and column), are presented in Fig. 10.2 for both the baseline scenario mentioned above and the base case (shifted forward by 18 years) for comparison. The hydrographs indicate a continuation of the historical slightly declining trend in water levels.

Table 10.1. Summary of water use (cfs) for baseline scenario (1995-2012).

year	gw.non	gw.irr	SrfIrr	tot.irr	SwatIrr	gw.irr	SrfIrr	asg.irr	discrep	asg.tot	%bsnIrr	Irr(in)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
1995	2.83	30.25	1.94	32.19	27.62	25.95	1.67	27.62	-4.57	30.45	4.45	4.8
1996	2.82	30.25	3.23	33.48	34.44	31.09	3.33	34.42	0.94	37.24	4.62	8.3
1997	2.83	30.25	3.45	33.70	32.23	28.82	3.30	32.12	-1.58	34.95	4.64	9.0
1998	4.49	48.06	8.41	56.46	59.85	52.09	8.91	61.00	4.53	65.49	5.73	13.5
1999	1.60	17.09	3.13	20.23	23.88	19.85	3.70	23.55	3.32	25.15	5.42	5.2
2000	1.57	16.80	2.07	18.87	21.81	19.17	2.39	21.56	2.68	23.12	4.73	5.4
2001	3.59	38.41	8.17	46.58	48.34	39.43	8.48	47.91	1.32	51.49	4.74	13.1
2002	3.60	38.46	7.27	45.73	46.62	38.76	7.41	46.17	0.44	49.76	4.73	12.8
2003	2.02	21.65	3.23	24.88	26.19	22.47	3.40	25.87	0.99	27.90	4.63	7.0
2004	1.78	19.06	2.11	21.17	22.10	19.72	2.21	21.93	0.75	23.71	4.51	6.0
2005	2.22	23.77	3.14	26.91	30.21	26.61	3.53	30.14	3.23	32.36	4.64	8.0
2006	4.23	45.23	6.20	51.42	54.96	47.95	6.62	54.57	3.15	58.80	4.92	14.3
2007	3.26	34.81	5.96	40.76	42.59	35.77	6.22	41.99	1.23	45.24	4.6	11.9
2008	3.09	33.13	4.62	37.75	37.88	32.79	4.64	37.43	-0.33	40.52	4.46	11.4
2009	4.35	46.52	3.97	50.50	54.39	48.30	4.28	52.58	2.08	56.92	4.63	15.2
2010	1.41	15.08	0.99	16.06	18.13	16.64	1.11	17.75	1.68	19.15	5.06	4.1
2011	1.08	11.57	0.72	12.29	12.37	11.59	0.73	12.32	0.03	13.40	5.92	2.2
2012	2.74	29.38	3.61	33.00	33.86	30.08	3.71	33.79	0.79	36.53	4.7	9.4

The simulated 1995-2012 cumulative streamflows at the Clay Center gaging station are presented in Fig. 10.3, and show little change from the base case (translated by 18 years for comparison). Figure 10.4 displays the 1995-2012 cumulative stream yield simulated for the baseline scenario overlaid over the corresponding cumulative yield of the base case (1977-1994). A relatively small decrease in cumulative stream yield can be seen from the figure.

The cumulative monthly hydrologic mass balance for the baseline scenario is shown in Fig. 10.5. Comparison of this hydrologic balance to that of the base case (Fig. 8.9) indicates that the simulated cumulative net streamflow-leakage loss of the Republican River between Concordia and Clay Center is 165,980 acre-feet (corresponding to an average loss of 9,221 ac-ft/yr), compared to 72,773 acre-feet loss during the base case (1977-1994) simulation (corresponding to an average loss of 4,043 ac-ft/yr).

The test scenarios described below involve a reduction of water rights in the subbasin. It was assumed that a modification of the water rights implied an equal reduction in water use. For example, a 10 percent reduction in appropriation is considered equivalent to a 10 percent reduction in water use for that particular water right. The hydrologic impact of the test scenarios were assessed by comparing the simulated streamflows and water levels with the baseline scenario results. Streamflows and/or stream yield between Concordia and Clay Center were compared at the Clay Center gaging station. The water-level hydrographs were compared at the four index locations indicated in Fig. 10.1. The test scenarios considered, which are variations on the baseline scenario, are as follows:

1. Reduce water rights by 25 percent;
2. Shut off all water rights junior to 3/22/74 (application numbers > 22310);
3. Shut off all water rights junior to 4/12/84 (application numbers > 37147);
4. Shut off all water rights within distance of 1/4 mile to Republican River;

5. Shut off all water rights within distance of 1/2 mile to Republican River;
6. Increase irrigated cropland area by 10 percent;
7. Decrease irrigated cropland area by 10 percent;
8. Increase pond storage by 25 percent (increase pond area by 25 percent);
9. Combine scenarios 2 and 4 above: shut off water rights junior to 3/22/74 within 1/4 mile of river;
10. Combine scenarios 3 and 5 above: shut off water rights junior to 4/12/84 within 1/2 mile of river;
11. Combine scenarios 9 and 10 above as follows: shut off all water rights junior to 3/22/74 within 1/4 mile of river, and all water rights junior to 4/12/84 within 1/2 mile of river.

Two additional test scenarios were considered to analyze a less drastic variant of scenario 4, and to evaluate the impact of irrigation water rights on streamflow.

12. In only those months when measured streamflow at Concordia (for the corresponding historical month) falls below the established minimum desirable streamflow, shut off all surface water rights and all ground water rights within 1/4 mile of the river.
13. Shut off all irrigation water rights for the study period 1977-1994. The purpose of this test is to determine how much stream yield is lost as a result of irrigation.

These scenarios, except for the eighth, are represented by varying both annual irrigation-water use Q_{irr} (cfs) in MODFLOW's WELL package input file, and irrigated areal fraction of the basin, $f_{irr} = A_{irr}/A$, in order to maintain equality on both sides of the equation

$$c.Q_{irr}.\Delta t = d_{irr}.f_{irr}.A, \qquad (10.1)$$

where d_{irr}=annual irrigation depth (mm) based on water-use estimates for 1977-1994, which is held constant; A=basin area (2,570 km^2), and c is a conversion factor; $A/(c\Delta t)$=2.8775 for a 365-day year. The annual irrigation depth (based on reported water use and irrigated acreage) is used in SWAT as an annual limit on irrigation. The irrigated fraction of the basin is incorporated into the weight functions applied to the 18 hydrologic response units (HRUs) by program SWBAVG to calculate an average balance file for each scenario.

The rationale for maintaining equality in the above equation (10.1) by varying $f_{irr}.A$ with Q_{irr}, instead of varying d_{irr}, is as follows. The annual irrigation depth, d_{irr} is treated as an upper limit by SWAT, so that less irrigation may be simulated by SWAT than that specified by d_{irr}. Through calibration of irrigated-corn cases, a threshold on available soil moisture to trigger irrigation has been set to 0.7 of maximum available soil-moisture capacity by trial-and-error calibration, and a maximum daily-irrigation depth has been set to 12.5 mm (0.5 inch); for these values, SWAT satisfactorily matches irrigation-depth estimates based on water-use reports as shown in Fig. 9.22.

The methodology employed to implement the above-mentioned scenarios is explained in more detail in Appendix 10A.

Table 10.2 summarizes the effect of each scenario on water use with respect to the baseline scenario. For each scenario and year, Table 10.2 shows the change in total estimated irrigation (cfs) as the sum of both ground- and surface-water diversions. At the left of Table 10.2 are estimated (reported) water use (cfs) for years 1977-1994 (base case) and projected water use 1995-2012 (baseline scenario). At the bottom of table 10.2 are values that show the average effect (and standard deviation) of the scenarios on irrigation water use, dQ_{irr}.

Table 10.2. Effect of scenarios 1-13 on assigned irrigation (cfs) with respect to the baseline scenario (1995-2012).

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
hist.	scen.	irr(cfs)					Scenarios								
year	year	baseline	1	2	3	4	5	6	7	8	9	10	11	12	13
1977	1995	27.6	-7.2	-13.2	-5.2	-3.2	-7.9	2.6	-2.9	-0.9	-1.7	-3.2	-4.0	-0.1	-27.6
1978	1996	34.4	-8.3	-16.6	-6.6	-4.0	-10.4	3.4	-3.4	0.0	-2.3	-4.0	-5.5	0.0	-34.4
1979	1997	32.1	-8.0	-15.4	-6.3	-3.5	-10.3	3.1	-2.8	0.0	-2.0	-4.0	-4.9	0.0	-32.1
1980	1998	61.0	-16.2	-15.6	-9.5	-3.6	-12.6	6.3	-6.1	0.0	-2.2	-6.5	-6.9	0.0	-61.0
1981	1999	23.6	-6.2	-11.0	-5.1	-3.2	-7.6	2.5	-2.8	0.0	-1.7	-3.2	-3.7	-2.0	-23.6
1982	2000	21.6	-5.6	-10.4	-4.6	-2.6	-6.8	1.9	-2.5	0.0	-1.7	-2.6	-3.4	0.0	-21.6
1983	2001	47.9	-11.8	-22.9	-10.3	-4.9	-10.0	7.2	-4.2	0.0	-2.6	-6.6	-8.0	0.0	-47.9
1984	2002	46.2	-12.1	-22.3	-10.3	-5.2	-15.3	4.2	-4.5	0.0	-3.2	-6.0	-7.5	0.0	-46.2
1985	2003	25.9	-6.7	-12.4	-5.7	-3.4	-8.0	2.2	-2.8	0.0	-2.0	-3.4	-4.3	0.0	-25.9
1986	2004	21.9	-5.6	-10.2	-4.3	-2.3	-6.8	2.5	-2.0	0.0	-1.4	-2.6	-3.2	0.0	-21.9
1987	2005	30.1	-7.4	-14.0	-6.0	-3.5	-9.2	3.4	-2.8	0.0	-2.0	-3.7	-4.6	0.0	-30.1
1988	2006	54.6	-13.5	-25.8	-11.1	-6.3	-17.1	5.3	-5.6	0.0	-4.0	-6.9	-8.6	0.0	-54.6
1989	2007	42.0	-10.3	-19.9	-9.1	-4.6	-13.8	3.6	-4.2	0.0	-2.9	-5.5	-6.9	-9.1	-42.0
1990	2008	37.4	-8.9	-17.6	-7.7	-4.0	-11.7	4.2	-3.6	0.0	-2.0	-4.6	-5.7	0.0	-37.4
1991	2009	52.6	-12.2	-14.4	-7.2	-3.9	-9.9	5.2	-4.4	0.0	-2.2	-4.6	-5.6	-7.7	-52.6
1992	2010	17.8	-4.2	-7.8	-3.1	-1.7	-5.0	1.9	-1.7	0.0	-1.2	-1.7	-2.6	-2.5	-17.8
1993	2011	12.3	-3.4	-6.0	-2.3	-1.7	-3.6	0.8	-1.1	0.0	-0.9	-1.4	-2.0	0.0	-12.3
1994	2012	33.8	-8.3	-16.6	-6.8	-4.0	-10.1	3.4	-3.4	0.0	-2.3	-4.0	-5.2	0.0	-33.8
	avg dQ_irr.		-8.7	-15.1	-6.7	-3.6	-9.8	3.5	-3.4		-2.1	-4.1	-5.1	-1.2	-34.6
	stdev dQ_irr.		3.4	5.3	2.5	1.2	3.5	1.6	1.3		0.7	1.6	1.9	2.7	13.7

Key to columns in Table 10.2:

1. Year of historical simulation (1977-1994).
2. Year of scenario; data for weather, streamflow, and crop rotations are based on corresponding historical year (col. 1).
3. Sum of assigned ground and surface water irrigation for baseline scenario (Table 10.1, col. 8).

4-16. Change in assigned ground and surface water irrigation with respect to the baseline for scenarios 1-13.

Tables 10.3-10.5 show the following for each scenario. Table 10.3 shows the change in stream yield dQ_{yield} (cfs) at Clay Center. Table 10.4 shows the sensitivity of stream yield to change in water use, $dQ_{yield}/dQ_{irrig.}$. Table 10.5 shows calculated streamflow at Clay Center.

The following discussion pertains to the original eleven test scenarios. The scenarios all produce approximately the same sensitivity of stream yield to water use (Table 10.4): a water-use reduction of 1 cfs increases stream yield by approximately 0.9 cfs. All scenarios show that a relatively large change in water use (Table 10.2) results in a relatively small change in stream yield (Table 10.3). These results are consistent with a comparison of hydrologic components of streamflow calculated by the model for the base case: stream

Table 10.3. Effect of scenarios 1-13 on stream yield (cfs) with respect to the baseline scenario.

hist. year	scen. year	yield (cfs) baselin	1	2	3	4	5	6	7	8	9	10	11	12	13
1977	1995	459.6	0.7	1.6	1.2	1.2	2.5	-0.1	0.3	-9.6	0.5	1.1	1.3	0.2	2.1
1978	1996	269.9	3.6	7.5	3.5	2.4	6.0	-1.4	1.5	-4.8	1.3	2.4	3.2	0.0	14.8
1979	1997	343.1	4.6	9.3	3.9	2.4	6.5	-1.9	1.7	-2.5	1.3	2.6	3.2	0.1	19.1
1980	1998	75.1	8.5	10.2	5.9	2.0	7.5	-3.4	3.1	-0.8	1.2	4.0	4.2	0.0	33.1
1981	1999	80.1	5.5	5.0	2.6	1.5	2.9	-2.0	2.2	-0.4	0.8	1.9	2.0	1.0	19.4
1982	2000	401.8	5.7	8.6	3.8	2.2	5.5	-2.2	2.4	-1.8	1.3	2.3	2.9	0.3	21.9
1983	2001	85.9	7.7	14.5	7.4	3.8	7.1	-4.2	2.9	-0.6	2.0	4.9	6.0	0.1	31.0
1984	2002	366.4	9.2	16.9	8.1	4.2	11.5	-4.1	3.4	-2.1	2.4	5.1	6.2	0.0	35.8
1985	2003	318.8	8.4	15.0	6.3	3.5	8.9	-3.2	3.3	-1.7	2.1	3.7	4.7	0.0	32.8
1986	2004	320.9	3.9	6.7	2.6	1.4	2.9	-1.6	1.4	-1.7	0.9	1.5	1.8	0.0	15.3
1987	2005	507.1	6.3	11.6	5.1	2.9	7.8	-2.7	2.4	-2.5	1.7	3.2	3.9	0.0	25.2
1988	2006	31.1	9.2	17.8	8.4	5.0	13.8	-3.7	3.7	-0.2	3.0	5.4	6.8	0.0	37.4
1989	2007	116.1	9.2	17.4	7.8	4.1	11.9	-3.4	3.7	-0.5	2.6	4.8	6.0	6.0	37.1
1990	2008	202.9	8.1	15.6	6.8	3.6	10.4	-3.3	3.3	-0.7	2.0	4.1	5.1	1.4	33.4
1991	2009	87.6	7.5	11.5	5.2	2.5	6.9	-3.1	2.8	-0.4	1.4	3.1	3.8	5.3	33.5
1992	2010	256.7	6.8	9.0	3.5	1.9	4.3	-3.0	2.7	-1.2	1.2	2.0	2.6	3.6	27.8
1993	2011	854.2	4.9	7.4	2.7	1.5	3.3	-1.9	1.8	-3.9	0.9	1.4	2.0	1.2	19.6
1994	2012	130.9	5.5	10.6	4.8	3.0	7.4	-2.2	2.2	-0.6	1.6	3.0	3.9	0.5	22.7
	avg dQ_yield		6.4	10.9	5.0	2.7	7.1	-2.6	2.5	-2.0	1.6	3.1	3.9	1.1	25.7
	stdev dQ_yld		2.3	4.6	2.1	1.1	3.3	1.1	0.9	2.3	0.7	1.3	1.6	1.9	9.6

Table 10.4. Sensitivity of stream yield to change in irrigation for scenarios 1-13.

hist. year	scen. year	1	2	3	4	5	6	7	8	9	10	11	12	13
1977	1995	-1.50	-1.61	-1.52	-5.95	-2.24	-0.60	-1.78		-5.30	-2.16	-2.48		-1.28
1978	1996	-0.44	-0.45	-0.53	-0.60	-0.58	-0.41	-0.44		-0.54	-0.60	-0.58		-0.43
1979	1997	-0.58	-0.60	-0.62	-0.69	-0.63	-0.60	-0.61		-0.63	-0.64	-0.66		-0.59
1980	1998	-0.53	-0.65	-0.63	-0.56	-0.59	-0.53	-0.51		-0.55	-0.61	-0.61		-0.54
1981	1999	-0.89	-0.45	-0.51	-0.47	-0.39	-0.81	-0.78		-0.47	-0.59	-0.53	-0.49	-0.82
1982	2000	-1.02	-0.83	-0.84	-0.85	-0.80	-1.12	-0.96		-0.78	-0.90	-0.84		-1.01
1983	2001	-0.65	-0.63	-0.72	-0.78	-0.71	-0.58	-0.69		-0.78	-0.75	-0.74		-0.65
1984	2002	-0.76	-0.76	-0.79	-0.81	-0.75	-0.99	-0.77		-0.76	-0.84	-0.83		-0.77
1985	2003	-1.26	-1.21	-1.11	-1.01	-1.11	-1.43	-1.19		-1.03	-1.08	-1.08		-1.27
1986	2004	-0.70	-0.66	-0.61	-0.60	-0.43	-0.64	-0.73		-0.62	-0.59	-0.57		-0.70
1987	2005	-0.85	-0.83	-0.85	-0.83	-0.84	-0.81	-0.85		-0.85	-0.84	-0.84		-0.84
1988	2006	-0.68	-0.69	-0.76	-0.80	-0.81	-0.70	-0.66		-0.74	-0.79	-0.79		-0.68
1989	2007	-0.89	-0.87	-0.86	-0.90	-0.86	-0.94	-0.89		-0.89	-0.87	-0.87	-0.66	-0.88
1990	2008	-0.90	-0.88	-0.88	-0.90	-0.89	-0.80	-0.91		-1.00	-0.89	-0.90		-0.89
1991	2009	-0.62	-0.80	-0.72	-0.64	-0.69	-0.61	-0.65		-0.61	-0.68	-0.68	-0.68	-0.64
1992	2010	-1.63	-1.15	-1.12	-1.10	-0.85	-1.56	-1.60		-1.03	-1.13	-1.02	-1.47	-1.57
1993	2011	-1.43	-1.23	-1.18	-0.86	-0.91	-2.24	-1.58		-1.00	-1.01	-1.00		-1.59
1994	2012	-0.67	-0.64	-0.70	-0.74	-0.74	-0.65	-0.63		-0.70	-0.74	-0.75		-0.67
avg dQ_yield/dQ_irr.		-0.89	-0.83	-0.83	-1.06	-0.82	-0.89	-0.90		-1.02	-0.87	-0.87		-0.88
stdev dQ_yld/dQ_irr.		0.35	0.30	0.26	1.23	0.39	0.45	0.39		1.08	0.36	0.43		0.34

Table 10.5. Calculated streamflow (cfs) at Clay Center for all scenarios.

hist. year	scen. year	baselin	1	2	3	4	5	6	7	8	9	10	11	12	13
1977	1995	869.6	870.2	871.2	870.8	870.8	872.0	869.5	869.9	859.9	870.1	870.6	870.9	869.79	871.7
1978	1996	646.9	650.6	654.5	650.5	649.4	653.0	645.6	648.4	642.1	648.2	649.4	650.1	646.95	661.7
1979	1997	934.3	938.9	943.6	938.3	936.7	940.8	932.5	936.0	931.8	935.6	936.9	937.6	934.38	953.38
1980	1998	444.0	452.5	454.1	449.9	446.0	451.4	440.6	447.1	443.2	445.1	447.9	448.2	443.95	477.05
1981	1999	379.3	384.8	384.2	381.9	380.8	382.2	377.3	381.5	378.9	380.1	381.1	381.2	380.25	398.69
1982	2000	1047.6	1053.3	1056.2	1051.4	1049.8	1053.1	1045.5	1050.1	1045.8	1049.0	1050.0	1050.5	1047.9	1069.5
1983	2001	787.4	795.2	802.0	794.8	791.3	794.5	783.3	790.3	786.9	789.5	792.4	793.4	787.55	818.42
1984	2002	1097.0	1106.2	1113.9	1105.1	1101.2	1108.5	1092.9	1100.5	1094.9	1099.4	1102.1	1103.2	1097.1	1132.8
1985	2003	923.9	932.3	938.8	930.2	927.3	932.8	920.7	927.2	922.2	925.9	927.6	928.5	923.9	956.69
1986	2004	923.2	927.2	929.9	925.8	924.6	926.2	921.6	924.7	921.6	924.1	924.8	925.0	923.24	938.47
1987	2005	1533.8	1540.1	1545.4	1538.9	1536.6	1541.6	1531.0	1536.2	1531.3	1535.5	1536.9	1537.6	1533.8	1559
1988	2006	297.9	307.1	315.7	306.3	302.9	311.7	294.2	301.6	297.7	300.8	303.3	304.6	297.88	335.24
1989	2007	368.8	377.9	386.2	376.6	372.9	380.6	365.4	372.5	368.3	371.3	373.5	374.7	374.74	405.9
1990	2008	464.0	472.0	479.5	470.7	467.6	474.3	460.6	467.3	463.2	466.0	468.0	469.1	465.36	497.35
1991	2009	197.7	205.2	209.2	202.9	200.2	204.6	194.6	200.5	197.3	199.1	200.8	201.5	202.96	231.2
1992	2010	696.8	703.6	705.8	700.3	698.7	701.1	693.8	699.5	695.6	698.0	698.8	699.5	700.43	724.66
1993	2011	3028.7	3033.5	3036.0	3031.3	3030.1	3031.9	3026.8	3030.5	3024.8	3029.5	3030.1	3030.7	3029.9	3048.2
1994	2012	614.6	620.1	625.2	619.3	617.5	622.0	612.3	616.7	614.0	616.2	617.5	618.4	615.04	637.24

yield is largely dominated by tributary flow, which is much larger than either baseflow or irrigation most of the time. Figure 10.6 shows that the year 1988 is a notable exception to this, when irrigation is approximately equal to tributary flow; and that other drought periods also show low tributary flow, when irrigation use has a relatively significant effect on stream yield. The scenarios that had the greatest relative impact on stream yield were scenarios 2, 5, and 1.

Tables 10.6a and 10.6b focus on the impact of drought years on water use and streamflows. As far as stream yield is concerned, 1988 was the most severe drought the study area experienced during the simulation period 1977-1994. This drought condition was repeated in 2006 during the baseline and test-management scenario simulations. The simulated impacts of this drought year are shown in Table 10.6a, where a maximum change (increase) in stream yield (57.3 percent) was observed for scenario 2, compared to the baseline scenario. Scenario 2 also caused the largest reduction in irrigation use (47.3 percent).

Table 10.6. Effect of scenarios 1-13 on water use and stream yield in two drought years.

a. Year 2006 (1988):

Water use	1	2	3	4	5	6	7	8	9	10	11	12	13
dQirr (cfs, Table 10.2)	-13.5	-25.8	-11.1	-6.3	-17.1	5.3	-5.6	0.0	-4.0	-6.9	-8.6	0.0	-54.6
dQirr(cfs, gw)	-11.8	-21.9	-7.9	-5.5	-12.7	4.6	-4.9	0.0	-3.6	-4.9	-6.5	0.0	-48.0
dQirr(cfs, surf.)	-1.7	-3.9	-3.2	-0.8	-4.4	0.7	-0.7	0.0	-0.5	-2.0	-2.1	0.0	-6.6
%change irrig.	-24.7	-47.3	-20.4	-11.6	-31.3	9.7	-10.3	0.0	-7.4	-12.6	-15.8	0.0	-100.0
Streamflow													
dQyld (cfs, Table 10.3)	9.2	17.8	8.4	5.0	13.8	-3.7	3.7	-0.2	3.0	5.4	6.8	0.0	37.4
%chg in yield	29.5	57.3	27.0	16.2	44.3	-12.0	12.0	-0.6	9.5	17.5	21.8	0.0	120.1
%chg in Q-CC	3.1	6.0	2.8	1.7	4.6	-1.2	1.3	-0.1	1.0	1.8	2.3	0.0	12.5
dQyld/dQirr	-0.68	-0.69	-0.76	-0.80	-0.81	-0.70	-0.66		-0.74	-0.79	-0.79	1.00	-0.68

b. Year 2009 (1991):

Water use	1	2	3	4	5	6	7	8	9	10	11	12	13
dQirr (cfs, Table 10.2)	-12.2	-14.4	-7.2	-3.9	-9.9	5.2	-4.4	0.0	-2.2	-4.6	-5.6	-7.7	-52.6
dQirr(cfs, gw)	-11.1	-11.9	-5.1	-3.4	-7.1	4.7	-4.0	0.0	-2.0	-3.3	-4.2	-5.6	-48.3
dQirr(cfs, surf.)	-1.1	-2.5	-2.1	-0.5	-2.8	0.4	-0.4	0.0	-0.3	-1.3	-1.4	-2.1	-4.3
%change irrig.	-23.1	-27.5	-13.7	-7.4	-18.9	9.8	-8.3	0.0	-4.3	-8.7	-10.6	-14.6	-100.0
Streamflow													
dQyld (cfs, Table 10.3)	7.5	11.5	5.2	2.5	6.9	-3.1	2.8	-0.4	1.4	3.1	3.8	5.3	33.5
%chg in yield	8.6	13.1	5.9	2.9	7.8	-3.6	3.2	-0.5	1.6	3.6	4.3	6.0	38.3
%chg in Q-CC	3.8	5.8	2.6	1.3	3.5	-1.6	1.4	-0.2	0.7	1.6	1.9	2.7	16.9
dQyld/dQirr	-0.62	-0.80	-0.72	-0.64	-0.69	-0.61	-0.65		-0.61	-0.68	-0.68	-0.68	-0.64

The second major drought year with respect to stream yield during the simulation period (1977-1994) occurred in 1991, although streamflow at Clay Center was less than during 1988. The corresponding baseline scenario year (to 1991) is 2009, and its simulated impact on water use and stream yield for the different test-management scenarios is shown in Table 10.6b. Scenario 2 also had the greatest impact on stream yield compared to all other scenarios (1-11), although it was much smaller than the corresponding one during 1988.

Figures 10.7 to 10.17 display cumulative yields for each scenario compared to the baseline scenario. The scenario that results in the greatest simulated increase in stream yield is scenario 2, which involves shutting off all water rights junior to 3/22/74. However, the average increase in yield during the 1995-2012 simulation period for scenario 2 (10.9 cfs; Table 10.3) is relatively small, and the yearly increase in streamflow at Clay Center is even smaller relative to the baseline case (Table 10.5). Only during drought years, these increases become more relatively significant, as shown in Tables 10.6a and 10.6b. The impact of all scenarios on ground-water levels at the four index locations are shown in figs. 10.18 to 10.28, where it can be seen that water-level changes are relatively small. The scenarios that had the greatest impact on ground-water levels were scenarios 5, 2, and 1.

To further visualize the impact of drought conditions, we present, in fig. 10.29, the basin hydrologic components from the baseline scenario during the 2005-2009 period, corresponding to the 1987-1992 period. In Fig. 10.29, we see that the dominant control on stream yield is net surface (tributary) inflow. Only when tributary inflow becomes negligible, stream baseflow could be a significant determinant of stream yield.

Scenario 12 was conceived to investigate the question of what administrative action might be reasonably effective in enhancing streamflows under drought conditions only when streamflows are well below established MDS. In contrast to scenario 12, which is effective only when streamflows are below MDS (at Concordia), scenarios 1-11 are in effect throughout the simulation period. Table 10.7 shows the monthly streamflows at Clay Center and stream yield of the Republican River between Concordia and Clay Center under the various scenarios during the drought of 2009, which corresponds to the 1991 drought. For August 2009, scenario 12 was practically as effective as scenario 5, and more effective than scenarios 1-11 except scenario 2.

Table 10.7.

(a) Projected monthly streamflow at Clay Center for scenarios in drought year 2009 (1991).

hist.	scen.		monthly streamflow at Clay Center (cfs)													
year	year	mon	baseln	sc.1	sc.2	sc.3	sc.4	sc.5	sc.6	sc.7	sc.8	sc.9	sc.10	sc.11	sc.12	sc.13
1991	2009	1	94	99	104	97	95	97	91	96	94	95	95	96	95	117
1991	2009	2	170	178	183	175	172	175	167	173	170	172	172	173	172	200
1991	2009	3	142	147	150	144	143	144	140	144	142	142	143	143	143	162
1991	2009	4	617	617	617	616	616	613	616	617	616	616	616	615	617	619
1991	2009	5	230	231	231	230	230	228	229	230	229	230	230	230	233	233
1991	2009	6	741	747	755	749	746	754	738	744	739	743	746	748	758	767
1991	2009	7	60	77	87	77	66	83	53	65	60	63	70	72	66	141
1991	2009	8	75	87	94	84	80	90	69	79	74	77	81	82	89	135
1991	2009	9	115	126	130	122	120	125	111	120	115	118	120	121	121	164
1991	2009	10	14	20	21	17	16	18	12	16	14	15	16	16	17	42
1991	2009	11	81	91	93	86	84	88	77	85	81	83	84	85	86	123
1991	2009	12	51	59	61	55	53	56	48	54	51	52	53	54	55	86

(b) Projected monthly stream yield of the Republican River between Concordia and Clay Center for scenarios in drought year 2009 (1991).

hist.	scen.		simulated stream yield (cfs), Concordia to Clay Center													
year	year	mon	baseln	sc.1	sc.2	sc.3	sc.4	sc.5	sc.6	sc.7	sc.8	sc.9	sc.10	sc.11	sc.12	sc.13
1991	2009	1	8	14	18	11	10	12	6	11	8	9	10	10	10	32
1991	2009	2	-30	-23	-18	-26	-29	-26	-34	-27	-30	-29	-28	-28	-28	-1
1991	2009	3	35	40	44	38	36	37	33	37	35	36	36	37	36	55
1991	2009	4	541	541	541	540	540	537	540	541	540	540	540	540	541	543
1991	2009	5	118	119	120	119	118	117	118	119	117	118	119	118	122	122
1991	2009	6	289	295	303	297	293	301	286	291	286	290	294	295	305	315
1991	2009	7	-29	-12	-1	-11	-23	-5	-36	-23	-29	-25	-18	-17	-23	52
1991	2009	8	-11	1	8	-2	-6	4	-17	-7	-12	-9	-5	-4	3	49
1991	2009	9	84	95	99	90	88	94	80	88	84	86	88	89	90	133
1991	2009	10	0	5	7	2	1	4	-3	2	0	1	1	2	3	27
1991	2009	11	47	57	59	52	50	54	43	51	47	49	50	51	52	89
1991	2009	12	2	10	12	6	4	7	-1	5	2	3	4	5	6	37

It should be noted that for scenarios 1 through 11 we treated both surface and ground-water rights by their distance from the Republican River in deciding which ones to shut down in a given scenario (and also by their water-right number). Therefore, if the surface water right was used to irrigate a field that was outside the restricted corridor of 1/4 or 1/2 mile from the stream in a given scenario, then that water right was kept intact in the scenario. This procedure however was not followed in scenario 12, where all surface water rights in the Republican River valley were curtailed when streamflows dropped below MDS at Concordia, irrespective of the distance of surface-water irrigation application from the Republican River.

Scenario 13 indicates the total impact of irrigation water rights on stream yield (Table 10.3) and streamflows at Clay Center (Table 10.5) and represents an extreme upper limit against which to compare the previous water-rights manipulation scenarios. This scenario reinforces the previous conclusion that water rights in the Lower Republican basin represent a relatively minor component of stream yield. Only during drought conditions when streamflows are well below the established MDS, the totality of irrigation water rights represents a significant component of potential stream yield. This can be seen in Table 10.7 during the months of July and August

11. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

This report presents the development and implementation of a computer model capable of simulating the flow of surface-water, ground-water, and stream-aquifer interactions on a continuous basis for the Lower Republican River basin. The model provides a tool for evaluating long-term water management strategies. The surface-water model SWAT and the ground-water model MODFLOW were utilized for constructing the comprehensive basin model SWATMOD. Extensive coding and testing was implemented to link the two models.

The SWATMOD model accounts for the weather-related variables of precipitation, air temperature, solar radiation, wind speed, and relative humidity. These along with the hydrogeologic properties of the soils/aquifer and stream channels, basin geomorphology, vegetation parameters, irrigation demand, and land-use practices were incorporated to simulate surface runoff, evapotranspiration, pond seepage, subsurface percolation, ground-water flow, and stream-aquifer interaction.

In order to construct a representative and reliable simulator of the basin, the model was first calibrated to historical conditions of streamflows and water levels observed during the early development period from 1977 to 1990. The model was then verified with more recent hydrologic data recorded from 1991 to 1994. The calibration statistics indicated a satisfactory match between the observed and simulated water levels and streamflows for both the calibration and verification periods.

Following model calibration and verification, the impact of continued withdrawals at existing rates was investigated. The model was run for an 18-year (1995-2012) simulation period with 1994 initial and boundary conditions, 1994 land- and water-use conditions, and a repeat of climatic conditions of the past 18 years (1977-1994). This was also defined as the baseline scenario against which the hydrologic impact of various management scenarios were compared.

A number of hypothetical scenarios were implemented with the calibrated model and the resulting streamflows and water levels compared with the baseline case. Most scenarios involved a reduction in the withdrawal rates from the baseline case, which represented a continuation of present practices for the 18-year period from 1995 to 2012.

It should be noted that the last 18 years of climate may not repeat itself. Further, other changes (induced by humans and/or climate) may cause the hydrologic response to be altered significantly. Thus the present model simulations are not presented as "predictions" in the sense of forecasting watershed response to various management scenarios. Models such as SWATMOD are useful for comparing different scenarios, and to answer "what if" questions. Model use should be geared toward comparing alternatives rather than relying too heavily on actual magnitudes of simulated values. Model interpretation (after calibration and verification) is much more reliable in a comparative mode, rather than in any predictive sense.

The SWATMOD model was developed as a low-flow model. During the calibration process, greater emphasis was placed on trying to replicate low flows during dry weather conditions. The primary concern in the Lower Republican River basin is how to manage the resources when water is limited. There was less concern for flood events during this project, as water availability becomes a less crucial problem within the basin. The model is, therefore, better suited for analyzing the conditions in the basin when there is a shortage of water. It is under such conditions that careful and efficient management of limited water resources is required.

Our model indicates that tributary flow to the Republican River between Concordia and Clay Center, supplied by surface runoff from upland areas of the basin, is the dominating component of basin yield for this reach of the river. Only in drought years, such as 1988 and 1991 when tributary inflows are also negligible, other hydrologic components, such as baseflow, stream seepage losses, streamflow diversions, and ground-water withdrawals, appear to have a significant impact on yield. The impact of ground-water pumping on stream yield is shown to be relatively small and not immediate, in contrast to tributary inflows. Therefore, possible administrative action with regards to ground-water rights may not show an impact until a few months later, provided no additional tributary inflows occurred in the meantime to mask the ground-water impact on stream yield.

As a result of the dominating impact of upland runoff and consequent tributary inflows on stream yield, land-use impacts that may affect runoff consequently affect basin yield. Unfortunately, tributary flow calculated by our model is not directly verifiable with data because tributary flows to the Republican River are not gaged. However, calculated runoff is corroborated first, by a satisfactory match between simulated and measured streamflow at Clay Center, and, second, by a comparison with runoff from adjacent watersheds to gaged streams at Chapman and Washington, KS, extrapolated from their contributing areas to that of the Lower Republican River basin.

In light of the above findings, administrative action to enhance streamflows may become meaningful only during drought periods (when streamflows drop appreciably below established minimum desirable standards) during crop growing seasons, and when tributary stream inflows are negligible to non-existent. Given the previously-mentioned hydrologic importance of upland runoff, long term policies to maintain and enhance tributary inflows to the Republican River during drought periods are likely to also be effective in enhancing streamflows in the Lower Republican River basin.

Despite our best efforts to accomplish the project objectives during the allotted time frame, certain areas where further improvement can be made to improve model performance remain. The spatial variability of soils and land use over the basin is currently handled through an averaging procedure over several SWAT runs as discussed earlier in the report. In this project, 18 soil/crop combinations were employed based on six primary soil types and three dominant crop practices within the basin. This can be further improved by increasing the number of soils and land-use options. The same applies for aquifer and stream hydrogeologic properties, since average values are currently employed.

However, the most important need for improving this model is an extensive field-data-gathering effort. Ground-water levels need to be measured yearly throughout the basin (such as the survey we conducted in 1994) to establish a database which will also be useful in model calibration. Tributary inflows to the Republican River need to be monitored because, as we found out, these tributary inflows constitute the major determinants of stream yield; such monitoring will also greatly assist in model calibration. Hydrogeologic-property data for the Lower Republican River alluvial aquifer are practically non-existent, and several aquifer tests to determine such hydrogeologic properties are recommended.

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APPENDIX 3A

Listing of GIS database for Lower Republican River basin

Appendix 3A

Listing of GIS Database for the Lower Republican River Basin

Listing for /home/mariossun_2/margis/rep created Tue Jul 23 11:40:18 CDT 1996 by margis

LIST OF COVERAGES THAT FOLLOW ARE THE BASE & DERIVED COVERAGES FOR REPUBLICAN RIVER BASIN

Coverages are abbreviated as cov; polygons as poly; water levels as WL.

Coverages beginning with wr... are the Water Rights coverages.

Coverage name beginning with rep... only means they refer to Republican area.

The string following rep... suggests more as to what the cover is about (eg. rephuc14 would mean HUC 14 boundary cover; rephypso would mean hypsography cover, etc.). Thus look for the intuitive part of the name after rep...

A coverage name ending with ..clp or ...clip suggests that it is the clipped part of any coverage which falls within the modeling grid area.

DIRECTORY .....home/mariossun_2/margis/rep

COVER NAME	DESCRIPTION
albncdc	NCDC climatic data point cov
albstrms	line cov of all streams in Rep basin (Albers)
bedrck_tin	TIN cover of bedrock surface
beloitlat	LATTICE from older DEM
box_cov	copy of box_cov2 (for Plotting of Landuse map)
box_cov2	box created for legend in landuse(pie_diag) map
buff_elev	derived cov for getting elevs of stream segments
buffelev_main	Main stem (3 levels of annotation for elev)
chkponds	polygon cov of ponds in Rep area (Albers)
chkresvr	copy of cover resvr
clip_grd	clipped cov of model grid within rep basin
clip_h11	clip cov of reph11 to fit the model grid
clip_h14	clipped cov of HUC 14 subbasin boundaries
clip_hyd	clipped cov of streams to fit model grid
clip_wal	clipped cov of valley wall to fit model area
clip_wl	clip cov of wl_contr within model area
clp_wl77	clipped cov of 1977 water levels (line cov)
county	line cover of counties
cseats	point cov for county seats
elev_ano	clipped annotation cov for model grid
elev_mainstem	line cov of main Rep. river with elevs.

elev_mrk	line cov (of line segments to seperate stream evs)
elevtrib	Tributaries of Republican river - line cov
gagstat	point cov. of (two) stream Gauging stations
grid_box	outer boundary of model grid
grid_ext	line cov digitized to display part-bndy of Grid
grid_new	polygon cov one mile cells in Albers
grid_new2	copy of grid_new
grid_point	Point cov(grid centroids)with row & column
half_m	point cov with wr within half mile buffer
huc11soil	polygon cov. form IDENTITY of soil & HUC 11
hydro_alb4	line cov of Rep river & streams
hydro_alb5	edited cov from hydro_alb4
ks_cty2	polygon cov of Kansas counties (Albers)
ks_cty3	line cover of counties in Rep area
landc	polygon cov of Land use
landc2	UNION of replandc(land use) & reph11
landc4	INTERSECTed cov of landc & repsoil
landc_b	copy of landc (poly cov of land use)
lat_con2	lat_cont projected in Albers
lat_con3	copy lat_con2
lat_cont	line cover(contours) from LATTICE (LL proj)
mtics	Master TIC cover
one_m	wr points within one mile
onehaf_m	point cov of wr in half mile within stream
poly	polygon cover of valley wall
ponds	Older poly cov of ponds in Rep area
rbwl77_ara	1977 water levels line cov.
rep_iden	IDENTITY of wtrght & grid_new (point cov)
rep_tics	TIC cover for Rep basin coverages
repbedrck	line cov of bedrock in Rep area
repbound	polygon cov Rep river boundary
repcounty	polygon cov of counties in Rep Basin area
reph11	polygon cov of HUC 11 subbasins
reph14	polygon cov. of HUC 14 subbasins
reph14_c	polygon cov HUC 14 subbasins
rephuc_bound	Rep Basin boundary cov in LL projection
rephuc_hypso	Hypsography cover for Rep bsin (Geog. Projection)
rephuc_soil	polygon cov of soils in Rep basin (LL projection)
rephypso	Contour coverage from 1:100,000 DLG
rephypso_new	New contour cov with South-East part added
replandc	Land cover poly cov in LL projection
repsect	point cov of section corners in Rep basin
repsoil	polygon cov of soils in Rep basin (Albers)
repsoil2	polygon cov. of soils in Rep. basin
repthspcp	Thiessen poly of precipitation
reptownr	line cov of Township-Range within Rep basin
republat	LATTICE of Rep area in LL projection
repwl77	1977 water levels (albers proj)
repwl77_lat	LATTICE of 1977 water levels
repwl77_tin	TIN of 1977 water levels
resvr	polygon cov of Milford reservoir
rpwall_alb	line cov of valley Wall (Albers)

sam2	Digitized bnd, splitting subbasin # 9
soil_gd	poly cover of soils cov & grid_new INTERSECTed
soilassoc	polygon cov of (Kansas) soils in LL projection
stem	line cov. of Rep river main stream only
swat14	polygon cov SWAT 14 subbasins
swat_14b	polygon cov of SWAT 14 subbasins - edited basins
swat_14c	Editted cov of SWAT14
testwr2	point cov of old water rights
testwr3	IDENTITY of testwr & grid_new
tr2	Township-Range (line)cov for Rep area
tr3	Township-Range cov for Rep area - Albers
tr_clip	Township-Range cov. with rep Basin Erased
tribbuf2	200 m buffer around cover elevtrib
tribbuf3	100 m buffer around elevtrib
tribbufr	500 m buffer around elevtrib
tribelv2	INTERSECT of elevtrib & tribhypso2
tribhpso	Tributaries of Rep river with elevs.
tribhypso2	INTERSECTed cov of rephypo & tribbuf3
two_m	wr points within 2 mile buffer of stream
w_bodies	Original (polygon) cov of water bodies from DASC
w_body	BUILD from w_bodies
w_body2	polygon cover of water bodies
w_body3	water bodies in Rep area
w_body_b	Added ponds from 1:24K sheets to w_body
wall_cty	clipped cov of county with valley wall_ply
wall_ply	polygon cov valley wall
wl_contr	Version of wl_contr3
wl_lattc	LATTICE of water levels
wl_lattc_old	Old LATTICE of water levels
wl_tin	TIN of water levels within model grid
wr_final	Older wr point cov
wr_final3	INTERSECT of wr_final2 & grid_new (point cov)
wr_point	Old Water right cov.
wr_pts95	INTERSECTed cov of wr_rep95 & grid_new
wr_rep	point cov water rights
wr_surf	Old (surface) water right point cov
wr_surf3	Surface water rights (point cov) - older cov
wr_surf5	INTERSECTed cov of wr_surf2 & grid_new
wt95	Old water rights point cov.

THE NEW_WR DIRECTORY (..../rep/new_wr) CONTAINS LATER WATER RIGHT COVERAGES AND DERIVED COVERAGES FROM THEM. IT ALSO CONTAINS DIFFERENT BUFFERS AND WATER RIGHTS WITHIN THEM

THE GRIDS DIRECTORY (..../REP/GRIDS) CONTAINS ALL THE RASTER COVERAGES (DERIVED FROM DEM's) AND DERIVED COVERAGES FROM THEM

DIRECTORY ..../home/mariossun_2/margis/rep/new_wr

Listing for /home/mariossun_2/margis/rep/new_wr created Wed Jul 24 08:15:36 CDT 1996 by margis

buf1	polygon cov (buffer 1/8th mile around main stem)
buf10	1 and 1/4 m buffer around main stem
buf12	1 and 1/2 m buffer around main stem
buf16	2 mile buffer (polygon cov)
buf2	1/4 mile buffer around main stem
buf3	3/8 mile buffer around main stem
buf4	1/2 mile buffer around main stem
buf5	5/8 mile buffer around main stem
buf6	3/4 mile buffer around main stem
buf7	7/8 mile buffer around main stem
buf8	1 mile buffer around main stem
combin94	Combined pt. cov of Sam's pts & others
cont-92n	Edited (heads-up digi.) Water level (1992) contour
cont_80n	Edited Water level (1980) contour
cont_80t	WL contours (1980) interpolated from TINCONTOUR
cont_85n	Edited (heads-up digi.) Water level (1985) contour
cont_85t	WL contours interpolated from TINCONTOUR
cont_90n	Edited (heads-up digi.) Water level (1990) contour
cont_90t	WL contours interpolated from TINCONTOUR
cont_92n	Edited (heads-up digi.) Water level (1992) contour
cont_92t	WL contours (1992) interpo. from TINCONTOUR
cont_94b	WL contour cov from TINCONTOUR
cont_94n	- do - 1994
cont_94t	WL contours (1994) interpolated from TINCONTOUR
grep_geo	point cov of groundwater WR (geog. proj)
grep_wr	Groundwater WR point cov (Albers)
grep_wr2	point cov grep_geo in Albers
int1	INTERSECTed cov of grep_wr & buf1
int10	INTERSECTed pt. cov (grep_wr & buf10)
int12	INTERSECTed pt. cov (grep_wr & buf12)
int16	INTERSECed pt. cov (grep_wr & buf16)
int4	INTERSECTed pt. cov (grep_wr & buf4)
int6	INTERSECTed pt. cov (grep_wr & buf6)
int8	INTERSECTed pt. cov (grep_wr & buf8)
near_geo	WR points in Geo. prj. with x/y coord.
srep_wr	point cov. - surface WR
st_point	Main stem converted to point cov (ARCPOINT)
stem2	Main stem (line cov) within the model grid
stem_geo	Projected stem2 to Geograhic
tics	TIC cov for model grid area (Albers)
wells_94	1994 WL's measured by Sam (pt. cov)

DIRECTORY ....../home/mariossun_2/margis/rep/grids

Listing for /home/mariossun_2/margis/rep/grids created Wed Jul 24 08:16:04 CDT 1996 by margis

basin_poly2	poly cov basins using GRIDPOLY
basins2	Grid of basins in Albers
dir_topo2	FLOWDIRECTION of topo_grid2
dir_topo3	DIRECTION grid fm TOPOGRID
int_topo3	int_topo3 = int (dir_topo3)
latt_alb2	Lattice of Rep Basin in Albers
latt_alb3	1:250,000 lattice with filled SINKS
new_wbody	WATERSHED grid from topo_dir
shed3_clp	Poly cov from GRIDPOLY
shed3_clp2	clipped poly cov of shed3_poly
shed3_insct2	INTERSECTed poly cov fm shed3_clp2
shed3_insect	INTERSECTed cov of shed3_clp2 & swat bsns.
shed3_poly	Poly cov Watersheds from shed_topo3
shed_topo2	WATERSHED grid from dir_topo2
shed_topo3	WATERSHED grid from int_topo3
sink_depth	output of = sink max - sink min
sink_grid	Grid showing SINKS
sink_max	Result from FILL on latt_alb2
sink_min	Resulting Grid using ZONALMIN command
sink_poly	Poly cov of SINKS from a grid
topo_grid2	Original grid from TOPOGRID
w_bdy_grid	Grid of Water bodies from POLYGRID
w_body	Poly cov of W_bodies
w_body_c	W_bodies poly cov
w_body_clp	Clipped poly cov W_bodies
wb_c_clp	W_body clipped poly cov
wb_new	W_bodies poly cov
wb_new_clp2	W_body clipped edited poly cov

List of AMLS

AML is an acronym for Arc Marco Language. It is an interpretive language used to customise or automate repetitive processes in ArcInfo.

awc2.aml	Old AML showing ave. available water capacity
basin.aml	Plots subbasins obtained from watershed delineation
elev.aml	Plots elevation points along the main stream.
elev2.aml	Plots elevation points for model grid area
landc.aml	Plots landuse map for Republican basin
lc_grid.aml	Plots landuse types by sections
legend.aml	Plots only the lgend for soils and slope/elev. maps
lu_pie.aml	landuse types aggregated by subbasin - POLYGONSPOT
rephuc14.aml	Plots SWAT 14 subbasins
repsoil.aml	Soil types by subbasin
repsoil2.aml	- do - (different shade)
soil.aml	Soils for Rep. subbasins within model area
soil3.aml	- do - (different shade)
soil4.aml	- do - (different shade)
soil5.aml	- do - (different shade)
sub_bnd.aml	Base map - subbasin boundary
w_body.aml	Plots water bodies (ponds)
w_body2.aml	Water bodies and hypsography
wr_47.aml	Plots water rights with priority year till 1947
wr_55.aml	1955
wr_60.aml	1960
wr_65.aml	1965
wr_70.aml	1970
wr_75.aml	1975
wr_80.aml	1980
wr_85.aml	1985
wr_90.aml	1990
wr_95.aml	1995
wr_color.aml	Priority year upto 1995 (color plotting)
wr_map.aml	All water rights
wr_surfc.aml	Plots surface water rights

APPENDIX 3B1

Reported depth to water level data converted to water table elevations for selected years

Table 3B1.

Water Table Elevations from 7.5' USGS Topo-contours and Reported Depth to Water Table (topo-elev -- DTW)

The DTW year corresponds to the (Winter months) Nov. to Dec. of the preceeding year & Jan. to Mar. of the following year (e.g. dtw85 = Nov to Dec. of 1984 & Jan to Mar. of 1985)

file_id	row	col	topo_elev	dtw80	dtw85	dtw90	dtw92	dtw94
VCD00040005S03W330330752769	5	9	1355	0	0	0	0	0
VCY00010006S01E020642003550	6	28	1268	0	0	0	0	0
VCY00040008S03E070222000350	19	37	1180	0	1148	1149	1149	0
VCY00080006S01E011232505230	6	29	1266	0	0	1233	1235	1237
VCD00010005S01W260335201700	4	23	1285	0	0	0	0	0
VCY00010006S01E020542003600	6	28	1268	0	1244	1242	1241	1246
VCY00040008S03E071233002100	19	37	1201	0	0	0	0	0
VCD00110005S02W2501NWNWSW	5	17	1315	0	0	0	0	0
VCD00010005S01W260434951700	4	23	1285	0	0	0	0	0
VCY00040008S03E070127500500	19	37	1190	0	1157	1157	0	0
VCY00030007S02E030100504920	13	34	1229	0	1212	1206	1206	1214
VCD00010005S01W260235351700	4	22	1285	0	0	0	0	0
VWS00280005S01E3201NCS2N2SW	6	26	1275	0	0	0	0	0
A0009050008S02E110743501150	19	34	1205	0	0	0	1181	0
A0019620008S02E0201NESWSW	19	35	1193	0	0	0	0	0
A0011520005S02W2502SWNESE	4	17	1307	0	1282	0	0	0
A0017090005S02W2601SENENE	4	16	1305	0	0	0	0	0
A0015050005S02W2201NWNESW	4	15	1312	0	0	0	0	0
A0012990006S01E010234005230	6	29	1266	0	0	1233	1235	1236
A0017090005S02W2602SENWNE	4	17	1305	0	0	0	0	0
A0015450005S03W360144502600	5	11	1340	0	0	0	0	0
A0031360007S02E1803SWNWNE	14	31	1240	0	0	0	0	0
A0031360007S02E1804NWNWNE	14	30	1240	0	0	0	0	0
A0029830006S01W040632205200	6	20	1308	0	0	0	0	0
A0027900008S02E010552501470	19	36	1205	0	0	0	0	0
A0031360007S02E1801SWNENE	14	31	1232	0	0	0	0	0
A0032260006S02E331012501700	12	32	1240	0	0	1215	1212	1222
A0031360007S02E1802SWNENE	14	30	1232	0	0	0	0	0
A0044630005S01W3001NWSWNE	4	19	1296	0	0	0	0	0
A0034670006S01E2401SENWNE	9	29	1240	0	0	0	0	0
A0047050005S01W3003NWSWSE	5	19	1292	0	0	0	0	0
A0033890005S02W2503SWSWSW	5	17	1314	0	0	0	0	0
A0046090006S01E020322004450	7	29	1265	0	0	0	0	0
A0035410005S02W3602SESWNW	5	18	1315	0	0	0	0	0
A0041870005S02W2505NCSWNW	4	18	1310	0	0	0	0	0
A0045180005S03W3501NWNWNE	5	11	1341	0	0	0	0	0
A0033900005S02W2501NWNWSW	4	18	1315	0	0	0	0	0
A0038030006S01E130138402340	8	29	1250	0	0	0	1232	1236
A0046360005S02W2503SWSWSW	5	17	1314	0	0	0	0	0
A0045860006S02E3001NENWSE	11	31	1242	1222	0	0	0	0
A0046110005S02W3202NWNWSE	5	13	1337	0	0	0	0	0
A0045570005S02W3201NWNWSW	6	13	1320	0	0	0	0	0
A0044430006S01E0202NWSWNE	6	28	1262	0	0	0	0	0

Table 3B1. (continued)

A0049200006S02E291240150950	10	31	1232	0	0	0	0	0
A0047140006S01W020148501370	7	23	1280	0	0	0	1268	0
A0042020006S01E0201CNNWSE	6	28	1260	0	0	0	0	0
A0044630005S01W3002CEW2NE	4	18	1297	0	0	0	0	0
A0046550007S02E220713202610	16	34	1218	0	0	0	0	1190
A0045940005S01W3201SESWSW	6	19	1308	0	1284	0	0	0
A0040230006S01E2402NWSWNW	9	30	1254	0	0	0	1228	1235
A0039110005S03W3501NWNWNE	5	10	1341	0	0	0	0	0
A0047040006S01W0101NWSWSW	7	24	1293	0	0	0	0	0
A0045750005S01W3101CESENW	5	19	1310	0	0	0	0	0
A0046360005S02W2501NWNWSW	5	17	1315	0	0	0	0	0
A0060110006S01E2501CWSE	11	30	1248	0	0	0	0	0
A0057880005S03W240110502600	4	11	1330	0	0	0	0	0
A0062590005S01W3102NWSESW	6	19	1310	0	0	0	0	0
A0065830005S02W3501NWSWNE	5	17	1320	0	0	0	0	0
A0065250005S02W2201NWNESW	4	15	1312	0	0	0	0	0
A0051200005S02W2603CWE2SE	5	16	1316	0	0	0	0	0
A0060720005S01W3203SWSWNW	5	20	1306	0	0	0	0	0
A0064180006S01E0108NESWSW	7	30	1250	0	1242	0	0	0
A0063340006S02E3302NCNE	11	33	1220	0	1195	0	0	0
A0059550008S03E0602SENENW	18	37	1205	0	0	0	0	0
A0057200007S02E270312805200	17	34	1205	0	1193	0	1191	0
A0064150005S01W280239601188	4	21	1293	0	0	0	0	0
A0060200005S03W3302NWNENE	5	9	1345	0	0	0	0	0
A0056580005S01W3202NWSWNE	5	19	1290	0	0	0	0	0
A0059850005S03W3602NENWNW	6	12	1338	0	0	0	0	0
A0049910005S02W3401NWNENE	6	15	1320	0	0	0	0	0
A0060590007S02E2601NWSESW	17	34	1211	0	0	0	0	0
A0049750006S01E030126402040	7	28	1259	0	0	1247	1245	0
A0054750006S02E3002NESENW	10	30	1242	1222	0	0	0	0
A0064460006S02E300346055170	10	31	1245	0	0	0	1221	1224
A0052130006S01E040626401320	7	27	1259	0	0	0	0	0
A0063990005S01W330144653300	5	20	1290	0	0	0	0	0
A0059430008S03E0601NWNWSE	18	37	1201	0	0	0	0	0
A0070430005S01W3204NCSWSE	6	20	1300	0	0	0	0	0
A0069560005S03W2102SWNESW	4	9	1350	0	0	1337	1337	1337
A0075610005S01E3202NWNWSW	6	25	1280	0	0	0	0	0
A0070170005S02W210828001300	3	14	1320	0	0	0	0	0
A0070150005S02W3604SWSWNE	5	17	1312	0	0	0	0	0
A0069230007S02E1501SWNESE	15	34	1225	0	0	0	0	0
A0068400006S01E040626401320	7	27	1259	0	0	0	0	0
A0066770007S02E0302CWNWNE	13	33	1230	0	0	0	0	0
A0070410006S01E0601NCNE	6	24	1270	0	0	0	0	0
A0066230005S02W3603SENWNE	5	18	1311	0	0	0	0	0
A0070420005S01W3103NCN2SWNE	5	19	1310	0	0	0	0	0
A0077060007S02E1401CWNW	14	35	1227	0	0	0	0	0
A0077860006S01E0801CWSWSWNW	7	26	1265	0	0	0	0	0
A0081940006S01W040632205200	6	21	1308	0	0	0	0	0
A0081530005S02W3101SENWSW	6	12	1345	0	0	0	0	0
A0081950005S01E3203SWNWSE	6	25	1268	0	0	0	0	0
A0080020005S02W3401NWNENE	5	16	1320	0	0	0	0	0
A0081050006S01E1302NENWSE	9	29	1240	0	0	0	0	0

Table 3B1. (continued)

A0086880005S01W2003SWSENW	3	20	1310	0	0	0	0	0
A0090080005S01W300438503850	5	19	1297	0	0	0	0	0
A0094920006S01E2301SESWNW	9	28	1262	0	0	0	0	0
A0091210005S01W250120105165	5	23	1291	0	0	0	0	0
A0091050005S03W3604N2SWSE	6	11	1346	0	0	0	0	0
A0092030006S01E010430504980	6	29	1266	0	0	0	1235	1242
A0091050005S03W3605SENESE	6	11	1348	0	0	0	0	0
A0105850006S01W040539353155	6	21	1305	0	0	1278	1278	0
A0100440006S01E1401SWNWSE	9	29	1260	0	0	0	0	0
A0104340007S02E0303CWNWNW	13	34	1230	0	0	0	0	0
A0098890005S02W1901SESWNW	3	13	1347	0	0	0	0	0
A0099730006S01E0802NWNWSE	7	25	1270	0	0	0	0	0
A0114750005S01E3001SWNWSW	5	24	1320	0	0	0	0	0
A0114620006S01E2302SENESW	10	28	1259	1209	0	0	0	0
A0111240006S01E1001NWSWNE	7	28	1255	0	0	0	0	0
A0113520006S01W0302NWSENW	6	22	1300	0	0	0	1275	1276
A0106860006S01E1303NCW2	8	30	1260	0	0	0	0	0
A0111650006S01W030126352540	6	21	1299	0	0	0	0	0
A0110180006S01E0109SENWSW	7	29	1260	0	0	0	0	0
A0109690005S01W2301SENWSW	4	22	1292	0	0	0	0	0
A0109720006S01E250437503170	10	30	1249	0	0	0	0	0
A0114430007S02E2301NWNWSE	15	34	1220	0	0	0	0	0
A0108690006S02E3301NENENE	12	33	1245	0	0	0	1211	1230
A0118320006S01W040345352630	6	21	1304	0	0	0	1281	1281
A0115980005S01W2503NWNWNW	5	23	1330	0	0	0	0	0
A0124980005S01E3002NWSWNW	5	24	1322	0	0	0	0	0
A0124990005S02W210318355240	4	14	1323	0	0	0	0	0
A0118470006S01E0302NCW2NE	6	27	1259	0	0	0	0	0
A0122690006S01E0603SWNWSE	7	25	1268	0	0	0	0	0
A0119750005S01W340105352620	6	22	1285	0	0	0	0	0
A0119760005S01W2803NENWNW	4	20	1299	0	0	0	0	0
A0124980005S01E3001SWNWSW	5	24	1320	0	0	0	0	0
A0125070007S02E2202CWE2SE	16	33	1219	0	1196	0	0	0
A0122690006S01E0602SENESE	7	24	1267	0	0	0	0	0
A0142540005S01W260130350710	5	23	1290	0	0	0	0	0
A0126040006S01E230324802600	10	29	1259	0	0	0	1231	0
A0141500005S02W200306500660	4	13	1322	0	0	0	0	0
A0128230005S02W220217502600	4	16	1312	0	0	0	1297	0
A0136310005S01W2201SENWSE	4	21	1318	0	0	0	0	0
A0130910005S02W210431703000	3	14	1321	0	0	0	1302	1308
A0142550005S01W2202NENWNE	4	22	1310	0	0	0	0	0
A0131770006S01E020439404290	6	28	1264	0	0	0	0	0
A0130090007S02E270906000051	17	34	1215	0	0	1188	0	1197
A0132280005S02W3502NCN2NW	6	17	1325	0	0	0	0	0
A0146310007S02E270528401260	16	34	1216	0	1186	1188	1187	1197
A0158890006S02E1901NESWNE	9	31	1240	0	0	0	0	0
A0157230006S01E0701NWNWNW	8	25	1270	0	0	0	0	0
A0148350005S03W230136003895	3	10	1370	0	0	0	0	0
A0143010006S01E130637853635	8	30	1259	0	0	0	0	0
A0149450007S02E2501CNS2NW	16	36	1220	0	0	0	0	0
A0146310007S02E270640801260	16	34	1217	0	1186	1188	1186	1197
A0146630007S02E2102NESENE	15	33	1210	0	0	1182	0	1198

Table 3B1. (continued)

A0157910007S02E2302NWSWSE	16	35	1216	0	0	0	0	0
A0151500007S02E3601NWNENE	17	36	1212	0	1172	0	0	0
A0157950007S02E200123200030	16	32	1212	0	0	1196	1194	0
A0162150007S02E0901NESWNE	13	32	1235	0	1206	1204	1203	1211
A0166110007S02E0304NWSWNW	12	34	1238	0	1219	1211	1213	0
A0164530007S02E040239601320	13	33	1238	0	1214	1216	1212	0
A0164010008S02E010214802630	19	36	1204	0	0	1178	0	1186
A0164220005S01W310406301485	6	19	1308	0	1286	1285	1284	1286
A0161970006S01E1002SESWNE	7	28	1256	0	0	0	0	0
A0170290007S02E1501SWNESE	15	34	1225	0	0	0	0	0
A0170980007S02E3602NESWSW	18	36	1209	0	0	0	0	0
A0176600007S02E090232600600	13	33	1230	0	0	1208	1205	1210
A0170970007S02E0305NWNWSW	13	34	1233	0	0	0	0	0
A0172460008S02E1203NWNWNE	20	35	1205	0	0	0	0	0
A0170060006S02E3101SWNWSW	11	31	1250	0	0	0	0	0
A0170050006S01E3601SWSWNE	11	29	1252	0	0	0	0	0
A0169970007S02E2602NESWNE	16	35	1215	0	0	0	1185	0
A0171600006S01E260151802560	10	29	1266	0	0	0	1227	0
A0184160007S02E040314803280	13	32	1230	0	0	1202	1207	1212
A0184160007S02E040425200100	12	32	1233	0	1203	1206	1210	1215
A0185430007S02E260326805240	16	35	1215	0	0	0	0	0
A0182360005S02W360508002510	6	18	1320	0	0	0	1280	1280
A0196030007S02E230351804350	15	34	1220	0	0	0	0	0
A0198300006S01E260151802560	11	28	1266	0	0	0	0	0
A0211410005S02W210506603250	4	14	1319	0	0	0	1306	1311
A0215250007S02E340812000605	18	34	1189	0	0	0	0	0
A0207430006S02E180114804040	9	31	1245	0	0	1227	1227	0
A0215250007S02E340212000050	17	34	1198	0	0	0	0	1184
A0208540007S02E350139603960	17	35	1201	0	0	1175	0	1184
A0211940007S02E280106602640	17	33	1200	0	0	1190	1192	0
A0208550006S02E280113402660	11	33	1232	1197	0	1202	1211	1216
A0216520006S01W020313505240	7	23	1296	0	0	0	0	0
A0211790005S01E310204402500	6	25	1275	0	1255	0	0	0
A0207320007S02E210339603960	15	33	1213	0	0	0	0	0
A0222100006S01E2403SWNWSW	10	30	1252	0	0	0	1228	0
A0229850007S02E220340604120	16	34	1220	0	0	1194	0	1206
A0227970007S02E341111201150	18	34	1190	0	0	0	0	0
A0227960007S02E340338000100	17	33	1209	0	0	0	0	0
A0229830007S02E2604NENWSE	17	34	1215	0	0	0	0	0
A0232280005S02W300102505250	5	12	1335	0	0	0	0	0
A0232280005S02W300203003960	5	12	1326	0	0	0	0	0
A0234150007S02E2204NCN2NE	15	33	1219	0	0	0	0	0
A0237300005S01W280439603950	4	21	1299	0	0	0	0	0
A0252680005S01E300308005180	5	24	1299	0	1269	0	0	0
A0239060007S02E150252003150	14	34	1230	0	0	1206	1205	0
A0233940007S02E1403CNNW	15	35	1227	0	0	0	0	0
A0253360005S02W210626802500	3	15	1325	0	1305	0	0	0
A0243360005S03W240239703930	3	11	1379	0	0	0	1341	0
A0243360005S03W240339703795	3	11	1382	0	0	0	0	0
A0239050007S02E350208001260	18	34	1210	0	0	1180	1178	0
A0233810006S01E250316804340	11	30	1251	0	0	0	0	0
A0244070005S02W350339505250	5	17	1322	0	0	0	0	0

Table 3B1. (continued)

A0244290005S02W330146201250	5	15	1315	0	0	0	0	0
A0258790005S03W230223101220	4	10	1355	0	1333	0	1330	0
A0281330005S01E3204NWSESE	6	25	1268	0	0	0	0	0
A0267340005S03W210352153955	3	9	1360	0	0	0	0	0
A0279980006S02E330512603750	12	33	1238	1211	1211	1213	1212	1221
A0281330005S01E3301NWSESW	6	26	1275	0	0	0	0	0
A0259570006S01W020405303100	7	22	1300	0	0	0	0	0
A0259560006S01W050236602650	6	19	1315	0	0	0	0	0
A0259550006S01W050138301185	6	19	1308	0	0	0	0	0
A0279400006S02E320148201720	11	32	1231	0	0	0	0	0
A0277680005S03W360724755080	6	12	1350	0	0	0	0	0
A0278120006S01E140342203740	8	29	1265	0	0	0	0	0
A0254900005S02W320428702440	5	13	1337	0	1302	0	0	0
A0278110006S01E140242201330	8	28	1265	0	0	0	0	0
A0271200007S02E280246201340	16	33	1205	1197	0	0	1193	0
A0277710005S03W340252603800	5	10	1342	0	0	0	0	0
A0268550007S02E230415003850	16	35	1210	0	0	0	0	0
A0298520005S01W290226503820	5	19	1293	0	0	0	0	0
A0301580006S02E2002SWSWSW	10	31	1237	0	0	0	0	0
A0303120005S02W2507SWSWNE	4	18	1305	0	0	0	0	0
A0301580006S02E2001NWSWSW	10	32	1237	0	0	0	0	0
A0308470007S02E210452602990	16	33	1214	0	0	0	0	0
A0300760006S01E110234104130	7	29	1253	0	0	0	1240	1244
A0303120005S02W2506CWNWNE	5	18	1310	0	0	0	0	0
A0298480005S02W310236211254	5	13	1332	0	0	0	0	0
A0300780007S02E140251801860	15	35	1230	0	0	0	0	0
A0307690005S03W230323753895	4	11	1350	0	0	0	1342	0
A0289230007S02E100116501180	14	33	1220	0	0	0	0	0
A0295990006S01E240452005180	9	29	1255	0	1231	1229	1230	1232
A0289240007S02E100234321346	13	34	1230	0	0	0	0	0
A0301590007S02E030620803490	13	33	1230	0	1209	1207	1206	0
A0299340006S01E030335404020	6	28	1259	0	0	0	1245	0
A0300770008S02E010418504250	19	35	1208	0	0	0	0	0
A0295980006S01E140425403920	9	29	1261	0	0	1236	1236	1239
A0300770008S02E010340004250	18	35	1208	0	0	0	0	0
A0294980006S01E130533102400	8	29	1249	0	0	0	1225	1230
A0308460006S01W030326755150	6	21	1305	0	0	0	0	0
A0309850006S01W050332203970	6	19	1330	0	1270	1282	1282	1288
A0300790006S02E310230004990	11	31	1250	0	0	1218	1222	0
A0288650006S02E330939602680	12	33	1230	0	0	0	0	0
A0285430006S01W040406303930	7	20	1351	0	1224	0	1226	0
A0298480005S02W310321621257	6	12	1340	0	0	0	0	0
A0288380006S02E330426801250	11	33	1235	0	0	1208	1205	1212
A0302710005S01W340233003300	5	22	1285	0	0	0	0	0
A0301580006S02E2906NENWSE	10	31	1231	0	0	0	0	0
A0311080005S02W3505NCN2NE	5	16	1325	0	0	0	0	0
A0305260005S03W270311505180	5	10	1341	1278	0	0	1318	0
A0316480005S02W260427400034	5	16	1318	0	0	0	0	0
A0314590006S01E070231501580	7	24	1271	0	0	1254	1253	1254
A0325080006S01E040539603935	7	27	1267	0	1247	0	0	0
A0322320006S02E190232904700	9	30	1240	0	1223	0	1222	0
A0311820005S02W210731352650	3	14	1320	0	0	0	1302	1307

Table 3B1. (continued)

A0323270006S02E1802NCSESW	9	31	1235	0	0	0	0	0
A0313370008S02E1205SWSWNE	19	35	1205	0	0	0	0	0
A0313370008S02E1206NCE2SWNW	20	36	1201	0	0	0	0	0
A0313370008S02E1204CWSWNE	19	36	1205	0	0	0	0	0
A0319000005S01W350139603960	5	22	1280	0	1272	1268	0	0
A0336420006S01E110339401300	7	28	1248	0	1234	0	0	0
A0334280007S02E100314302590	14	34	1225	0	0	0	0	0
A0336400007S02E100422694856	13	34	1230	0	0	0	0	0
A0327690005S01E3004NWNESW	4	24	1315	0	0	0	0	0
A0329220005S01W330308601920	6	20	1295	0	1273	1274	1273	1278
A0326270005S01W350213504100	6	23	1280	0	0	0	0	0
A0334270006S02E180341803960	9	31	1240	0	0	1225	1225	0
A0331360007S02E230636202550	15	34	1221	1191	0	0	1200	1211
A0346990005S01W340303604300	6	22	1289	0	1270	1273	1273	1279
A0347490005S03W340639301755	5	10	1339	0	0	0	0	0
A0347490005S03W340540451950	5	10	1339	0	0	0	0	0
A0357930006S01E040200701500	7	26	1259	0	0	0	0	0
A0355260007S02E080142503090	14	31	1215	0	0	1200	1200	0
A0351140005S03W220139602050	3	9	1350	0	0	1335	1327	1333
A0356610006S01E140500202440	9	29	1259	0	0	1232	1232	1233
A0356990006S01E150112000050	9	27	1263	0	0	0	1227	0
A0357890007S02E040536003800	12	32	1228	0	0	0	0	0
A0357900006S02E310339600050	11	30	1241	0	0	0	0	0
A0349640007S02E2707NWSWSE	17	33	1216	0	0	0	0	0
A0352880006S01E0111NESWNW	7	30	1266	0	0	0	0	0
A0357940006S01E090129000080	7	27	1258	0	0	0	0	0
A0360600008S03E070844003800	19	37	1205	0	0	1183	1183	1184
A0364940005S01W260335201700	4	23	1285	0	0	0	0	0
A0365700005S03W250146405210	4	11	1332	0	1320	0	1318	0
A0366890006S01E230425001300	9	28	1256	0	0	0	1230	0
A0368630007S02E160144002800	14	33	1215	0	0	0	0	0
A0367320006S01W040406303930	7	20	1351	0	0	0	0	0
A0365930007S02E270826603590	16	33	1220	0	0	1190	1189	1198
A0371470007S02E260539602660	17	35	1215	0	0	0	0	0
A0383030007S02E150339800700	14	34	1225	0	0	1204	1189	0
A0382440005S02W210318355240	4	15	1323	0	0	0	0	0
A0381230006S01E050145505150	6	25	1265	0	0	1250	1250	0
A0381600005S03W340639301755	6	10	1339	0	0	0	0	0
A0381600005S03W340540451950	5	9	1339	0	0	0	0	0
A0386800007S02E210539601320	15	32	1210	0	0	0	0	0
A0385250006S01E240512501000	10	29	1250	0	0	0	0	0
A0386370007S02E160217950059	14	32	1225	0	0	0	0	0
A0385370008S02E020339501200	18	34	1210	0	0	1184	1180	1182
A0385350008S02E020246500100	18	35	1208	0	0	1182	1178	1180
A0385340008S02E010552501470	18	36	1205	0	0	0	0	0
A0390370007S02E150417002640	15	34	1225	0	0	1204	1200	0
A0388180006S01E030335404020	6	27	1259	0	0	0	0	0
A0389240008S02E110637400205	19	35	1210	0	0	0	0	0
A8891150008S02E020424004750	19	34	1192	0	0	0	0	0
A889117HD08S02E020624004750	19	34	1192	0	0	0	0	0
A889117IN08S02E020624004750	19	35	1192	0	0	0	0	0
A0391460006S01W050413201320	7	19	1325	0	0	0	0	0

Table 3B1. (continued)

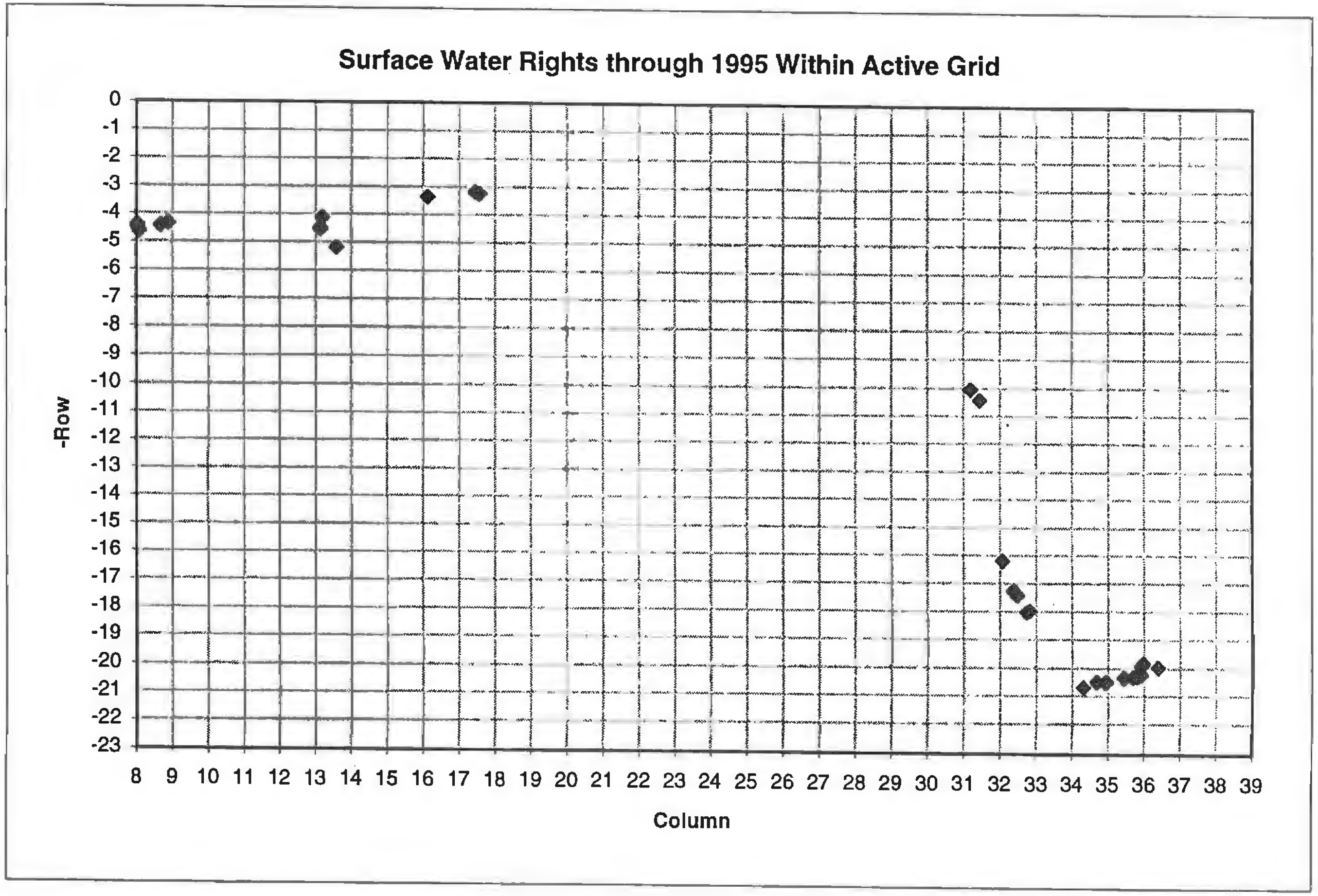
A0391060006S01E060452404950	6	24	1275	0	0	0	0	0
A0387540005S01W350139603960	5	23	1280	0	0	0	0	0
A0387240007S02E220509603940	16	34	1220	0	0	0	1192	1201
A889116HD05S03W260207263564	5	10	1340	0	0	0	0	0
A889116IN05S03W260207263564	5	10	1340	0	0	0	0	0
A0390310007S02E200123200030	16	32	1212	0	0	0	0	0
A0390900007S02E220827383965	15	34	1221	0	0	0	0	1201
A0398130005S03W250250003980	5	12	1330	0	0	0	0	0
A0395090007S02E150539705230	15	34	1225	0	0	0	0	0
A0392040005S03W230403501330	3	10	1335	0	0	0	1324	0
A0393840005S03W240517005000	4	12	1360	0	0	0	1340	0
A0393420008S02E020517002150	19	34	1211	0	0	0	0	0
A0393060007S02E340651501250	18	33	1215	0	0	1186	0	1199
A0393540007S02E280246201340	17	32	1205	0	0	0	0	0
A0394480007S02E230415003850	16	34	1210	0	0	0	0	0
A0399520005S03W250146405210	4	11	1332	0	0	0	0	0
A0400850005S02W200603504000	4	14	1323	0	0	0	0	0
A0399320005S03W240810103960	4	12	1334	0	0	0	0	0
A0398720005S03W220717401110	4	9	1335	0	0	0	0	0
A0398720005S03W220618101040	4	10	1335	0	0	0	0	0
A0398720005S03W220518800970	4	10	1340	0	0	0	0	0
A0398720005S03W220419500900	4	9	1340	0	0	0	0	0
A0399530005S02W201026583082	4	14	1339	0	0	0	0	0
A0399530005S02W200926582658	3	14	1335	0	0	0	0	0
A0399050005S03W220330150035	3	9	1350	0	0	1341	0	1344
A0399530005S02W200530823082	3	14	1339	0	0	0	0	0
A0399530005S02W200430822658	3	14	1340	0	0	0	0	0
A0398410006S01E240752403455	10	30	1255	0	0	0	0	0
A0401610007S02E340739604630	17	33	1200	0	0	0	1188	0
A0400970007S02E271000305240	17	34	1200	0	0	0	0	0
A0401470006S02E290215000600	11	31	1232	0	0	0	0	1224
A0401500006S02E290949001650	10	32	1230	0	0	0	0	1222
A0400910005S03W281329004100	5	8	1344	0	0	0	0	0
A0404490005S01W270233501100	4	22	1300	0	0	1290	0	0
A0405290007S02E180500500650	15	31	1235	0	0	0	0	0
A0403160006S01E110339401300	7	29	1248	0	0	0	0	0
A0404090005S03W360906752050	6	12	1360	0	0	0	0	0
A0406590005S01W290226503820	4	20	1293	0	0	0	0	0
A0406540007S02E040610002000	13	33	1235	0	0	0	0	0
A0406480005S03W360144502600	5	12	1340	0	0	0	0	0
A0406520005S02W300203003960	5	12	1326	0	0	0	0	0
A0406780005S03W260304703000	5	10	1340	0	0	0	0	0
A0406790005S03W260419804290	5	11	1340	0	0	0	0	0
A0411740007S02E040712500850	13	32	1232	0	0	0	0	0
A9491920008S03E071148001250	19	37	1200	0	0	0	0	0
A9590180008S03E071335500350	19	37	1198	0	0	0	0	0
No. of DTW occurences for ea. year				8	35	55	82	55

APPENDIX 3B2

Ground-water and surface-water rights in the Lower Republican River valley from Concordia to Clay Center and related graphs

Surface Water Rights

idx	file id leglocId Subsec	Cty	Use	Year	Qnew (acft)	row	col	longitude	latitude	Grid Node Elev. (ft)	Distance to Stream (mi)	Stream Reach No.
1	VCD00090005S02W290146004260	15	S3	1941	129	4.13	13.19	-97.571	39.594	1320	0.48	20
2	VCD00090005S02W290227254600	15	S3	1941	129	4.48	13.13	-97.572	39.588	1320	0.37	20
3	A0020410008S02E1401SWNESW	14	S3	1953	30	20.69	34.31	-97.178	39.355	1200	0.27	68
4	A0026680005S03W281032005100	15	S3	1954	11.86	4.39	8.03	-97.668	39.590	1330	0.48	13
5	A0026680005S03W281226405100	15	S3	1954	11.86	4.5	8.03	-97.668	39.588	1330	0.47	13
6	A0026680005S03W280119804850	15	S3	1954	11.86	4.63	8.08	-97.667	39.586	1330	0.44	13
7	A0045720005S02W2401SENENW	15	S3	1955	45	3.19	17.44	-97.484	39.602	1300	0.32	28
8	A0045720005S02W2301NCSWNW	15	S3	1955	45	3.38	16.13	-97.516	39.605	1305	0.4	27
9	A0056790008S02E121004000350	14	S3	1956	41.5	19.92	35.93	-97.148	39.367	1204	0.61	70
10	A0056790008S02E120909000100	14	S3	1956	41.5	19.83	35.98	-97.147	39.368	1204	0.58	70
11	A0059610008S02E130636001650	14	S3	1956	30.5	20.32	35.69	-97.152	39.361	1190	0.26	69
12	A0059610008S02E130541000400	14	S3	1956	30.5	20.22	35.92	-97.148	39.362	1190	0.51	69
13	A0059610008S02E130834802940	14	S3	1956	30.5	20.34	35.44	-97.157	39.361	1190	0.17	69
14	A0059610008S02E130337001050	14	S3	1956	30.5	20.3	35.8	-97.150	39.361	1190	0.36	69
15	A0099280006S02E2903NENWNW	14	S3	1964	76	10.06	31.19	-97.228	39.509	1230	0.54	52
16	A0099280006S02E2904SESENW	14	S3	1964	76	10.44	31.44	-97.223	39.498	1230	0.09	52
17	A0124250005S02W290325004554	15	S3	1966	75.5	4.53	13.14	-97.572	39.588	1320	0.36	20
18	A0124250005S02W320342902180	15	S3	1966	75.5	5.19	13.59	-97.563	39.578	1337	0.32	21
19	A0171090008S02E140426800250	14	S3	1970	29.33	20.49	34.95	-97.166	39.358	1200	0.45	68
20	A0171090008S02E140527001700	14	S3	1970	29.33	20.49	34.68	-97.171	39.358	1200	0.18	68
21	A0171090008S02E140826400500	14	S3	1970	29.33	20.5	34.91	-97.166	39.358	1200	0.41	68
22	A0259830008S02E130337001050	14	S3	1976	25.75	20.3	35.8	-97.150	39.361	1190	0.36	69
23	A0259830008S02E130541000400	14	S3	1976	25.75	20.22	35.92	-97.148	39.362	1190	0.51	69
24	A0259830008S02E130636001650	14	S3	1976	25.75	20.32	35.69	-97.152	39.361	1190	0.26	69
25	A0259830008S02E130834802940	14	S3	1976	25.75	20.34	35.44	-97.157	39.361	1190	0.17	69
26	A0263810005S03W280830351750	15	S3	1976	25.5	4.43	8.67	-97.656	39.589	1330	0.18	13
27	A0263810005S03W280734650595	15	S3	1976	25.5	4.34	8.89	-97.652	39.590	1330	0.42	13
28	A0303940008S02E130337001050	14	S3	1977	5	20.3	35.8	-97.150	39.361	1190	0.36	69
29	A0303940008S02E130541000400	14	S3	1977	5	20.22	35.92	-97.148	39.362	1190	0.51	69
30	A0303940008S02E130834802940	14	S3	1977	5	20.34	35.44	-97.157	39.361	1190	0.17	69
31	A0303940008S02E130636001650	14	S3	1977	5	20.32	35.69	-97.152	39.361	1190	0.26	69
32	A0357490007S02E280341804900	14	S3	1981	90	16.21	32.07	-97.218	39.420	1190	0.52	62
33	A0371480007S02E330131002750	14	S3	1984	98	17.41	32.48	-97.211	39.403	1200	0.09	63
34	A0391690008S02E121004000350	14	S3	1988	116	19.92	35.93	-97.148	39.367	1204	0.61	70
35	A0391690008S02E120909000100	14	S3	1988	116	19.83	35.98	-97.147	39.368	1204	0.58	70
36	A0394990005S02W240439602340	15	S3	1989	180	3.25	17.56	-97.489	39.606	1300	0.26	28
37	A0395490008S03E070901003200	14	S3	1989	335	19.98	36.39	-97.139	39.365	1185	0.49	71
38	A0398580007S02E330300860972	14	S3	1990	150	17.98	32.82	-97.205	39.394	1200	0.58	63
39	A0398590007S02E330239303225	14	S3	1990	120	17.26	32.39	-97.212	39.405	1200	0.27	63
40	A0408420008S02E040252001350	14	S3	1992	75	18.02	32.74	-97.207	39.394	1280	0.54	64



Surface Water Rights through 1995 Within Active Grid

Ground Water Rights

idx	file id legloc Subsec	Cty	Use	Year	Qnew (acft)	row	col	longitude	latitude	Elev. at Water Right Location (ft)	Grid Node Elev. (ft)	Distance to Stream (mi)	Stream Reach No.
1	VCY00010006S01E020642003550	14	G4	1941	30.7	6.2	28.33	-97.287	39.564	1268	1260	1.08	47
2	VCY00010006S01E020542003600	14	G4	1941	30.7	6.2	28.32	-97.287	39.564	1268	1260	1.08	47
3	VCD00010005S01W260235351700	15	G4	1941	36.67	4.33	22.68	-97.393	39.591	1285	1292	0.61	35
4	VCD00010005S01W260434951700	15	G4	1941	36.67	4.34	22.68	-97.393	39.591	1285	1292	0.61	35
5	VCD00010005S01W260335201700	15	G4	1941	36.67	4.33	22.68	-97.393	39.591	1285	1292	0.61	35
6	VCY00030007S02E030100504920	14	G4	1941	10.74	12.99	33.07	-97.200	39.467	1229	1230	1.03	55
7	VCY00040008S03E071233002100	14	G4	1941	104.34	19.38	36.6	-97.135	39.374	1201	1185	0.51	71
8	VCY00040008S03E070127500500	14	G4	1941	104.34	19.48	36.91	-97.130	39.373	1190	1185	0.68	71
9	VCD00040005S03W330330752769	15	G4	1941	149.14	5.42	8.48	-97.660	39.575	1355	1367	0.83	13
10	VCY00040008S03E070222000350	14	G4	1941	104.34	19.58	36.93	-97.129	39.371	1180	1185	0.65	71
11	VCY00080006S01E011232505230	14	G2	1941	114.77	6.38	29.01	-97.274	39.561	1266	1253	0.38	47
12	VCD00110005S02W2501NWNWSW	15	G3	1941	100	4.56	17.06	-97.498	39.593	1315	1310	1.19	28
13	VWS00280005S01E3201NCS2N2SW	101	G3	1942	87.5	5.69	25.25	-97.345	39.572	1275	1273	0.9	42
14	A0009050008S02E110743501150	14	G3	1952	89	19.18	34.78	-97.169	39.377	1205	1170	0.32	67
15	A0011520005S02W2502SWNESE	15	G3	1953	110	4.69	17.81	-97.491	39.586	1307	1310	1.21	28
16	A0012990006S01E010234005230	14	G2	1953	79.79	6.36	29.01	-97.274	39.562	1266	1253	0.43	47
17	A0015050005S02W2201NWNESW	15	G3	1953	78	3.56	15.31	-97.531	39.607	1312	1310	0.51	26
18	A0015450005S03W360144502600	15	G3	1953	98	5.16	11.51	-97.602	39.579	1340	1346	0.74	16
19	A0017090005S02W2601SENENE	15	G3	1953	48.5	4.19	16.94	-97.500	39.587	1305	1315	0.78	27
20	A0017090005S02W2602SENWNE	15	G3	1953	48.5	4.19	16.69	-97.505	39.587	1305	1315	0.78	27
21	A0019620008S02E0201NESWSW	14	G3	1953	130	18.81	34.19	-97.173	39.388	1193	1210	0.15	66
22	A0027900008S02E010552501470	14	G3	1954	85	18.01	35.72	-97.151	39.394	1205	1204	1.28	66
23	A0029830006S01W040632205200	15	G3	1954	75	6.39	20.02	-97.443	39.562	1308	1319	0.7	32
24	A0031360007S02E1802SWNENE	14	G3	1954	54.5	14.19	30.81	-97.248	39.444	1232	1245	0.54	59
25	A0031360007S02E1801SWNENE	14	G3	1954	54.5	14.19	30.81	-97.248	39.444	1232	1245	0.54	59
26	A0031360007S02E1804NWNWNE	14	G3	1954	54.5	14.06	30.56	-97.253	39.451	1240	1245	0.84	59
27	A0031360007S02E1803SWNWNE	14	G3	1954	54.5	14.19	30.56	-97.253	39.444	1240	1245	0.8	59
28	A0032260006S02E331012501700	14	G3	1954	268	11.76	32.68	-97.207	39.484	1240	1220	0.92	55
29	A0033890005S02W2503SWSWSW	15	G3	1955	120	4.94	17.06	-97.498	39.582	1314	1310	1.53	28
30	A0033900005S02W2501NWNWSW	15	G3	1955	65	4.56	17.06	-97.498	39.593	1315	1310	1.19	28
31	A0034670006S01E2401SENWNE	14	G3	1955	120	9.19	29.69	-97.262	39.516	1240	1251	0.23	50
32	A0035410005S02W3602SESWNW	15	G3	1955	67.5	5.44	17.19	-97.488	39.569	1315	1315	2.01	24
33	A0038030006S01E130138402340	14	G3	1955	175	8.27	29.56	-97.265	39.535	1250	1260	0.47	46
34	A0039110005S03W3501NWNWNE	15	G3	1955	111	5.06	10.56	-97.627	39.580	1341	1353	0.46	15
35	A0040230006S01E2402NWSWNW	14	G3	1955	195	9.31	29.06	-97.274	39.520	1254	1251	0.88	50
36	A0041870005S02W2505NCSWNW	15	G3	1955	228	4.31	17.19	-97.496	39.591	1310	1310	1.14	28
37	A0042020006S01E0201CNNWSE	14	G3	1955	144	6.5	28.63	-97.282	39.560	1260	1260	0.83	47
38	A0044430006S01E0202NWSWNE	14	G3	1955	128	6.31	28.56	-97.290	39.563	1262	1260	0.82	47
39	A0044630005S01W3002CEW2NE	15	G3	1955	7	4.13	18.75	-97.467	39.594	1297	1297	1.07	29
40	A0044630005S01W3001NWSWNE	15	G3	1955	7	4.31	18.56	-97.477	39.591	1296	1297	0.89	29
41	A0045180005S03W3501NWNWNE	15	G3	1955	81	5.06	10.56	-97.627	39.580	1341	1353	0.46	15
42	A0045570005S02W3201NWNWSW	15	G3	1955	48	5.56	13.06	-97.573	39.578	1320	1337	0.39	21
43	A0045750005S01W3101CESENW	15	G3	1955	107	5.38	18.5	-97.471	39.576	1310	1311	1.41	31
44	A0045860006S02E3001NENWSE	14	G3	1955	220	10.56	30.69	-97.244	39.507	1242	1246	0.53	51
45	A0045940005S01W3201SESWSW	15	G3	1955	180	5.94	19.19	-97.452	39.568	1308	1302	0.9	32
46	A0046090006S01E020322004450	14	G3	1955	130	6.58	28.16	-97.290	39.559	1265	1260	1.04	45
47	A0046110005S02W3202NWNWSE	15	G3	1955	212	5.56	13.56	-97.571	39.578	1337	1337	0.22	21
48	A0046360005S02W2501NWNWSW	15	G3	1955	165	4.56	17.06	-97.498	39.593	1315	1310	1.19	28
49	A0046360005S02W2503SWSWSW	15	G3	1955	165	4.94	17.06	-97.498	39.582	1314	1310	1.53	28
50	A0046550007S02E220713202610	14	G3	1955	120	15.75	33.51	-97.192	39.427	1218	1218	1.11	62
51	A0047040006S01W0101NWSWSW	15	G3	1955	120	6.81	23.06	-97.386	39.561	1293	1270	0.61	39

52	A0047050005S01W3003NWSWSE	15	G3	1955	189	4.81	18.56	-97.477	39.589	1292	1297	1.15	31
53	A0047140006S01W020148501370	15	G3	1955	49	6.08	22.74	-97.392	39.566	1280	1275	0.45	36
54	A0049200006S02E291240150950	14	G3	1955	100	10.24	31.82	-97.223	39.506	1232	1230	0.37	52
55	A0049750006S01E030126402040	14	G3	1956	177	6.5	27.61	-97.301	39.560	1259	1261	1.1	44
56	A0049910005S02W3401NWNENE	15	G3	1956	240	5.06	15.81	-97.528	39.580	1320	1325	0.69	24
57	A0051200005S02W2603CWE2SE	15	G3	1956	111	4.63	16.75	-97.504	39.586	1316	1315	0.88	27
58	A0052130006S01E040626401320	14	G3	1956	160	6.5	26.75	-97.317	39.560	1259	1260	0.8	43
59	A0054750006S02E3002NESENW	14	G3	1956	141	10.31	30.44	-97.242	39.505	1242	1246	0.26	51
60	A0056580005S01W3202NWSWNE	15	G3	1956	51	5.31	19.56	-97.459	39.577	1290	1302	0.39	31
61	A0057200007S02E270312805200	14	G3	1956	70	16.76	33.02	-97.201	39.412	1205	1219	0.37	62
62	A0057880005S03W240110502600	15	G3	1956	56	3.8	11.51	-97.603	39.598	1330	1350	0.33	17
63	A0059430008S03E0601NWNWSE	14	G3	1956	103.5	18.56	36.56	-97.142	39.391	1201	1204	1.2	71
64	A0059550008S03E0602SENENW	14	G3	1956	163	18.19	36.44	-97.131	39.386	1205	1204	1.52	71
65	A0059850005S03W3602NENWNW	15	G3	1956	254	5.06	11.19	-97.602	39.580	1338	1346	0.62	16
66	A0060110006S01E2501CWSE	14	G3	1956	55	10.63	29.5	-97.266	39.501	1248	1245	0.9	51
67	A0060200005S03W3302NWNENE	15	G3	1956	60	5.06	8.81	-97.660	39.580	1345	1367	0.61	13
68	A0060590007S02E2601NWSESW	14	G3	1956	155	16.81	34.31	-97.177	39.417	1211	1217	1.35	66
69	A0060720005S01W3203SWSWNW	15	G3	1956	189	5.44	19.06	-97.461	39.569	1306	1302	0.87	31
70	A0062590005S01W3102NWSESW	15	G3	1956	75	5.81	18.31	-97.474	39.575	1310	1311	1.64	31
71	A0063340006S02E3302NCNE	14	G3	1956	120	11.13	32.75	-97.206	39.494	1220	1220	0.87	53
72	A0063990005S01W330144653300	15	G3	1956	90	5.15	20.38	-97.437	39.579	1290	1295	0.37	32
73	A0064150005S01W280239601188	15	G3	1956	100	4.25	20.77	-97.429	39.592	1293	1293	0.68	33
74	A0064180006S01E0108NESWSW	14	G3	1956	34	6.81	29.19	-97.264	39.561	1250	1253	0.14	47
75	A0064460006S02E300346055170	14	G3	1956	91	10.13	30.02	-97.256	39.508	1245	1246	0.22	51
76	A0065250005S02W2201NWNESW	15	G3	1956	59.52	3.56	15.31	-97.531	39.607	1312	1310	0.51	26
77	A0065830005S02W3501NWSWNE	15	G3	1956	100	5.31	16.56	-97.514	39.577	1320	1327	1.48	24
78	A0066230005S02W3603SENWNE	15	G3	1957	60	5.19	17.69	-97.486	39.573	1311	1315	1.77	28
79	A0066770007S02E0302CWNWNE	14	G3	1957	34	12.13	33.5	-97.192	39.479	1230	1230	1.5	55
80	A0068400006S01E040626401320	14	G3	1957	44	6.5	26.75	-97.317	39.560	1259	1260	0.8	43
81	A0069230007S02E1501SWNESE	14	G3	1957	107	14.69	33.81	-97.193	39.442	1225	1225	1.78	58
82	A0069560005S03W2102SWNESW	15	G3	1957	17	3.69	8.31	-97.663	39.600	1350	1361	0.51	13
83	A0070150005S02W3604SWSWNE	15	G3	1957	126	5.44	17.56	-97.495	39.569	1312	1315	1.99	28
84	A0070170005S02W210828001300	15	G3	1957	111	3.47	14.75	-97.541	39.603	1320	1325	0.83	26
85	A0070410006S01E0601NCNE	14	G3	1957	110	6.25	24.75	-97.355	39.564	1270	1270	0.68	42
86	A0070420005S01W3103NCN2SWNE	15	G3	1957	159	5.31	18.63	-97.469	39.577	1310	1311	1.29	31
87	A0070430005S01W3204NCSWSE	15	G3	1957	175	5.88	19.63	-97.451	39.568	1300	1302	0.46	32
88	A0075610005S01E3202NWNWSW	101	G3	1957	63	5.56	25.06	-97.349	39.579	1280	1273	1.08	42
89	A0077060007S02E1401CWNW	14	G3	1958	165	14.38	34	-97.183	39.446	1227	1226	2.39	58
90	A0077860006S01E0801CWSWSWNW	14	G3	1958	152	7.44	25	-97.350	39.547	1265	1282	0.2	40
91	A0080020005S02W3401NWNENE	15	G3	1959	70	5.06	15.81	-97.528	39.580	1320	1325	0.69	24
92	A0081050006S01E1302NENWSE	14	G3	1959	112	8.56	29.69	-97.262	39.536	1240	1260	0.32	49
93	A0081530005S02W3101SENWSW	15	G3	1959	41	5.69	12.19	-97.582	39.571	1345	1340	1.11	21
94	A0081940006S01W040632205200	15	G3	1959	34.58	6.39	20.02	-97.443	39.562	1308	1319	0.7	32
95	A0081950005S01E3203SWNWSE	101	G3	1959	39	5.69	25.56	-97.346	39.572	1268	1273	0.87	42
96	A0086880005S01W2003SWSENW	15	G3	1961	29	3.44	19.31	-97.456	39.598	1310	1307	0.26	30
97	A0090080005S01W300438503850	15	G3	1962	94	4.27	18.27	-97.475	39.592	1297	1297	0.84	29
98	A0091050005S03W3604N2SWSE	15	G3	1963	84	5.81	11.63	-97.600	39.569	1346	1346	1.07	16
99	A0091050005S03W3605SENESE	15	G3	1963	44	5.69	11.94	-97.594	39.571	1348	1346	1.29	16
100	A0091210005S01W250120105165	15	G3	1963	102	4.62	23.02	-97.387	39.587	1291	1310	0.61	38
101	A0092030006S01E010430504980	14	G2	1963	65.98	6.42	29.06	-97.274	39.561	1266	1253	0.38	47
102	A0094920006S01E2301SESWNW	14	G3	1963	157	9.44	28.19	-97.283	39.512	1262	1258	1.35	45
103	A0098890005S02W1901SESWNW	15	G3	1964	187	3.44	12.19	-97.583	39.598	1347	1325	0.21	18
104	A0099730006S01E0802NWNWSE	14	G3	1964	110	7.56	25.56	-97.347	39.550	1270	1282	0.17	41
105	A0100440006S01E1401SWNWSE	14	G3	1964	244	8.69	28.56	-97.290	39.529	1260	1260	0.58	45

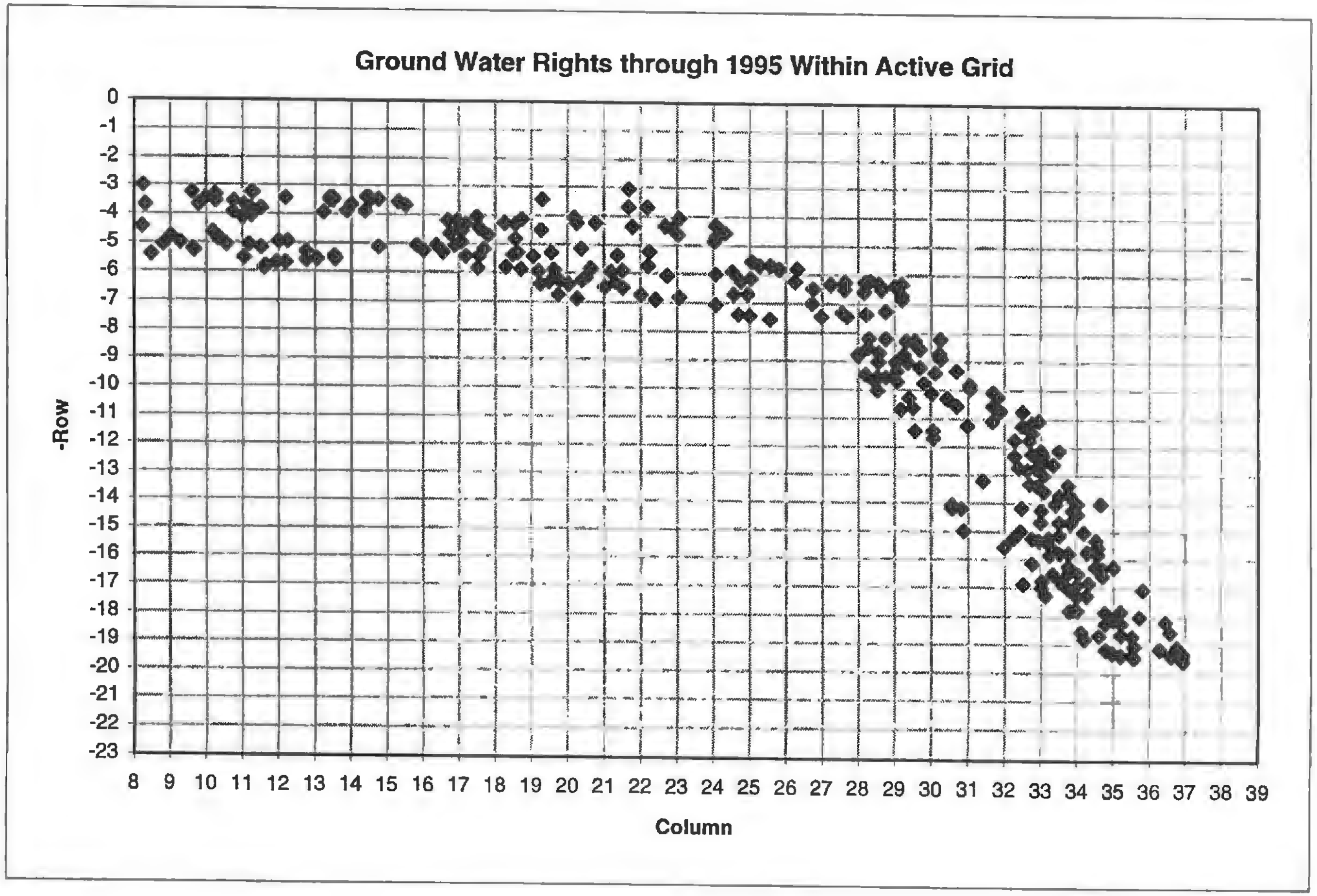
106	A0104340007S02E0303CWNWNW	14	G3	1964	120	12.13	33	-97.201	39.479	1230	1230	1.5	55
107	A0105850006S01W040539353155	15	G3	1964	62	6.25	20.4	-97.436	39.563	1305	1319	0.6	32
108	A0106860006S01E1303NCW2	14	G3	1965	152	8.75	29.25	-97.271	39.528	1260	1260	0.52	46
109	A0108690006S02E3301NENENE	14	G4	1965	30.2	11.06	32.94	-97.203	39.494	1245	1220	1.48	53
110	A0109690005S01W2301SENWSW	15	G3	1965	102	3.69	22.19	-97.395	39.600	1292	1290	0.99	35
111	A0109720006S01E250437503170	14	G3	1965	155	10.29	29.4	-97.268	39.505	1249	1245	0.86	51
112	A0110180006S01E0109SENWSW	14	G3	1965	129	6.69	29.19	-97.264	39.557	1260	1253	0.12	47
113	A0111240006S01E1001NWSWNE	14	G3	1965	165	7.31	27.56	-97.309	39.549	1255	1255	0.38	44
114	A0111650006S01W030126352540	15	G3	1965	202	6.5	21.52	-97.415	39.560	1299	1305	1.29	36
115	A0113520006S01W0302NWSENW	15	G3	1965	171	6.31	21.31	-97.419	39.563	1300	1305	1.04	32
116	A0114430007S02E2301NWNWSE	14	G3	1965	133	15.56	34.56	-97.179	39.435	1220	1220	2.16	62
117	A0114620006S01E2302SENESW	14	G3	1965	162	9.69	28.44	-97.279	39.514	1259	1258	1.48	50
118	A0114750005S01E3001SWNWSW	101	G3	1965	112	4.69	24.06	-97.367	39.586	1320	1290	0.28	38
119	A0115980005S01W2503NWNWNW	15	G3	1966	94	4.06	23.06	-97.386	39.595	1330	1310	0.83	38
120	A0118320006S01W040345352630	15	G3	1966	116	6.14	20.5	-97.434	39.565	1304	1319	0.47	32
121	A0118470006S01E0302NCW2NE	14	G3	1966	90	6.25	27.63	-97.301	39.564	1259	1261	1.11	44
122	A0119750005S01W340105352620	15	G3	1966	173	5.9	21.5	-97.415	39.568	1285	1283	0.95	36
123	A0119760005S01W2803NENWNW	15	G3	1966	108	4.06	20.19	-97.433	39.595	1299	1293	0.43	33
124	A0122690006S01E0603SWNWSE	14	G3	1966	190	6.69	24.56	-97.365	39.557	1268	1270	0.5	40
125	A0122690006S01E0602SENESE	14	G3	1966	95	6.69	24.94	-97.351	39.557	1267	1270	0.33	42
126	A0124980005S01E3002NWSWNW	101	G3	1966	60.5	4.31	24.06	-97.367	39.592	1322	1290	0.5	38
127	A0124980005S01E3001SWNWSW	101	G3	1966	60.5	4.69	24.06	-97.367	39.586	1320	1290	0.28	38
128	A0124990005S02W210318355240	15	G3	1966	60	3.65	14.01	-97.556	39.600	1323	1325	0.84	19
129	A0125070007S02E2202CWE2SE	14	G3	1966	114	15.75	33.75	-97.188	39.427	1219	1218	1.22	62
130	A0126040006S01E230324802600	14	G3	1967	103	9.53	28.51	-97.284	39.516	1259	1258	1.42	50
131	A0128230005S02W220217502600	15	G3	1967	100	3.67	15.51	-97.527	39.600	1312	1310	0.33	26
132	A0130090007S02E270906000051	14	G3	1967	135	16.89	33.99	-97.183	39.410	1215	1219	1.22	62
133	A0130910005S02W210431703000	15	G3	1967	105	3.4	14.43	-97.548	39.604	1321	1325	1.11	19
134	A0131770006S01E020439404290	14	G3	1967	51	6.25	28.19	-97.290	39.563	1264	1260	1.2	45
135	A0132280005S02W3502NCN2NW	15	G3	1967	98	5.06	16.38	-97.511	39.580	1325	1327	1.47	24
136	A0136310005S01W2201SENWSE	15	G3	1967	142	3.69	21.69	-97.412	39.601	1318	1320	0.86	34
137	A0141500005S02W200306500660	15	G3	1967	204	3.88	13.88	-97.558	39.597	1322	1330	0.7	19
138	A0142540005S01W260130350710	15	G3	1967	14	4.43	22.87	-97.390	39.590	1290	1292	0.66	35
139	A0142550005S01W2202NENWNE	15	G3	1967	108	3.06	21.69	-97.412	39.610	1310	1320	1.55	34
140	A0143010006S01E130637853635	14	G3	1968	92	8.28	29.31	-97.269	39.535	1259	1260	0.47	46
141	A0146310007S02E270528401260	14	G3	1968	40	16.46	33.76	-97.187	39.416	1216	1219	1.17	62
142	A0146310007S02E270640801260	14	G3	1968	26	16.23	33.76	-97.187	39.420	1217	1219	1.26	62
143	A0146630007S02E2102NESENE	14	G3	1968	57	15.31	32.94	-97.203	39.433	1210	1210	0.97	58
144	A0148350005S03W230136003895	15	G3	1968	32	3.32	10.26	-97.626	39.605	1370	1340	0.95	15
145	A0149450007S02E2501CNS2NW	14	G3	1968	75	16.25	35	-97.164	39.419	1220	1215	2	66
146	A0151500007S02E3601NWNENE	14	G3	1968	90	17.06	35.81	-97.156	39.407	1212	1207	1.75	66
147	A0157230006S01E0701NWNWNW	14	G3	1968	120	7.06	24.06	-97.367	39.552	1270	1282	0.02	40
148	A0157910007S02E2302NWSWSE	14	G3	1968	51	15.81	34.56	-97.179	39.431	1216	1220	2.11	62
149	A0157950007S02E200123200030	14	G3	1968	115	15.56	31.99	-97.219	39.429	1212	1210	0.58	60
150	A0158890006S02E1901NESWNE	14	G3	1968	72.3	9.31	30.69	-97.244	39.520	1240	1240	0.73	50
151	A0161970006S01E1002SESWNE	14	G3	1969	63	7.44	27.69	-97.300	39.541	1256	1255	0.21	44
152	A0162150007S02E0901NESWNE	14	G3	1969	133	13.31	32.69	-97.207	39.462	1235	1230	0.74	57
153	A0164010008S02E010214802630	14	G3	1969	129	18.72	35.5	-97.155	39.384	1204	1204	1.09	70
154	A0164220005S01W310406301485	15	G3	1969	30	5.88	18.72	-97.467	39.568	1308	1311	1.29	31
155	A0164530007S02E040239601320	14	G3	1969	139	12.25	32.75	-97.206	39.477	1238	1236	0.87	55
156	A0166110007S02E0304NWSWNW	14	G3	1969	131	12.31	33.06	-97.200	39.476	1238	1230	1.13	55
157	A0169970007S02E2602NESWNE	14	G3	1970	80	16.31	34.69	-97.170	39.418	1215	1217	1.85	62
158	A0170050006S01E3601SWSWNE	14	G3	1970	194	11.44	29.56	-97.272	39.483	1252	1252	1.59	51
159	A0170060006S02E3101SWNWSW	14	G3	1970	220	11.69	30.06	-97.255	39.485	1250	1230	1.21	51

160	A0170290007S02E1501SWNESE	14	G3	1970	64	14.69	33.81	-97.193	39.442	1225	1225	1.78	58
161	A0170970007S02E0305NWNWSW	14	G3	1970	140	12.56	33.06	-97.200	39.478	1233	1230	1.07	55
162	A0170980007S02E3602NESWSW	14	G3	1970	99	17.81	35.19	-97.154	39.402	1209	1207	0.84	66
163	A0171600006S01E260151802560	14	G3	1970	130	10.02	28.52	-97.284	39.509	1266	1277	1.5	51
164	A0172460008S02E1203NWNWNE	14	G3	1970	210	19.06	35.56	-97.161	39.379	1205	1204	0.86	70
165	A0176600007S02E090232600600	14	G3	1970	51	13.38	32.89	-97.203	39.461	1230	1230	0.95	57
166	A0182360005S02W360508002510	15	G3	1971	98.1	5.85	17.52	-97.489	39.569	1320	1315	2.41	24
167	A0184160007S02E040314803280	14	G3	1971	125	12.72	32.38	-97.213	39.471	1230	1236	0.34	55
168	A0184160007S02E040425200100	14	G3	1971	81	12.52	32.98	-97.202	39.473	1233	1236	0.96	55
169	A0185430007S02E260326805240	14	G3	1971	69	16.49	34.01	-97.183	39.416	1215	1217	1.36	62
170	A0196030007S02E230351804350	14	G3	1972	453	15.02	34.18	-97.180	39.437	1220	1220	2.07	58
171	A0198300006S01E260151802560	14	G3	1972	80	10.02	28.52	-97.284	39.509	1266	1277	1.5	51
172	A0207320007S02E210339603960	14	G3	1973	135	15.25	32.25	-97.215	39.434	1213	1210	0.82	58
173	A0207430006S02E180114804040	14	G3	1973	114	8.72	30.23	-97.252	39.528	1245	1230	0.2	49
174	A0208540007S02E350139603960	14	G3	1973	94	17.25	34.25	-97.178	39.405	1201	1208	0.95	66
175	A0208550006S02E280113402660	14	G3	1973	66.4	10.75	32.5	-97.210	39.499	1232	1235	1.06	52
176	A0211410005S02W210506603250	15	G3	1973	67	3.88	14.38	-97.548	39.597	1319	1325	0.95	23
177	A0211790005S01E310204402500	101	G3	1973	282	5.92	24.53	-97.359	39.568	1275	1285	0.71	37
178	A0211940007S02E280106602640	14	G3	1973	147	16.88	32.5	-97.211	39.410	1200	1190	0.15	62
179	A0215250007S02E340212000050	14	G3	1973	93	17.77	33.99	-97.184	39.397	1198	1200	0.52	65
180	A0215250007S02E340812000605	14	G3	1973	93	17.77	33.89	-97.185	39.397	1189	1200	0.55	65
181	A0216520006S01W020313505240	15	G3	1973	65	6.74	22.01	-97.406	39.557	1296	1275	1.39	36
182	A0222100006S01E2403SWNWSW	14	G3	1974	160	9.69	29.06	-97.274	39.514	1252	1251	0.9	50
183	A0227960007S02E340338000100	14	G3	1974	90	17.28	33.98	-97.184	39.404	1209	1200	0.98	65
184	A0227970007S02E341111201150	14	G3	1974	22	17.79	33.78	-97.187	39.397	1190	1200	0.61	65
185	A0229830007S02E2604NENWSE	14	G3	1974	110	16.56	34.69	-97.170	39.420	1215	1217	1.64	66
186	A0229850007S02E220340604120	14	G3	1974	80	15.23	33.22	-97.197	39.434	1220	1218	1.21	58
187	A0232280005S02W300102505250	15	G3	1974	29	4.95	12.01	-97.593	39.582	1335	1325	0.87	16
188	A0232280005S02W300203003960	15	G3	1974	105	4.94	12.25	-97.589	39.582	1326	1325	0.8	16
189	A0233810006S01E250316804340	14	G3	1975	180	10.68	29.18	-97.272	39.500	1251	1245	1.24	51
190	A0233940007S02E1403CNNW	14	G3	1975	75	14	34	-97.183	39.452	1227	1226	2.39	57
191	A0234150007S02E2204NCN2NE	14	G3	1975	70	15.13	33.5	-97.192	39.436	1219	1218	1.22	58
192	A0237300005S01W280439603950	15	G3	1975	141	4.25	20.25	-97.439	39.592	1299	1293	0.41	33
193	A0239050007S02E350208001260	14	G3	1975	91	17.85	34.76	-97.169	39.396	1210	1208	0.44	66
194	A0239060007S02E150252003150	14	G3	1975	219	14.02	33.4	-97.194	39.452	1230	1225	1.21	58
195	A0243360005S03W240339703795	15	G3	1975	19	3.25	11.28	-97.607	39.606	1382	1350	0.71	17
196	A0243360005S03W240239703930	15	G3	1975	29	3.25	11.26	-97.608	39.606	1379	1350	0.76	17
197	A0244070005S02W350339505250	15	G3	1975	109	5.25	16.01	-97.517	39.577	1322	1327	0.95	24
198	A0244290005S02W330146201250	15	G3	1975	135	5.13	14.76	-97.541	39.579	1315	1335	0.09	22
199	A0252680005S01E300308005180	101	G3	1975	96	4.85	24.02	-97.368	39.584	1299	1290	0.16	38
200	A0253360005S02W210626802500	15	G3	1975	189	3.49	14.53	-97.546	39.603	1325	1325	1.03	26
201	A0254900005S02W320428702440	15	G3	1976	147	5.46	13.54	-97.564	39.574	1337	1337	0.16	21
202	A0258790005S03W230223101220	15	G3	1976	45	3.56	10.77	-97.617	39.602	1355	1340	0.75	17
203	A0259550006S01W050138301185	15	G3	1976	105	6.27	19.78	-97.448	39.563	1308	1330	0.73	32
204	A0259560006S01W050236602650	15	G3	1976	103	6.31	19.5	-97.453	39.563	1315	1330	0.87	32
205	A0259570006S01W020405303100	15	G3	1976	105	6.9	22.41	-97.398	39.554	1300	1275	1.24	39
206	A0267340005S03W210352153955	15	G3	1976	11	3.01	8.25	-97.664	39.609	1360	1361	1.13	13
207	A0268550007S02E230415003850	14	G3	1976	74.6	15.72	34.27	-97.178	39.427	1210	1220	1.82	62
208	A0271200007S02E280246201340	14	G3	1976	107	16.13	32.75	-97.206	39.421	1205	1190	0.26	62
209	A0277680005S03W360724755080	15	G3	1976	65	5.53	11.04	-97.611	39.573	1350	1346	1.04	16
210	A0277710005S03W340252603800	15	G3	1976	252	5	9.28	-97.644	39.581	1342	1344	0.73	14
211	A0278110006S01E140242201330	14	G3	1976	94	8.2	28.75	-97.280	39.536	1265	1260	0.08	45
212	A0278120006S01E140342203740	14	G3	1976	114	8.2	28.29	-97.289	39.536	1265	1260	0.14	45
213	A0279400006S02E320148201720	14	G3	1976	103.06	11.09	31.67	-97.226	39.494	1231	1220	0.33	53

214	A0279980006S02E330512603750	14	G3	1976	79.62	11.76	32.29	-97.215	39.484	1238	1220	0.53	55
215	A0281330005S01E3204NWSESE	101	G3	1976	180	5.81	25.81	-97.342	39.575	1268	1273	0.84	42
216	A0281330005S01E3301NWSESW	101	G3	1976	180	5.81	26.31	-97.325	39.575	1275	1290	1.1	42
217	A0285430006S01W040406303930	15	G3	1977	75	6.88	20.26	-97.439	39.555	1351	1319	1.16	32
218	A0288380006S02E330426801250	14	G3	1977	9	11.49	32.76	-97.206	39.488	1235	1220	1.09	55
219	A0288650006S02E330939602680	14	G3	1977	94	11.25	32.49	-97.211	39.492	1230	1220	0.98	53
220	A0289230007S02E100116501180	14	G3	1977	84	13.69	33.78	-97.187	39.456	1220	1223	1.61	57
221	A0289240007S02E100234321346	14	G3	1977	162	13.35	33.75	-97.187	39.461	1230	1223	1.71	57
222	A0294980006S01E130533102400	14	G3	1977	158	8.37	29.55	-97.265	39.533	1249	1260	0.46	46
223	A0295980006S01E140425403920	14	G3	1977	210	8.52	28.26	-97.289	39.531	1261	1260	0.47	45
224	A0295990006S01E240452005180	14	G3	1977	55	9.02	29.02	-97.275	39.524	1255	1251	0.92	50
225	A0298480005S02W310321621257	15	G3	1977	21	5.59	12.76	-97.579	39.572	1340	1340	0.62	21
226	A0298480005S02W310236211254	15	G3	1977	46	5.31	12.76	-97.579	39.576	1332	1340	0.43	21
227	A0298520005S01W290226503820	15	G3	1977	39	4.5	19.28	-97.457	39.588	1293	1295	0.43	31
228	A0299340006S01E030335404020	14	G3	1977	144	6.33	27.24	-97.308	39.562	1259	1261	1.12	44
229	A0300760006S01E110234104130	14	G3	1977	184	7.35	28.22	-97.289	39.548	1253	1255	0.36	45
230	A0300770008S02E010418504250	14	G3	1977	97	18.65	35.2	-97.161	39.385	1208	1204	0.79	66
231	A0300770008S02E010340004250	14	G3	1977	95	18.24	35.2	-97.161	39.390	1208	1204	0.71	66
232	A0300780007S02E140251801860	14	G3	1977	101	14.02	34.65	-97.171	39.452	1230	1226	2.44	58
233	A0300790006S02E310230004990	14	G3	1977	165	11.43	30.05	-97.256	39.489	1250	1230	1.27	51
234	A0301580006S02E2906NENWSE	14	G3	1977	29.32	10.56	31.69	-97.225	39.507	1231	1230	0.18	52
235	A0301580006S02E2002SWSWSW	14	G3	1977	29.32	9.94	31.06	-97.237	39.511	1237	1235	0.18	50
236	A0301580006S02E2001NWSWSW	14	G3	1977	29.32	9.81	31.06	-97.237	39.518	1237	1235	0.24	50
237	A0301590007S02E030620803490	14	G3	1977	171	12.61	33.34	-97.195	39.472	1230	1230	1.32	55
238	A0302710005S01W340233003300	15	G3	1977	36	5.38	21.38	-97.418	39.576	1285	1283	0.51	32
239	A0303120005S02W2507SWSWNE	15	G3	1977	118.5	4.44	17.56	-97.495	39.584	1305	1310	1.04	28
240	A0303120005S02W2506CWNWNE	15	G3	1977	118.5	4.06	17.5	-97.490	39.595	1310	1310	1.14	28
241	A0305260005S03W270311505180	15	G4	1977	306.8	4.78	9.02	-97.650	39.584	1341	1340	0.4	14
242	A0307690005S03W230323753895	15	G3	1977	70	3.55	10.26	-97.626	39.602	1350	1340	0.75	15
243	A0308460006S01W030326755150	15	G3	1977	102	6.49	21.02	-97.425	39.560	1305	1305	0.97	32
244	A0308470007S02E210452602990	14	G3	1977	23	15	32.43	-97.212	39.438	1214	1210	0.86	58
245	A0309850006S01W050332203970	15	G3	1977	132	6.39	19.25	-97.458	39.562	1330	1330	1.1	32
246	A0311080005S02W3505NCN2NE	15	G3	1977	90	5.06	16.88	-97.501	39.580	1325	1327	1.47	24
247	A0311820005S02W210731352650	15	G3	1978	52	3.41	14.5	-97.546	39.604	1320	1325	1.07	19
248	A0313370008S02E1205SWSWNE	14	G3	1978	73.5	19.44	35.56	-97.161	39.368	1205	1204	0.6	70
249	A0313370008S02E1206NCE2SWNW	14	G3	1978	73.5	19.38	35.19	-97.161	39.375	1201	1204	0.72	70
250	A0313370008S02E1204CWSWNE	14	G3	1978	73.5	19.38	35.5	-97.156	39.375	1205	1204	0.64	70
251	A0314590006S01E070231501580	14	G3	1978	94	7.4	24.7	-97.356	39.547	1271	1282	0.14	40
252	A0316480005S02W260427400034	15	G3	1978	4.6	4.48	16.99	-97.499	39.589	1318	1315	1.05	27
253	A0319000005S01W350139603960	15	G3	1978	72	5.25	22.25	-97.401	39.578	1280	1280	0.24	36
254	A0322320006S02E190232904700	14	G3	1978	180	9.38	30.11	-97.255	39.519	1240	1240	0.19	50
255	A0323270006S02E1802NCSESW	14	G3	1978	147	8.88	30.25	-97.252	39.526	1235	1230	0.49	49
256	A0325080006S01E040539603935	14	G3	1978	135	6.25	26.25	-97.326	39.564	1267	1260	0.74	42
257	A0326270005S01W350213504100	15	G3	1979	5.6	5.74	22.22	-97.402	39.571	1280	1280	0.62	36
258	A0327690005S01E3004NWNESW	101	G3	1979	97	4.56	24.31	-97.363	39.593	1315	1290	0.54	38
259	A0329220005S01W330308601920	15	G3	1979	152	5.84	20.64	-97.432	39.569	1295	1295	0.25	32
260	A0331360007S02E230636202550	14	G3	1979	117	15.31	34.52	-97.173	39.433	1221	1220	2.21	58
261	A0334270006S02E180341803960	14	G3	1979	69	8.21	30.25	-97.252	39.536	1240	1230	0.18	49
262	A0334280007S02E100314302590	14	G3	1979	92	13.73	33.51	-97.192	39.456	1225	1223	1.35	57
263	A0336400007S02E100422694856	14	G3	1979	183	13.57	33.08	-97.200	39.458	1230	1223	0.98	57
264	A0336420006S01E110339401300	14	G3	1979	87	7.25	28.75	-97.280	39.550	1248	1255	0.36	45
265	A0346990005S01W340303604300	15	G3	1980	128	5.93	21.19	-97.422	39.568	1289	1283	0.69	32
266	A0347490005S03W340639301755	15	G3	1980	56	5.26	9.67	-97.637	39.577	1339	1344	0.98	14
267	A0347490005S03W340540451950	15	G3	1980	56	5.23	9.63	-97.638	39.578	1339	1344	0.97	14

268	A0349640007S02E2707NWSWSE	14	G3	1981	180	16.81	33.56	-97.198	39.417	1216	1219	0.85	62
269	A0351140005S03W220139602050	15	G3	1981	76	3.25	9.61	-97.638	39.606	1350	1340	0.79	14
270	A0352880006S01E0111NESWNW	14	G3	1981	143	6.31	29.19	-97.264	39.562	1266	1253	0.33	47
271	A0355260007S02E080142503090	14	G3	1981	10	13.2	31.41	-97.231	39.464	1215	1210	0.02	56
272	A0356610006S01E140500202440	14	G3	1981	131.5	9	28.54	-97.284	39.524	1259	1260	0.93	45
273	A0356990006S01E150112000050	14	G3	1981	48	8.77	27.99	-97.294	39.528	1263	1270	0.82	44
274	A0357890007S02E040536003800	14	G3	1981	109	12.32	32.28	-97.215	39.476	1228	1236	0.39	55
275	A0357900006S02E310339600050	14	G3	1981	201	11.25	30.99	-97.239	39.492	1241	1230	0.34	53
276	A0357930006S01E040200701500	14	G3	1981	255	6.99	26.72	-97.318	39.553	1259	1260	0.32	43
277	A0357940006S01E090129000080	14	G3	1981	170	7.45	26.98	-97.313	39.547	1258	1260	0.25	43
278	A0360600008S03E070844003800	14	G4	1982	368.2	19.17	36.28	-97.141	39.377	1205	1185	0.54	71
279	A0364940005S01W260335201700	15	G4	1983	49.96	4.33	22.68	-97.393	39.591	1285	1292	0.61	35
280	A0365700005S03W250146405210	15	G3	1983	151	4.12	11.01	-97.612	39.594	1332	1332	0.15	16
281	A0365930007S02E270826603590	14	G3	1983	160	16.5	33.32	-97.196	39.416	1220	1219	0.73	62
282	A0366890006S01E230425001300	14	G3	1983	99	9.53	28.75	-97.280	39.517	1256	1258	1.21	50
283	A0367320006S01W040406303930	15	G3	1983	45	6.88	20.26	-97.439	39.555	1351	1319	1.16	32
284	A0368630007S02E160144002800	14	G3	1983	221	14.17	32.47	-97.211	39.450	1215	1215	0.33	58
285	A0371470007S02E260539602660	14	G3	1984	90	16.25	34.5	-97.174	39.419	1215	1217	1.88	62
286	A0381230006S01E050145505150	14	G3	1986	103	6.14	25.02	-97.349	39.565	1265	1265	0.56	42
287	A0381600005S03W340639301755	15	G3	1986	40	5.26	9.67	-97.637	39.577	1339	1344	0.98	14
288	A0381600005S03W340540451950	15	G3	1986	40	5.23	9.63	-97.638	39.578	1339	1344	0.97	14
289	A0382440005S02W210318355240	15	G3	1986	108	3.65	14.01	-97.556	39.600	1323	1325	0.84	19
290	A0383030007S02E150339800700	14	G3	1986	68	14.25	33.87	-97.185	39.448	1225	1225	1.72	58
291	A0385250006S01E240512501000	14	G3	1987	192	9.76	29.81	-97.260	39.513	1250	1251	0.22	50
292	A0385340008S02E010552501470	14	G3	1987	110	18.01	35.72	-97.151	39.394	1205	1204	1.28	66
293	A0385350008S02E020246500100	14	G3	1987	113	18.12	34.98	-97.165	39.392	1208	1210	0.52	66
294	A0385370008S02E020339501200	14	G3	1987	102	18.25	34.77	-97.169	39.391	1210	1210	0.28	66
295	A0386370007S02E160217950059	14	G3	1987	100	14.66	32.99	-97.202	39.443	1225	1215	1.01	58
296	A0386800007S02E210539601320	14	G3	1987	109	15.25	32.75	-97.206	39.434	1210	1210	0.97	58
297	A0387240007S02E220509603940	14	G3	1988	180	15.82	33.25	-97.197	39.426	1220	1218	0.84	62
298	A0387540005S01W350139603960	15	G3	1988	158	5.25	22.25	-97.401	39.578	1280	1280	0.24	36
299	A0388180006S01E030335404020	14	G3	1988	17	6.33	27.24	-97.308	39.562	1259	1261	1.12	44
300	A0389240008S02E110637400205	14	G3	1988	320	19.29	34.96	-97.166	39.376	1210	1170	0.47	67
301	A0390310007S02E200123200030	14	G3	1988	95	15.56	31.99	-97.219	39.429	1212	1210	0.58	60
302	A0390370007S02E150417002640	14	G3	1988	152	14.68	33.5	-97.192	39.442	1225	1225	1.48	58
303	A0390900007S02E220827383965	14	G3	1988	120	15.48	33.25	-97.197	39.430	1221	1218	1.01	58
304	A0391060006S01E060452404950	14	G3	1988	127	6.01	24.06	-97.367	39.567	1275	1270	0.37	39
305	A0391460006S01W050413201320	15	G3	1988	198	6.75	19.75	-97.448	39.557	1325	1330	1.1	32
306	A0392040005S03W230403501330	15	G3	1989	120	3.93	10.75	-97.617	39.596	1335	1340	0.38	15
307	A0393060007S02E340651501250	14	G3	1989	61.4	17.02	33.76	-97.188	39.408	1215	1200	0.92	63
308	A0393420008S02E020517002150	14	G3	1989	68	18.68	34.59	-97.172	39.385	1211	1210	0.25	66
309	A0393540007S02E280246201340	14	G3	1989	85	16.13	32.75	-97.206	39.421	1205	1190	0.26	62
310	A0393840005S03W240517005000	15	G3	1989	156	3.68	11.05	-97.612	39.600	1360	1350	0.56	17
311	A0394480007S02E230415003850	14	G3	1989	92	15.72	34.27	-97.178	39.427	1210	1220	1.82	62
312	A0395090007S02E150539705230	14	G3	1989	102	14.25	33.01	-97.201	39.448	1225	1225	0.88	58
313	A0398130005S03W250250003980	15	G3	1989	165	4.05	11.25	-97.608	39.595	1330	1332	0.26	16
314	A0398410006S01E240752403455	14	G3	1990	43	9.01	29.35	-97.269	39.524	1255	1251	0.63	50
315	A0398720005S03W220717401110	15	G3	1990	42.5	3.67	9.79	-97.635	39.600	1335	1340	0.42	14
316	A0398720005S03W220618101040	15	G3	1990	42.5	3.66	9.8	-97.635	39.600	1335	1340	0.42	14
317	A0398720005S03W220518800970	15	G3	1990	42.5	3.64	9.82	-97.635	39.601	1340	1340	0.5	14
318	A0398720005S03W220419500900	15	G3	1990	42.5	3.63	9.83	-97.634	39.601	1340	1340	0.5	14
319	A0399050005S03W220330150035	15	G3	1990	72	3.43	9.99	-97.631	39.604	1350	1340	0.76	14
320	A0399320005S03W240810103960	15	G3	1990	45	3.81	11.25	-97.608	39.598	1334	1350	0.46	17
321	A0399520005S03W250146405210	15	G3	1990	110	4.12	11.01	-97.612	39.594	1332	1332	0.15	16

322	A0399530005S02W200530823082	15	G3	1990	47.5	3.42	13.42	-97.567	39.604	1339	1330	0.42	19
323	A0399530005S02W200430822658	15	G3	1990	47.5	3.42	13.5	-97.565	39.604	1340	1330	0.49	19
324	A0399530005S02W201026583082	15	G3	1990	47.5	3.5	13.42	-97.567	39.603	1339	1330	0.37	19
325	A0399530005S02W200926582658	15	G3	1990	47.5	3.5	13.5	-97.565	39.603	1335	1330	0.45	19
326	A0400850005S02W200603504000	15	G3	1990	148.5	3.93	13.24	-97.570	39.596	1323	1330	0.07	19
327	A0400910005S03W281329004100	15	G3	1990	407	4.45	8.22	-97.665	39.589	1344	1330	0.18	13
328	A0400970007S02E271000305240	14	G3	1990	189	16.99	33.01	-97.201	39.409	1200	1219	0.29	62
329	A0401470006S02E290215000600	14	G3	1990	135	10.72	31.89	-97.222	39.499	1232	1230	0.44	52
330	A0401500006S02E290949001650	14	G3	1990	80	10.07	31.69	-97.226	39.509	1230	1230	0.4	52
331	A0401610007S02E340739604630	14	G3	1990	212	17.25	33.12	-97.200	39.405	1200	1200	0.35	63
332	A0403160006S01E110339401300	14	G3	1991	111	7.25	28.75	-97.280	39.550	1248	1255	0.36	45
333	A0404090005S03W360906752050	15	G3	1991	27	5.87	11.61	-97.600	39.568	1360	1346	1.5	16
334	A0404490005S01W270233501100	15	G3	1991	95	4.37	21.79	-97.410	39.591	1300	1288	0.25	34
335	A0405290007S02E180500500650	14	G3	1991	150	14.99	30.88	-97.240	39.438	1235	1245	0.26	59
336	A0406480005S03W360144502600	15	G3	1992	50	5.16	11.51	-97.602	39.579	1340	1346	0.74	16
337	A0406520005S02W300203003960	15	G3	1992	80	4.94	12.25	-97.589	39.582	1326	1325	0.8	16
338	A0406540007S02E040610002000	14	G2	1992	18	12.81	32.62	-97.208	39.469	1235	1236	0.61	55
339	A0406590005S01W290226503820	15	G3	1992	100	4.5	19.28	-97.457	39.588	1293	1295	0.43	31
340	A0406780005S03W260304703000	15	G3	1992	37.5	4.91	10.43	-97.623	39.582	1340	1335	0.31	15
341	A0406790005S03W260419804290	15	G3	1992	19.5	4.63	10.19	-97.627	39.586	1340	1335	0.16	15
342	A0411740007S02E040712500850	14	G2	1993	3.71	12.76	32.84	-97.204	39.470	1232	1236	0.82	55
343	A8891150008S02E020424004750	14	G2	1988	335	18.55	34.1	-97.182	39.386	1192	1210	0.15	66
344	A889116HD05S03W260207263564	15	G9	1988	413.5	4.86	10.32	-97.625	39.583	1340	1335	0.29	15
345	A889116IN05S03W260207263564	15	G2	1988	67.5	4.86	10.32	-97.625	39.583	1340	1335	0.29	15
346	A889117HD08S02E020624004750	14	G9	1988	557.4	18.55	34.1	-97.182	39.386	1192	1210	0.15	66
347	A889117IN08S02E020624004750	14	G2	1988	25.6	18.55	34.1	-97.182	39.386	1192	1210	0.15	66
348	A9491920008S03E071148001250	14	GA	1994	161	19.09	36.76	-97.132	39.378	1200	1185	0.82	71
349	A9590180008S03E071335500350	14	GA	1995	322	19.33	36.93	-97.129	39.375	1198	1185	0.47	71


Ground Water Rights through 1995 Within Active Grid
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Column

APPENDIX 3B3

November 1994 ground-water-level survey data

Appendix 3.B.3. November 1994 ground water level survey data

id	row	col	row	col	SurfElev	dtw	GwElev	EstErr	Legal	locat	Subd	label	QuadMap	long(deg)	lat(deg)	north	west
1	1	4	0.59	3.59	1393	12.13	1380.9	1.08	5 S	4 W 3	dbbd	s2	KACKLEY	-97.7514	39.6450	2145.	2145.
2	1	4	0.97	3.34	1381	7.51	1373.5	1.08	5 S	4 W 3	cdcd	s2a	KACKLEY	-97.7560	39.6396	165.	3465.
3	0	3	-0.06	2.19	1386	9.60	1376.4	1.08	4 S	4 W 33	ccd	s5a	KACKLEY	-97.7777	39.6546	330.	4290.
4	2	2	1.66	1.91	1392	19.80	1372.2	2.08	5 S	4 W 8	dadb	s6a	KACKLEY	-97.7829	39.6297	1815.	495.
5	3	2	2.03	1.97	1389	14.05	1375.0	1.17	5 S	4 W 17	aaaa	s6b	JAMESTOWN	-97.7817	39.6243	5115.	165.
6	3	3	2.03	2.97	1380	9.32	1370.7	1.67	5 S	4 W 16	aaaa	s9a	JAMESTOWN	-97.7630	39.6242	5115.	165.
7	4	4	3.03	3.59	1380	12.92	1367.1	1.08	5 S	4 W 22	abba	s10	JAMESTOWN	-97.7513	39.6096	5115.	2145.
8	1	4	0.97	3.59	1385	18.60	1366.4	1.08	5 S	4 W 3	dccd	s1a	CONCORDIA NW	-97.7514	39.6396	165.	2145.
9	4	10	3.53	9.97	1337	8.45	1328.6	1.50	5 S	3 W 22	daaa	55	CONCORDIA	-97.6317	39.6021	2475.	165.
10	4	7	3.09	6.34	1370	13.25	1356.8	1.08	5 S	3 W 19	babd	50	CONCORDIA	-97.6997	39.6086	4785.	3465.
11	3	5	2.66	4.84	1365	8.09	1356.9	1.08	5 S	4 W 14	daca	s7	CONCORDIA	-97.7279	39.6151	1815.	825.
12	4	6	3.59	5.03	1362	11.61	1350.4	1.08	5 S	4 W 24	cbbc	s12a	CONCORDIA	-97.7242	39.6015	2145.	5115.
13	3	4	2.16	3.59	1375	8.98	1366.0	1.08	5 S	4 W 15	abca	s8	JAMESTOWN	-97.7513	39.6223	4455.	2145.
14	3	7	2.97	6.16	1375	22.00	1353.0	1.08	5 S	3 W 18	ccdc	47	CONCORDIA	-97.7032	39.6104	165.	4455.
15	3	7	2.47	6.03	1382	25.33	1356.7	1.08	5 S	3 W 18	bccc	47a	CONCORDIA	-97.7056	39.6177	2805.	5115.
16	3	6	2.72	5.97	1377	27.30	1349.7	1.08	5 S	4 W 13	dadd	47b	CONCORDIA	-97.7067	39.6141	1485.	165.
17	4	7	3.84	6.66	1359	11.92	1347.1	1.08	5 S	3 W 19	dcac	49	CONCORDIA	-97.6939	39.5976	825.	1815.
18	4	8	3.78	7.66	1350	8.50	1341.5	1.08	5 S	3 W 20	dcab	49a	CONCORDIA	-97.6752	39.5983	1155.	1815.
19	4	9	3.03	8.28	1370	41.96	1328.0	1.08	5 S	3 W 21	babb	49b	CONCORDIA	-97.6637	39.6092	5115.	3795.
20	4	8	3.09	7.03	1370	21.67	1348.3	1.08	5 S	3 W 20	bbbc	49c	CONCORDIA	-97.6869	39.6084	4785.	5115.
21	4	16	3.66	15.47	1312	12.26	1299.7	2.08	5 S	2 W 22	cada	21a	RICE	-97.5279	39.6004	1815.	2805.
22	6	17	5.28	16.03	1323	22.54	1300.5	1.08	5 S	2 W 35	bcbb	39a	RICE	-97.5169	39.5769	3795.	5115.
23	6	14	5.53	13.53	1335	25.73	1309.3	1.08	5 S	2 W 32	dbbb	39b	RICE	-97.5641	39.5732	2475.	2475.
24	4	15	3.72	14.03	1320	13.55	1306.5	1.08	5 S	2 W 21	cbcc	17a	RICE	-97.5550	39.5993	1485.	5115.
25	5	13	4.91	12.22	1327	9.97	1317.0	4.00	5 S	2 W 30	ccda	69a	RICE	-97.5891	39.5823	495.	4125.
26	4	12	3.91	11.03	1333	13.92	1319.1	3.00	5 S	3 W 24	cccb	27a	RICE	-97.6118	39.5967	495.	5115.
27	4	12	3.84	11.41	1330	14.40	1315.6	1.08	5 S	3 W 24	cdac	27b	RICE	-97.6048	39.5976	825.	3135.
28	5	18	4.53	17.03	1317	19.32	1297.7	1.08	5 S	2 W 25	cbbb	24a	CLYDE	-97.4984	39.5878	2475.	5115.
29	5	20	4.16	19.03	1294	10.16	1283.8	1.08	5 S	1 W 29	bbcb	A	CLYDE	-97.4615	39.5933	4455.	5115.
30	5	22	4.41	21.59	1288	9.13	1278.9	1.08	5 S	1 W 27	acca	Cc	CLYDE	-97.4137	39.5900	3135.	2145.
31	6	23	5.09	22.22	1280	9.09	1270.9	1.08	5 S	1 W 35	bbad	Cd	CLYDE	-97.4019	39.5800	4785.	4125.
32	7	23	6.09	22.59	1280	9.18	1270.8	1.08	6 S	1 W 2	abbd	Ce	CLYDE	-97.3947	39.5657	4785.	2145.
33	6	22	5.91	21.53	1285	11.08	1273.9	1.08	5 S	1 W 34	dccb	Da	CLYDE	-97.4149	39.5681	495.	2475.
34	6	20	5.84	19.53	1307	24.22	1282.8	1.08	5 S	1 W 32	dcbc	Db	CLYDE	-97.4524	39.5688	825.	2475.
35	5	23	4.47	22.84	1291	50.00	1241.0	1.08	5 S	1 W 26	adcd	Ca	CLYDE	-97.3901	39.5891	2805.	825.
36	4	22	3.03	21.72	1308	49.67	1258.3	1.08	5 S	1 W 22	abaa	Cb	CLYDE	-97.4113	39.6100	5115.	1485.
37	9	31	8.72	30.16	1245	15.06	1229.9	1.58	6 S	2 E 18	cbdc	R9a	CLIFTON	-97.2536	39.5282	1485.	4455.
38	9	31	8.84	30.22	1245	14.63	1230.4	1.08	6 S	2 E 18	ccad	R9b	CLIFTON	-97.2524	39.5264	825.	4125.
39	9	30	8.47	29.22	1259	28.95	1230.1	1.08	6 S	1 E 13	bcdd	5	CLIFTON	-97.2711	39.5318	2805.	4125.
40	9	30	8.22	29.53	1248	16.43	1231.6	1.08	6 S	1 E 13	abcc	5a	CLIFTON	-97.2652	39.5354	4125.	2475.

Appendix 3.B.3. (continued)

id	row	col	row	col	SurfElev	dtw	GwElev	EstErr	Legal	locat	Subd	label	QuadMap	long(deg)	lat(deg)	north	west
41	9	29	8.97	28.53	1259	26.54	1232.5	1.58	6 S	1 E 14	dccc	C4	CLIFTON	-97.2838	39.5245	165.	2475.
42	10	29	9.47	28.16	1265	31.52	1233.5	1.08	6 S	1 E 23	bcdc	C4a	CLIFTON	-97.2907	39.5174	2805.	4455.
43	10	30	9.22	29.22	1253	25.51	1227.5	1.08	6 S	1 E 24	bbdd	C4b	CLIFTON	-97.2710	39.5209	4125.	4125.
44	7	29	6.22	28.53	1264	18.53	1245.5	1.17	6 S	1 E 2	abcc	C3a	CLIFTON	-97.2834	39.5638	4125.	2475.
45	8	28	7.28	27.47	1255	8.98	1246.0	1.08	6 S	1 E 10	bdaa	21a	CLIFTON	-97.3036	39.5492	3795.	2805.
46	8	27	7.03	26.66	1262	9.04	1253.0	1.75	6 S	1 E 9	abab	21b	CLIFTON	-97.3188	39.5527	5115.	1815.
47	8	28	7.34	27.03	1259	10.14	1248.9	1.75	6 S	1 E 10	bcbc	21c	CLIFTON	-97.3118	39.5482	3465.	5115.
48	6	28	5.97	27.53	1274	23.73	1250.3	1.08	5 S	1 E 34	dccc	21d	CLIFTON	-97.3021	39.5673	165.	2475.
49	7	26	6.09	25.03	1267	12.82	1254.2	1.42	6 S	1 E 5	bbbc	C1a	CLIFTON	-97.3491	39.5656	4785.	5115.
50	7	25	6.47	24.53	1269	8.64	1260.4	1.17	6 S	1 E 6	accc	C1b	CLIFTON	-97.3585	39.5603	2805.	2475.
51	7	25	6.03	24.09	1275	13.23	1261.8	1.08	6 S	1 E 6	bbba	C1c	CLIFTON	-97.3666	39.5666	5115.	4785.
52	10	32	9.78	31.03	1236	11.08	1224.9	1.08	6 S	2 E 20	ccbb	R14a	LINN SW	-97.2376	39.5129	1155.	5115.
53	10	31	9.28	30.66	1240	14.56	1225.4	1.08	6 S	2 E 19	acab	R14b	LINN SW	-97.2445	39.5201	3795.	1815.
54	18	34	17.22	33.03	1200	10.17	1189.8	1.08	7 S	2 E 34	bbcc	97	CLAY CTR NW	-97.2012	39.4054	4125.	5115.
55	17	33	16.97	32.97	1198	11.71	1186.3	1.08	7 S	2 E 28	dddd	97a	CLAY CTR NW	-97.2023	39.4090	165.	165.
56	17	34	16.78	33.47	1218	24.25	1193.8	1.08	7 S	2 E 27	cdaa	90	CLAY CTR NW	-97.1929	39.4116	1155.	2805.
57	18	34	17.03	33.72	1215	23.43	1191.6	1.08	7 S	2 E 34	abaa	90a	CLAY CTR NW	-97.1883	39.4080	5115.	1485.
58	17	34	16.84	33.97	1215	25.67	1189.3	1.08	7 S	2 E 27	ddad	90b	CLAY CTR NW	-97.1836	39.4107	825.	165.
59	18	34	17.28	33.97	1209	19.90	1189.1	1.08	7 S	2 E 34	adaa	90c	CLAY CTR NW	-97.1837	39.4043	3795.	165.
60	18	34	17.84	33.97	1201	19.70	1181.3	1.08	7 S	2 E 34	ddad	90d	CLAY CTR NW	-97.1839	39.3962	825.	165.
61	19	35	18.03	34.91	1209	29.10	1179.9	1.08	8 S	2 E 2	aaab	201	CLAY CTR NW	-97.1664	39.3935	5115.	495.
62	19	36	18.31	35.69	1203	24.25	1178.7	1.08	8 S	2 E 1	aca	200	CLAY CTR NW	-97.1517	39.3894	3630.	1650.
63	19	36	18.28	35.28	1206	25.65	1180.4	1.08	8 S	2 E 1	bdbb	200a	CLAY CTR NW	-97.1594	39.3899	3795.	3795.
64	19	36	18.72	35.28	1207	24.78	1182.2	1.08	8 S	2 E 1	cacc	200b	CLAY CTR NW	-97.1595	39.3838	1485.	3795.
65	19	36	18.03	35.72	1205	24.59	1180.4	1.08	8 S	2 E 1	abaa	200c	CLAY CTR NW	-97.1511	39.3934	5115.	1485.
66	16	34	15.22	33.91	1220	17.46	1202.5	1.08	7 S	2 E 22	aadc	79	CLAY CTR NW	-97.1845	39.4342	4125.	495.
67	15	33	14.22	32.41	1215	10.17	1204.8	1.08	7 S	2 E 16	badc	70	CLAY CTR NW	-97.2121	39.4489	4125.	3135.
68	15	33	14.72	32.97	1225	17.67	1207.3	1.08	7 S	2 E 16	dadd	70a	CLAY CTR NW	-97.2020	39.4415	1485.	165.
69	15	34	14.69	33.44	1223	17.13	1205.9	1.08	7 S	2 E 15	cad	64	CLAY CTR NW	-97.1932	39.4420	1650.	2970.
70	15	34	14.34	33.03	1225	16.13	1208.9	1.08	7 S	2 E 15	bcbc	64a	CLAY CTR NW	-97.2008	39.4470	3465.	5115.
71	14	35	13.94	34.06	1227	15.00	1212.0	1.08	7 S	2 E 11	ccc	57a	CLAY CTR NW	-97.1815	39.4528	330.	4950.
72	14	35	13.47	34.03	1231	18.08	1212.9	1.08	7 S	2 E 11	bccc	57n	CLAY CTR NW	-97.1820	39.4596	2805.	5115.
73	13	33	12.72	32.34	1240	25.67	1214.3	2.08	7 S	2 E 4	cacd	51a	CLAY CTR NW	-97.2134	39.4705	1485.	3465.
74	13	34	12.34	33.03	1235	20.90	1214.1	1.08	7 S	2 E 3	bcbc	51b	CLAY CTR NW	-97.2007	39.4758	3465.	5115.
75	17	36	16.97	35.09	1210	26.14	1183.9	1.08	7 S	2 E 25	cccd	85	CLAY CTR NW	-97.1625	39.4087	165.	4785.
76	21	36	20.69	35.81	1198	13.25	1184.8	1.08	8 S	2 E 13	dac	216	CLAY CTR SW	-97.1497	39.3556	1650.	990.
77	20	36	19.59	35.53	1200	29.44	1170.6	5.08	8 S	2 E 12	dbbc	213	CLAY CTR SW	-97.1550	39.3712	2145.	2475.
78	20	36	19.28	35.53	1205	27.38	1177.6	1.08	8 S	2 E 12	acbb	213a	CLAY CTR NW	-97.1549	39.3757	3795.	2475.
79	20	36	19.03	35.53	1205	26.75	1178.3	1.08	8 S	2 E 12	abbb	213b	CLAY CTR NW	-97.1549	39.3793	5115.	2475.
80	21	36	20.56	35.56	1190	12.18	1177.8	1.08	8 S	2 E 13	dbb	W	CLAY CTR SW	-97.1544	39.3574	2310.	2310.

APPENDIX 3C

Various Crop Acreages in Clay and Cloud Counties based on "Kansas Farm Facts"

Table 3C. Various Crop Acreages in Clay and Cloud Counties based of Kansas Farm Facts.

	CLAY	CLOUD	CLAY	CLOUD	CLAY	CLOUD	CLAY	CLOUD	CLAY	CLOUD	CLAY	CLOUD
year	Wheat (acres) planted, harvested, irrigated		Sorghum (acres) planted, harvested, irrigated		Corn (acres) planted, harvested, irrigated		Soybeans (acres) harvested		Alfalfa Hay (acres) harvested		All other Hay (acres harvested	
77	117000 103000 -	173000 152000 -	78000 72000 -	58000 57400 1900	12500 12300 9500	9200 8800 5400	4900	1800	10400	10700	12900	8700
78	94000 91500 -	135000 131200 -	73000 71200 2000	59000 58700 4100	16000 9000 8100	11400 11000 9800	9200	9000	9500	11000	15400	7000
79	103000 99400 100	146000 144100 100	56000 55400 1100	49000 48900 4000	11300 11100 9000	9400 9300 7600	11000	4400	10000	15700	12000	8000
80	117000 107000	163000 157000	56000 42000 1600	53000 28000 2700	15600 15600 9300	11500 11500 7700	12300	6500	8000	15300	12600	8400
81	133000 123900	180000 163300	34300 33300 1600	33800 31000 2400	10000 10000 6600	9500 9500 7900	14000	6900	8000	13900	6400	5400
82	135000 126000 500	194000 180000 1800	35000 34500 1600	25100 24700 1400	10500 10300 9100	8800 8300 5500	15000	10800	11900	14000	11100	6900
83	120000 112700 400	182000 155400 500	39300 37300 1000	25900 23800 2400	9700 9100 6200	10000 9800 7100	11700	7600	9900	13200	14400	9400
84	128000 116500 1000pl	157000 149200 1500	33000 32800 1700	42000 38700 4500	9200 9100 6800	8000 7500 6100	16000 14200 3600	8000 7400 2800	10100	13200	14600	10500
85	107000 102400	152000 150500 500	38400 38400 2000	42800 42800 5800	9500 9500 6300	6800 6800 6300	12800 11400 4500	4800 4800 2000	11900	16200	16700	13700
86	99000 87500 -	141000 128700 500	36600 35200 2100	45500 43700 4100	1300 11100 8400	7500 7200 6500	14900 14300 4000	7700 7600 1600	8100	10200	15100	14000
87	90000 81700 300	130000 121000 2400	38300 36400 1500	44000 42100 4000	9400 8100 7900	5200 4700 4300	16500 16400 1800	8800 8800 1500	7300	10600	18500	11000
88	85000 81600 1000	121000 116400 1700	40000 39000 1300	38000 36600 1900	8300 6100 5500	7200 6700 5700	22000 20700 2900	12000 11400 2900	6000	10800	17500	13500
89	110000 30000 500p	142000 42000 1600p	42000 37500 800	40000 37700 1900	8200 6800 6300	8300 8100 7700	34000 32900 4700	13500 11600 1800	5900	10000	15100	13600
90	105000 102000 100	140000 133000 600p	33000 31200 400	37000 35500 1500	12500 11000 7900	11600 11100 8200	35200 34800 6500	16500 16500 3700	6100	12000	19000	14200
91	99000 94500 -	135000 128200 200	40000 38500 400	39000 3400 1500	11200 9200	13700 11400	27900 27100 6500	13000 12200 3300	7800	10000	17000	11800
92	105000 95500 -	137000 109400 -	46000 43700 400	45000 43400 1800	9900 9100 7700	11400 11000 9800	24300 24200 4000	11000 10800 1600	9100	12400	17700	11900
93	114000 99400 -	148000 107700 -	48400 44200 300	45200 40600 1900	11300 9500 8400	14400 12500 9200	28200 24900 5900	12000 10400 2500	9100	12400	18300	12300
94	93000 92400 200	126800 123800 200	53000 51600 200	60000 59000 1800	11500 10400 8500	14600 13800 10700	40000 39000 7200	19000 18600 3600	9000	12200	24500	25200

APPENDIX 5B

Summaries and Assessment of Selected Models

Initial Assessment of Selected Stream-Aquifer and Watershed Models

(i) Stream-Aquifer Models

1. **MAEP** (Ozbilgin and Dickerman, 1986). **Modified Aquifer Evaluation Program**

Model Summary Description: The Trescott, Pinder, and Larson (1976) two-dimensional finite-difference program USGS-2D Flow (which simulates steady and transient ground-water flow in an irregularly shaped, heterogeneous and anisotropic aquifer that can be a confined or unconfined aquifer or both) assumes that the water level in streams in hydraulic connection with an aquifer are not appreciably affected by the flow between the streams and the aquifer. That model was modified to enable simulation of the interaction between surface-water and ground-water systems subject to variable rates of stream flow and stage levels. Modifications were designed to allow calculation of surface-water heads and flow either to or from contiguous surface-water bodies in response to imposed stresses; and to allow more convenient data input.

Arrays were added or rearranged in the modified program so that recharge, evapotranspiration, inflow to surface-water bodies, number of wells, pumping rate, and duration of pumping could be varied for any time period. The Manning formula was used to relate stream depth and discharge in surface water streams. The interaction between surface water and ground water is represented through the leakage term which is included in both the ground-water flow and surface-water mass balance equations.

The modified program has been tested under a variety of conditions simulated for idealized aquifers. It has been used to develop a field model of a stream-pond-aquifer system in the Beaver-Pasquiset ground-water reservoir in southern Rhode Island. Numerical results from the modified program were in good agreement with published analytical results.

Model Summary Critique: This model is now dated. It is superseded by the actively-supported USGS MODFLOW program with the Streamflow Routing Package (see below). Until recently, the USGS-2D flow model was one of the most used ground-water flow models for two-dimensional problems.

2. **TRACY 2D-FE** (Dunlap et al., 1984) **Two-Dimensional Finite Element Galerkin Model** developed by J.V. Tracy.

Model Summary Description: This model simulates steady and non-steady two-dimensional ground-water flow in an irregularly shaped confined or unconfined aquifer. The aquifer's transmissive and storage properties may be heterogeneous. The model accounts for gains and losses from the river flow in each reach based on the incoming river and tributary flows and the gain from or loss to the aquifer in the reach. With an estimate of river discharge, the river stage is computed for each reach using an input stage-discharge relationship given for each reach. The river-aquifer gains and losses are calculated as a function of streambed area, riverbed leakance, and the head gradient between the river and the aquifer. Evapotranspiration from ground water is estimated using monthly values of precipitation, applied water rate, evapotranspiration demand, the moisture capacity of the soil zone, and depth of root zone. Well discharges can vary monthly. Specified flux and specified head boundaries can be simulated.

A "regular" finite element grid is used in the simulation i.e., the region is subdivided by a given number of columns, each of which has an equal number of elements, where the columns need not be parallel or of the same lengths. The effect is of a deformed rectangular grid. Applying the Galerkin method results in an associated matrix which is solved using a direct method. Mass balances are computed for each time step and the cumulative simulation period. This model has been applied to the Arkansas River Valley in southwestern Kansas.

Model Summary Critique: This model is also dated, with limited or non-existent support. It is superseded by MODFLOW (see below).

3. **MODFLOW** (McDonald and Harbaugh, 1988). **A Modular Three-Dimensional Finite Difference Ground-Water Flow Model.**

Model Summary Description: MODFLOW is a modular three-dimensional finite-difference flow code developed by the USGS. MODFLOW can simulate fully three-dimensional systems and quasi-three-dimensional anisotropic, heterogeneous and layered systems in which flow in aquifers is horizontal and flow through confining beds in vertical. The code can also be used to simulate flow in two dimensions either in one horizontal layer or in a cross section. The model is based on a block-centered finite difference approach, using variable grid spacing in x-, y-, and z- directions. The model can simulate confined, unconfined, or conditions convertible between the two. The model can also handle layers that pinch out. MODFLOW has been used in numerous applications, many of which are documented in USGS Water-Supply Paper, Professional Papers, and Water-Resources Investigations Reports.

The code permits the user to select a series of packages (or modules) to be used during a given simulation. The packages include three equation-solver packages, stream packages, a recharge package, and packages to simulate pumping or injection wells, drains, and evapotranspiration from the water table.

Options set in an output control module allow the user to specify the print format of the head and/or drawdown arrays and to request printout of the water balance. Water balance output includes a summary statement of total flows to and from the system. If desired, flows to specified head nodes and discharges via pumping and evapotranspiration can also be printed. Preprocessors available for MODFLOW include PM and MODINP from the Scientific Software Group, PREPRO3FLO and PREMOD from GeoTrans, Inc., and Model-CAD from Geraghty and Miller, Inc. Postprocessors include PM and MODGRAF from the Scientific Software Group, POSTMOD from IGWMC, a statistical package from the USGS, contouring packages provided with some versions of the code, and the particle-tracking codes MODPATH (Pollock, D.W., 1989) and PATH3D (Zheng, C., 1991). These particle-tracking codes calculate ground-water paths and travel times in two or three-dimensional flow fields. They can be used to simulate the movement of ground-water and the advection of contaminant solutes in ground-water. In addition a number of parameter estimation packages exist (MODFLOWP, MODINV, and others) that can be used with MODFLOW to improve model construction and calibration.

MODFLOW is written in strict FORTRAN 77. It runs on all computers that have a FORTRAN 77 compiler. It has been run without modification on many different types of mainframes, minicomputers, and workstations. It also has been run without modification on IBM and Apple personal computers and their clones. The allowable size of a problem, as measured by the number of finite-difference cells, depends on the size of MODFLOW's X array, which can be set at compilation time. On 8088 and 80286 computers, the practical limit is about 8000 cells. Extended-memory versions have no theoretical limits. Because of our interest in stream-aquifer relations, the Streamflow Routing Package (STREAM) of MODFLOW is highlighted here.

The STREAM Routing Package (Prudic, 1989) was written to account for the amount of flow in streams and to simulate the interaction between surface streams and ground water. The Streamflow-Routing Package is an accounting program that tracks the flow in one or more streams which interact with ground water. It permits two or more streams to merge into one with flow in the merged stream equal to the sum of the tributary flows. The program also permits diversions from streams.

Streams are divided into segments and reaches. Each reach corresponds to individual cells in the finite-difference grid used to simulate ground-water flow. A segment consists of a group of reaches connected in downstream order. Leakage is calculated for each reach on the basis of the head difference between the stream and aquifer and a conductance term. It is subtracted or added to the amount of streamflow into the reach. The stage in each reach can be computed using the Manning formula under the assumption of a rectangular stream channel.

The amount of leakage in each reach (either into or out of the aquifer) is incorporated into the ground-water flow model by adding terms to the finite-difference equations. Recharge to the aquifer in a reach ceases when all the streamflow in upstream reaches has leaked into the aquifer and the stream is dry. A stream is permitted to flow again in downstream reaches if the head in the aquifer is above the elevation of the streambed.

Results from the program have been compared to results from two analytical solutions. One assumes time varying areal recharge to the aquifer and discharge only to a stream and the other assumes recharge to the aquifer from a change in stream stage. Results from the program reasonably duplicated the analytical solutions. In addition, several field applications of MODFLOW with the stream package are documented by the USGS and other agencies.

The ground-water flow model with the Streamflow-Routing Package has an advantage over the analytical solution in simulating the interaction between aquifer and stream because it can be used to simulate complex systems that cannot be readily solved analytically.

The Streamflow-Routing Package does not include a time function for streamflow but rather streamflow entering the modeled area is assumed to be instantly available to downstream reaches during each time period. This assumption is generally reasonable because of the relatively slow rate of ground-water flow in comparison with the rate of flow in streams. Another assumption is that leakage between streams and aquifers is instantaneous. This assumption may not be reasonable if the streams and aquifers are separated by a thick unsaturated zone.

<u>Model Summary Critique</u>: MODFLOW is the most widely used and best supported numerical code available at present. Its flexible modular structure can handle a great variety of flow problems.

4. **MODBRANCH** (Swain and Wexler, 1993). **A Coupled Surface-Water and Ground-Water Flow Model for Simulation of Stream-Aquifer Interaction.**

<u>Model Summary Description</u>: This new coupled ground-water and surface-water model was developed by combining the U.S. Geological Survey models MODFLOW and BRANCH (Schaffranek et al., 1981); the interfacing code is referred to as MODBRANCH. MODFLOW is the widely used modular three-dimensional, finite-difference, ground-water model, and BRANCH is a one-dimensional, numerical model commonly used to simulate unsteady flow in open-channel networks.

MODFLOW was originally written with the River package that calculates leakage between the aquifer and stream, assuming that the stream's stage remains constant during one model stress period. A simple streamflow routing model has been added to MODFLOW, but it is limited to steady flow in rectangular, prismatic channels. To overcome these limitations, the BRANCH model, which simulates unsteady, nonuniform flow by solving the entire Saint-Venant equations, was restructured and incorporated into MODFLOW. Terms that describe leakage between stream and aquifer as a function of streambed conductance and differences in aquifer and stream stage were added to the continuity equation in BRANCH. Thus, leakage between the aquifer and stream can be calculated separately in each model, or leakages calculated in BRANCH can be used in MODFLOW. Total mass in the coupled models is accounted for and conserved.

The BRANCH model calculates new stream stages for each time interval in a transient simulation based on upstream boundary conditions, stream properties, and initial estimates of aquifer heads. Next, aquifer heads are calculated in MODFLOW based on stream stages calculated by BRANCH, aquifer properties, and stresses. This process is repeated until convergence criteria are met for head and stage. Because time steps used in ground-water modeling can be much longer than time intervals used in surface-water simulations, provision has been made for handling multiple BRANCH time intervals within one MODFLOW time step. An option was also added to BRANCH to allow the simulation of channel drying and rewetting. Testing of the coupled model was verified by using data from previous studies; by comparing results with output from a simpler, four-point implicit, open-channel flow model linked with MODFLOW; and by comparison to field studies of the L-31N canal in southern Florida.

Model Summary Critique: Although this model addresses the dynamic aspects of streamflow, the additional data requirements and the time scale of streamflow modeling, which is of the order of minutes, make its applicability to long-term (multi-year) simulations of interest in our study impractical.

(ii) Watershed Models

1. **BHS** (Green and Pogge, 1973). **Basin Hydrologic Simulator**

Model Summary Description: The Basin Hydrology Simulator is a digital computer model to simulate the hydrology of a stream basin. The model simulates both surface-water and ground-water phases and their interaction by combining the features of the watershed rainfall-runoff model known as the Kansas Water Budget Model (Smith and Lumb, 1966) and of ground-water flow simulators. Input to the model includes precipitation, climatic conditions, boundary and initial conditions, and basin constants. Provision has been made for modeling withdrawals from both groundwater and surface waters for consumptive use. The computer output includes streamflow hydrographs at selected points, groundwater levels, and summaries of important moisture fluxes. The model is designed to be general in nature so that it will be applicable to other basins with similar geographical and geological conditions.

The structure of the model is such that the basin is divided vertically into four layers and a stream network. Provision is also made to subdivide each layer horizontally into grids or subbasins. The groundwater grids are on the order of one-mile square, while the upper layers are divided into a few relatively large subbasins. The surface-layer subbasins are determined by considering topography, soil types, and climatic data.

In the surface layer, precipitation in each subbasin is divided into runoff and infiltration. Runoff is routed to the outflow point of the subbasin using a unit hydrograph for that subbasin. Water infiltrates from the surface layer to an upper soil zone where it is stored for later evapotranspiration or percolation into the lower soil zone. This upper soil zone is assumed to include the root zone of the shallow rooted annual plants.

The lower soil zone provides consumptive water for deeper rooted plants. It also feeds the stream through interflow and loses water to the aquifer through percolation.

The runoff and the interflow from the subbasin are gathered at the out-flow point of the subbasin. At this location water enters the stream network, which consists of nodes and reaches. Nodes represent locations where subbasins drain into the stream. The flows are routed through the reaches using the Muskingum routing method.

Water flow in the groundwater layer is assumed to be governed by the linear equation of ground-water flow. The equation is solved using the alternating direction implicit numerical technique.

Model Summary Critique: This model, although pioneering during its development time, is now dated and not maintained nor supported.

2. **SHE** (Abbott et al., 1986) **European Hydrologic System Model** (Systeme Hydrologique Europeen)

Model Summary Description: SHE is a physically-based, distributed-parameter catchment modeling system. The model considers the major hydrologic processes which govern water movement through a catchment, namely: snowmelt, canopy interception, evapotranspiration, overland flow, channel flow, and unsaturated and saturated subsurface flow. Spatial variability of hydrologic processes is described by using a rectangular grid of (x, y) points in the horizontal plane with vertical variation in properties represented by a series of horizontal planes of various depths.

SHE is applicable to a wide range of hydrologic processes and can be applied to a variety of hydrologic problems, including irrigation schemes, determination of landuse changes, water development studies, groundwater contamination, erosion and sediment transport, and flood prediction.

Model Summary Critique: SHE applications have been performed on mainframe computers. Applications of the program on PCs are limited due to the large number of computations that must be made. Because of its intensive data and computing requirements this model has not been considered suitable for our application.

3. **TOPMODEL** (Beven and Kirby, 1979) **TOPography-Based Hydrologic MODEL**

Model Summary Description: TOPMODEL is a topography-based hydrologic model derived from the variable contributing area theory. The inputs of the model are the hourly rainfall and potential evaporation, and the distribution of the topographical index derived from the digital terrain map of the catchment. The outputs are the hourly average and local soil moisture deficits below saturation, and the hourly discharge, separated into two components (surface runoff on the saturated area, and subsurface flow/groundwater discharge).

Model Summary Critique: This model has high temporal resolution input data requirements; in addition, vegetation and land management factors have not been explicitly considered. Because of these reasons, this model has not been considered further.

4. **HSPF** (Johanson et al., 1980) **Hydrological Simulation Program-Fortran**

Model Summary Description: The Hydrologic Simulation Program-Fortran (HSPF) model simulates both watershed hydrology and water quality. It allows an integrated simulation of land and soil contaminant runoff processes with in-stream hydraulic and sediment-chemical interactions. The program provides a time history of runoff rate, sediment load, and nutrient and pesticide concentration, along with a time history of water quality and quantity at specific points in a watershed.

HSPF computes a continuous hydrograph of stream flow at the basin outlet. Input is a continuous record of precipitation and evaporation data. Rainfall is distributed into interception loss, rainfall on impervious areas which contributes directly to runoff, and an infiltrated portion. The infiltration is divided into (1) surface runoff and interflow which moves through the upper soil zone to channel flow and (2) flow into the lower soil zone or groundwater storage which contributes to active and inactive groundwater storage. The model utilizes three soil moisture zones: an upper soil zone, a lower soil zone, and a groundwater storage zone. Rapid runoff is accounted for in the upper zone. Both the upper and lower zones influence factors such as overland flow, infiltration, and groundwater storage. Water that is computed as moving into the lower zone can move into deep groundwater storage, some of which can become base flow to the stream. Total stream flow is a combination of overland flow, interflow, and groundwater flow.

The program user must supply parameters for each of the various processes. More than 20 parameters are needed to describe merely the hydrological parameters, some of which cannot be directly measured (such as the various soil moisture parameters). Without calibration data, it can be difficult to verify the flows computed by this model.

Model Summary Critique: Although this model seems to meet a number of our requirements, it has been mainly applied to urban, as opposed to agricultural watersheds, and that seems to be its strength. A drawback of this model is that several parameters of the model are not physically based, therefore they cannot be estimated from readily available information. In addition, the model is so large that it is more suitable for execution on mainframe computers. For these reasons we have not pursued it further.

5. **SPAW** (Saxton et al., 1974) **Soil-Plant-Air-Water Model**

Model Summary Description: SPAW was developed to provide daily soil-water estimates on cultivated cropland in the Midwest. The model computes daily estimates of runoff, actual evapotranspiration and deep percolation. Runoff is estimated using the SCS curve number method. Water added to the soil is distributed based on pressure gradients and unsaturated conductivity of the soil. Potential evapotranspiration is computed using pan evaporation (actual or estimated) and a pan coefficient. Plant transpiration is a function of a canopy cover factor and a phenology factor. Soil evaporation is represented by an inclusion of a separate, thin (1.23 cm), upper boundary layer of soil, also called the evaporation layer. The water is evaporated from this thin layer. The evaporation process is limited by the potential evapotranspiration and the available soil water. A daily estimate of the actual evapotranspiration is computed by adding the interception evaporation, soil water evaporation and soil transpiration components.

Model Summary Critique: This agricultural and soil-physics-based model requires too detailed unsaturated soil physical and plant parameters which are not available, and thus this model was not considered further.

6. **VSMB** (Baier et al., 1979) **Versatile Soil Moisture Budget**

Model Summary Description: VSMB calculates the water budget of the soil within the rooting zone of crops from evapotranspiration, precipitation, and deep drainage. Each day the net loss or gain is added to the water already in the rooting zone. Water is withdrawn simultaneously, but at different rates, from different depths in the soil profile, depending on the rate of potential evapotranspiration, the stage of crop development, the water release characteristic of the soil, and the available water content.

The available water-holding capacity of the soil is subdivided into standard zones representing horizontal layers. These zones contain respectively 5, 7.5, 12.5, 25, 25 and 25 percent of the available water within the root zone. Adoption of the standard zones facilitates the use of a single set of crop (or root) coefficients for wheat and other crops. The coefficients express the amount of water extracted simultaneously from the different zones as a fraction of the potential evapotranspiration rate.

Apart from a set of crop coefficients, the relationship between available soil water and the ratio of actual to potential evapotranspiration (AET/PET) also depends on the physical characteristics of the soil. The VSMB makes use of standard empirical curves (the so-called Z curves) for this purpose.

Model Summary Critique: This is not a distributed parameter model. Its strength lies in a detailed representation of the root zone processes. It has been implemented on a watershed scale by Sophocleous and McAllister (1987, 1990). However it lacks streamflow routing routines and its surface runoff estimation procedures are crude. Its major advantage is its simplicity.

7. **SWAT** (Arnold et al., 1993) **Soil and Water Assessment Tool**

Model Summary Description: SWAT is a mostly physically-based, linked surface-subsurface watershed model. The objective in model development was to predict the effect of management decisions (climate and vegetative changes, groundwater withdrawals, reservoir management, and water transfer) on water, sediment, and chemical yields with reasonable accuracy for river basins. The major processes simulated are: 1) Precipitation; 2) Snowmelt; 3) Infiltration; 4) Evapotranspiration; 5) Surface runoff; 6) Routing; 7) Erosion; 8) Chemical movement; 9) Groundwater flow and lateral flow; 10) Irrigation water transfer; 11) Lake water quality; 12) Reservoir and pond component.

SWAT was developed by adding some components, e.g., ground-water flow and streamflow routing procedures for large basins, to the spatially detailed, continuous time model, SWRRB (Williams et al., 1985), which was developed by modifying the CREAMS (Knisel, 1980) daily rainfall-runoff model for application to large, complex, rural basins.

The model allows considerable flexibility in watershed configuration and discretization, and is operated continuously on a daily time step. Watersheds can be subdivided into subbasins. The divisions may be based on stream network, soils, land use, tillage operations, elevation, temperature, rainfall, etc. Sediment and associated chemicals are then routed to the basin outlet. Also, in the vertical direction the model is capable of working with any variation in soil properties--the soil profile can be divided into a maximum of 10 layers.

SWAT input and output files are split into separate files by subbasin and data type. There are 12 basin input data files, 7 output files, and 8 to 10 subbasin input data files for each of the subbasins. This input data structure facilitates the use of several subbasins in the modeling and simplifies GIS linkages.

SWAT has also been used by Bureau of Indian Affairs and Texas River Authorities.

Model Summary Critique: SWAT is the state of the art in agricultural watershed modeling. Inputs for the surface water model are easily obtained and weather, soils, crops, and pesticide databases for the USA are supplied to users. Groundwater inputs are also relatively easy to obtain and are similar in similar hydrogeological regions. However, the groundwater aspects of the model are too oversimplified.

Recommendations

Based on the study objectives, model selection criteria, and analysis of model candidates, a combination of watershed and stream-aquifer models is required to address study objectives. Of the models readily available for preliminary assessment for this report, the state of the art in stream-aquifer modeling at scales appropriate to this study seems to be the MODFLOW program with the streamflow routing package. The corresponding state of the art in models reviewed to date for agriculturally-oriented, large scale basin analysis is probably SWAT. A combination approach of the two models (MODFLOW and SWAT) is therefore recommended.

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APPENDIX 10A

Method for implementing management scenarios

Method for implementing management scenarios

The baseline scenario represents an 18-year future simulated period (1995-2012) with initial conditions defined by the end of the base case simulation (1977-1994) for hydraulic heads (i.e., water table elevations), water use appropriations, and land use. The climate conditions (i.e., daily precipitation and temperature) for the period 1977-1994 are used to represent the scenario time period (1995-2012). Irrigation depths and water use as a fraction of appropriation, estimated for the period 1977-1994, are repeated for the scenario time period, but applied to appropriations as they existed in 1994, as shown in Table 3.2a. Conditions for the eighteen combinations of soil type and land use simulated by SWAT are the same for the baseline scenario as for the base case.

Projected water use is shown in Table 10.1. The increase in water use from a historical year to a projected year (e.g. from 1980 to 1998) is reflected both in flow rate Q_{irr} and irrigated area A_{irr}, while irrigation depth d_{irr} is held to the value of the historical year. This scheme satisfies continuity as expressed in the equation $Q_{irr}c\Delta t = d_{irr}f_{irr}A$ (eqn. 10.1). Total irrigation use $Q_{irr} = U_{gi} + U_s$ (cfs), where U_{gi} is the irrigation component of total ground-water use U_g, and U_s = total surface water diversions, all of which are for irrigation. The baseline scenario is a variation on the base case in which projected water use, U_g and U_s, shown in Table 10.1, is represented by input files to the WELL and SURFACE packages in MODFLOW; the corresponding irrigated area increases are represented by the weighted average irrigation (in depth units) read by the soil water balance (MODSWB) package.

The baseline and the 11 scenarios described in section 10, except for the eighth, are implemented by varying annual irrigation water use Q_{irr} (cfs) and the irrigated areal fraction of the basin f_{irr} while holding irrigation depth d_{irr} equal to that for the base case. These variations are designed to satisfy mass balance as described in eqn (10.1), and are represented by input to the SURFACE and WELL input files for Q_{irr}, and by a balance file incorporating irrigation fractions f_{irr}. For each scenario, MODFLOW reads data from the MODSWB package input file which specifies the scenario and the name of the corresponding balance file written by SWBAVG. The specified scenario, except for no. 8, is used at the beginning of each year (stress period) to select or scale water rights accordingly. Ground and surface water diversions for irrigation are treated similarly but separately, by the WELL and SURFACE packages in MODFLOW, respectively. Application number and distance from the river are specified by input to these packages for each water right in order to allow these selections to be made during execution of MODFLOW rather than beforehand, which would require a greater effort in data handling. These scenarios are implemented by subr USEMGT, which is called to examine each surface and ground water diversion for irrigation at the beginning of a stress period (year). In the case of ground-water diversions, USEMGT is called within the expanded version of the WELL package. For surface water diversions, USEMGT is called as follows within the SURFACE package written for MODFLOW to handle surface water diversions:

```
      DO II=1,NSURFS                     !number of surface water rights
          READ (IN,4) K,I,J,Q,Qwr,rwr,cwr,dsstrm,iappno,idxrch,wruse,iwr
    4     FORMAT(3i10,2f10.0,3f8.0,i8,i5,4x,a,i5)
          SURF(1,II)=K          !layer
          SURF(2,II)=I          !row
          SURF(3,II)=J          !column
c ----        water use management scenarios:
          call USEMGT (iadcod,welmpy,dsstrm,iappno,Q,Qwr)
          surf(4,ii) = Q        !water use for time step
          surf(5,ii) = Q        !water use for current stress period
          surf(6,ii) = Qwr      !appropriation for current stress period
          surf(7,ii) = idxrch   !index to stream reach
          srfsum = srfsum+q     !total annial surface water use
      end do
```

Selections for each scenario are described by the code in USEMGT as follows.

```
      subroutine USEMGT (iadcod,welmpy,dsstrm,iappno,Q,Qwr)
c ----    implement water use management scenarios---------------
c-----------------------------------------------------------------------------
c iadcod: use management option: this subroutine handles options 1-11 except option 8.
c welmpy: if iadcod > 0,scaling factor applied to water use for each water right;
c         if iadcod < 0, welmpy specifies a use fraction that is to be applied to all
c         water rights for all stress periods (years).
c dsstrm  distance from water right to stream (miles)
c iappno  water right application number;
c Q       estimated use for a water right (cfs for Repub. R. model);
c Qwr     appropriation for a water right (cfs for Repub. R. model).
c------------------------------------------------------------------------------
      if (iadcod.eq.-1) then
        Q =  welmpy*Qwr    ! use = avg use fraction times appropriation, Qwr
      else if (iadcod.gt.0) then
c             apply administrative options on water rights restrictions to Qnew:
c             > 0: multiply use and appropriation by factor welmpy:
        Q   = welmpy*Q
        Qwr = welmpy*Qwr
        iadmin=0 !assume no use restriction, subject to options below:
        if (iadcod.eq.2) then        ! 2: shut off add'l water rights after 3/22/74:

          if (iappno.gt.22310) iadmin=1
        else if (iadcod.eq.3) then    ! 3: shut off add'l water rights after 4/12/84:
          if (iappno.gt.37147) iadmin=1
        else if (iadcod.eq.4) then    ! 4: shut off if within 1/4 mile of Repub R.
          if (dsstrm.lt.0.25) iadmin=1
        else if (iadcod.eq.5) then    ! 5: shut off if within 1/2 mile of Repub R.
          if (dsstrm.lt.0.5) iadmin=1
        else if (iadcod.eq.9) then    ! 9: shut off rights after 3/22/74 within 1/4 mi
          if (iappno.gt.22310 .and. dsstrm.lt.0.25) iadmin=1
        else if (iadcod.eq.10) then   !10: shut off rights after 4/12/84 within 1/2 mi
          if (iappno.gt.37147 .and. dsstrm.lt.0.5) iadmin=1
        else if (iadcod.eq.11) then   !11: shut off rights after 3/22/74 within 1/4 mi;
c                                          shut off rights after 4/12/84 within 1/2 mi.
          if ((iappno.gt.22310 .and. dsstrm.lt.0.25) .or.
     1         (iappno.gt.37147 .and. dsstrm.lt.0.5)) iadmin=1
        end if
        if (iadmin.eq.1) then         !diversion pt is to be excluded
          Q   = 0.                    !set water use to zero
          Qwr = 0.                    !set appropriation to zero
        end if
      end if   !iadcod > 0
      return
      end
```

Scenarios 1, 6 and 7 all entail corresponding changes in water use and irrigated area to satisfy continuity as described above. For these cases, the water use scaling factor (*welmpy* in the above code) is set to 0.75, 1.1, and 0.9, respectively; corresponding changes in irrigated fraction f_{irr} are handled by weights and SWBAVG to produce balance files for input to MODFLOW for monthly time steps. Other scenarios are run with the selections shown above but without scaling water use, i.e. *welmpy* = 1.

A preliminary simulation with MODFLOW using annual time steps was run for each of these scenarios except for the eighth, in order to determine the effect of the particular scenario on water use with respect to the baseline scenario. The change in water use Q_{irr} as shown in Table 10.2 was reflected in a change in irrigated areal fraction f_{irr}, which was applied using programs WEIGHTS and SWBAVG to produce a balance file representing the heterogeneous watershed for each scenario. The resulting balance file was then used in a monthly simulation with MODFLOW in which continuity was satisfied as described above.

In contrast to the others, the eighth scenario is implemented by running SWAT for a variation on each of the eighteen homogeneous cases (HRU) by increasing noncontributing fraction and the corresponding pond area specified in the pond (~.pnd file) for each subbasin. These balance files written by SWAT are averaged by SWBAVG, which applies the weight functions of the baseline scenario; and MODFLOW reads the SURFACE and WELL input files of the baseline scenario.

FIGURES

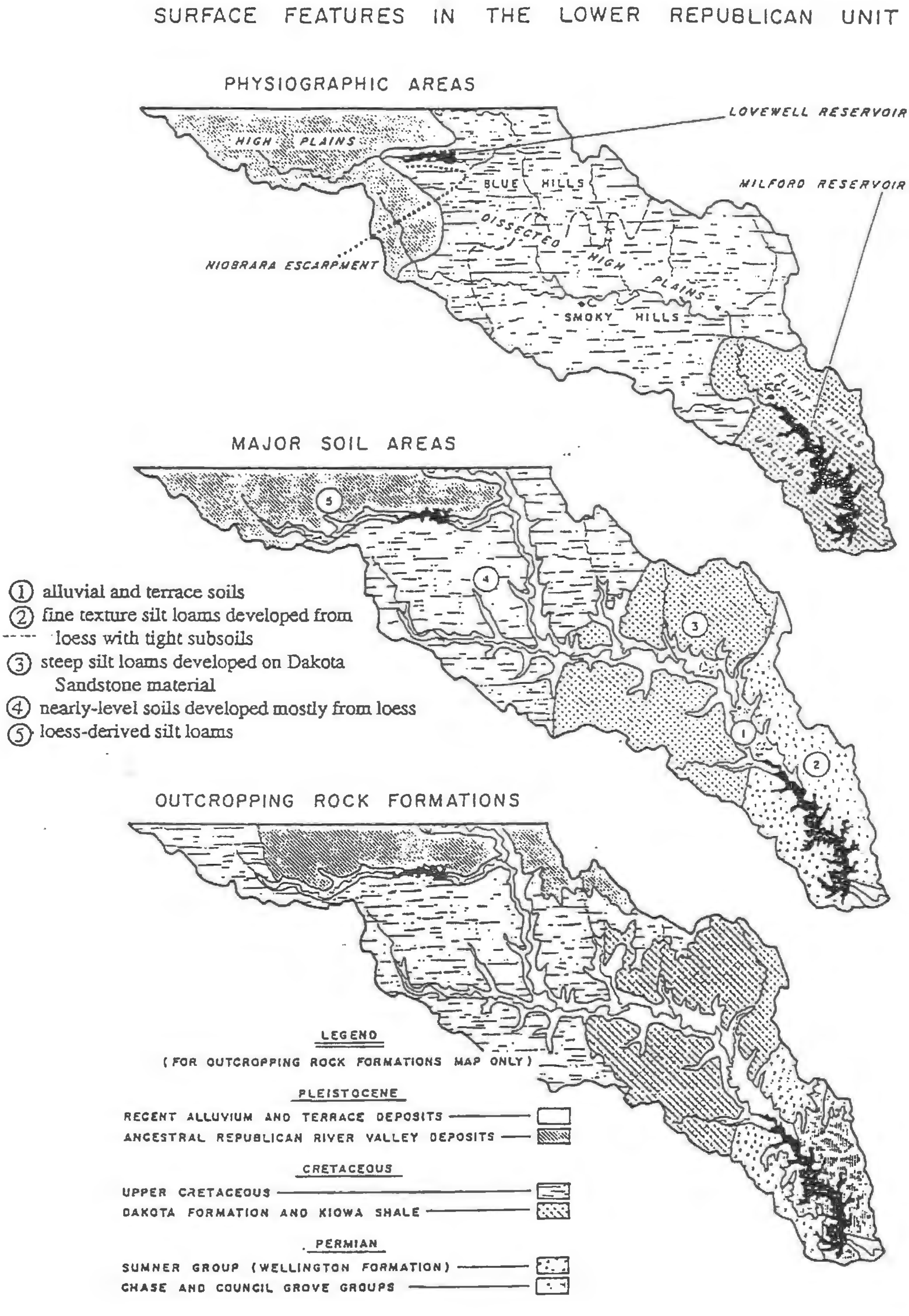


Figure 2.1. Major physiographic areas, geologic formations that crop out, and major soil areas of the Lower Republican River basin (Adapted from KWRB, 1961).

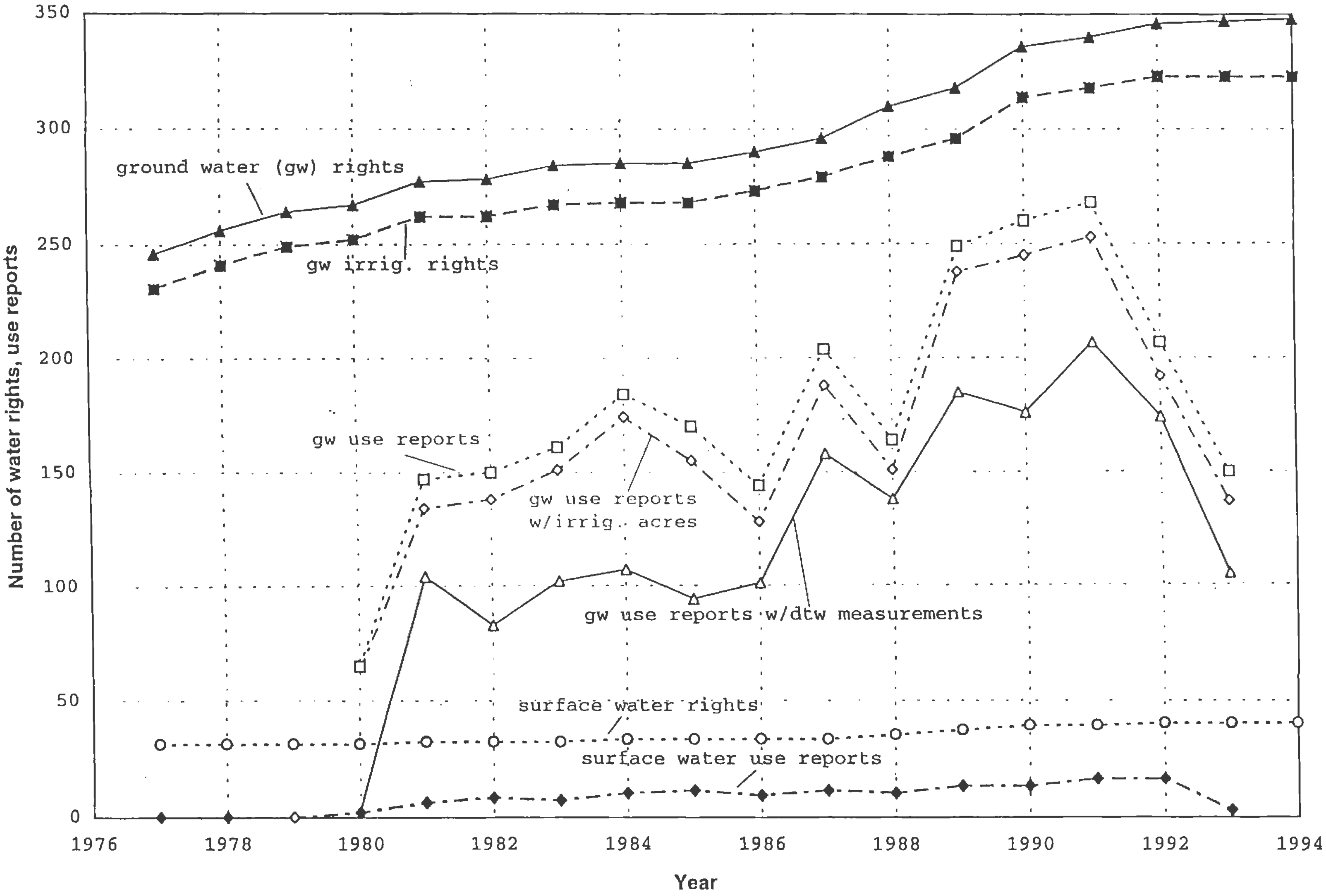


Figure 3.1. Number of appropriations, use reports, and reported depth to water table measurements.

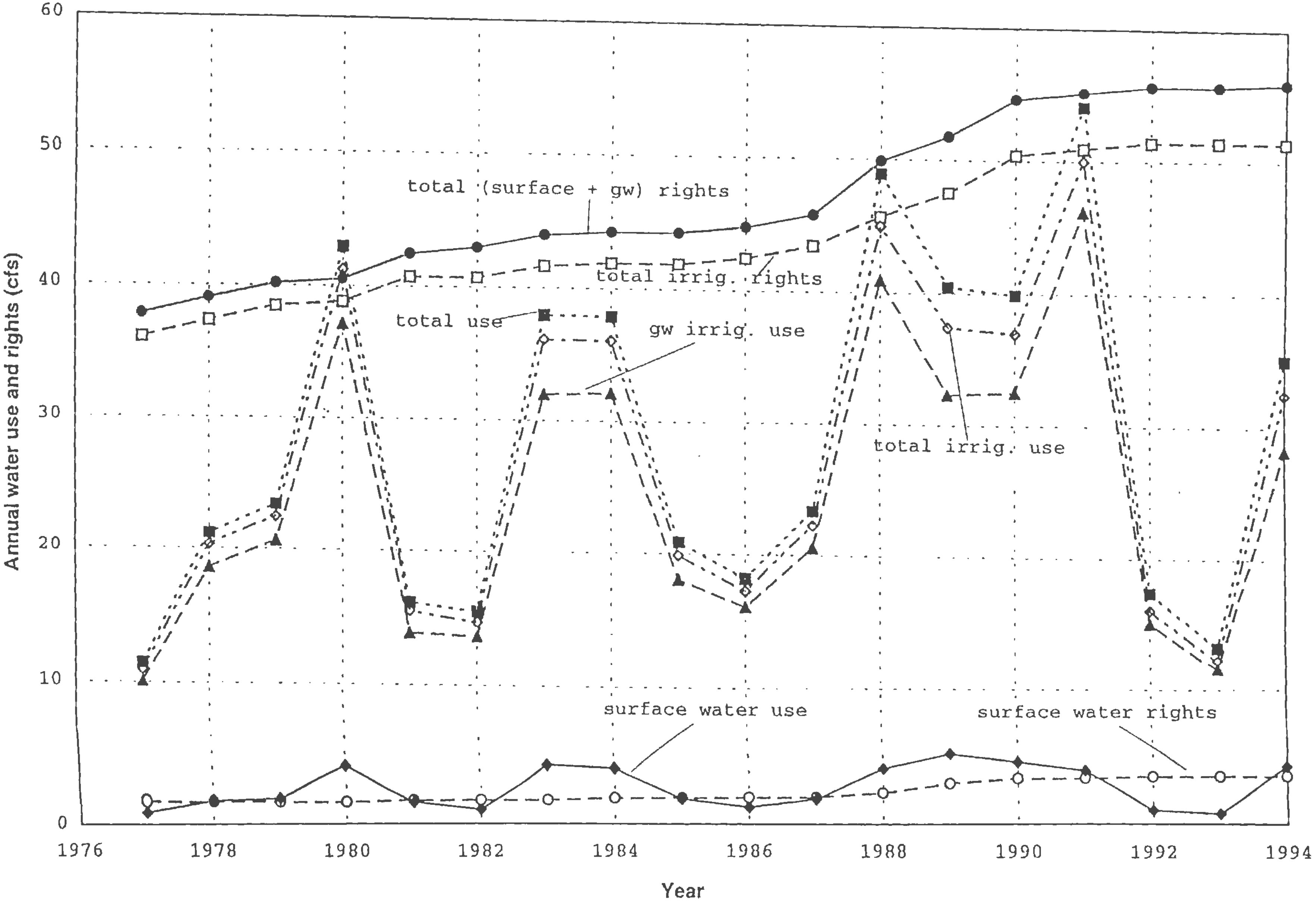


Figure 3.2. Water use and appropriations.

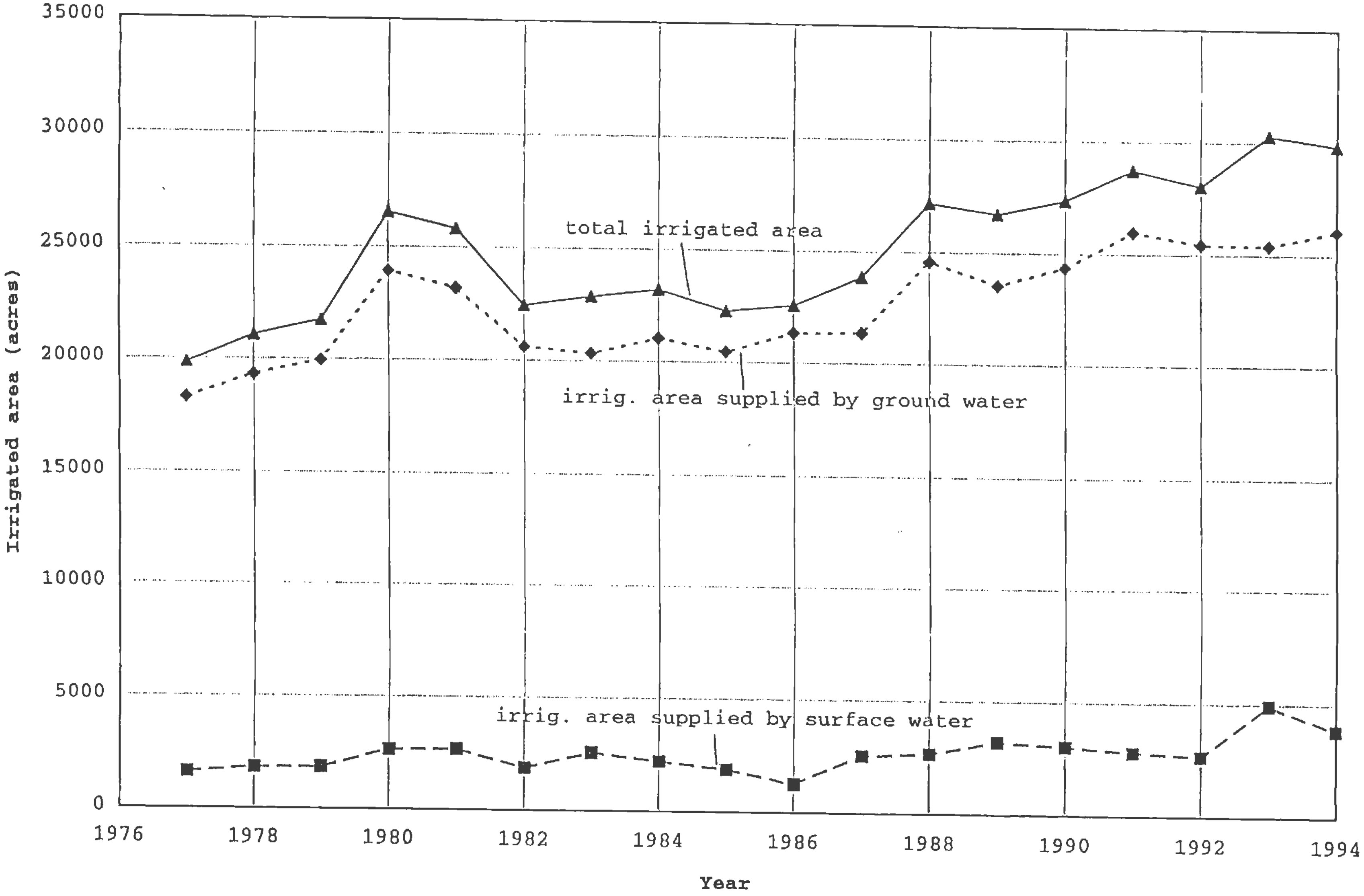


Figure 3.3. Irrigated acres based on water use reports.

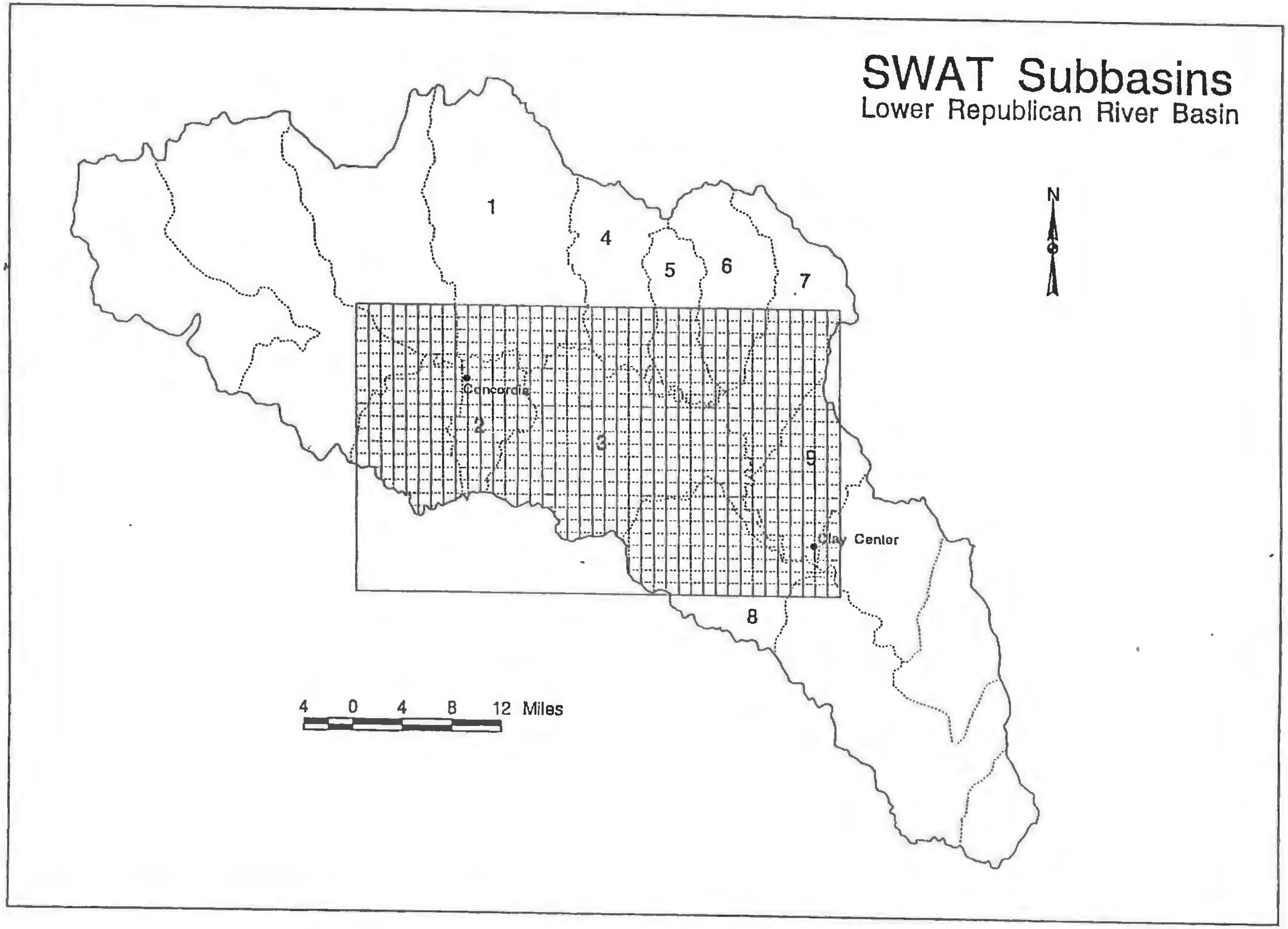


Figure 3.4. Lower Republican River basin and Model Gridded Area. Numbered Subbasins Cover the basin area between Concordia and Clay Center.

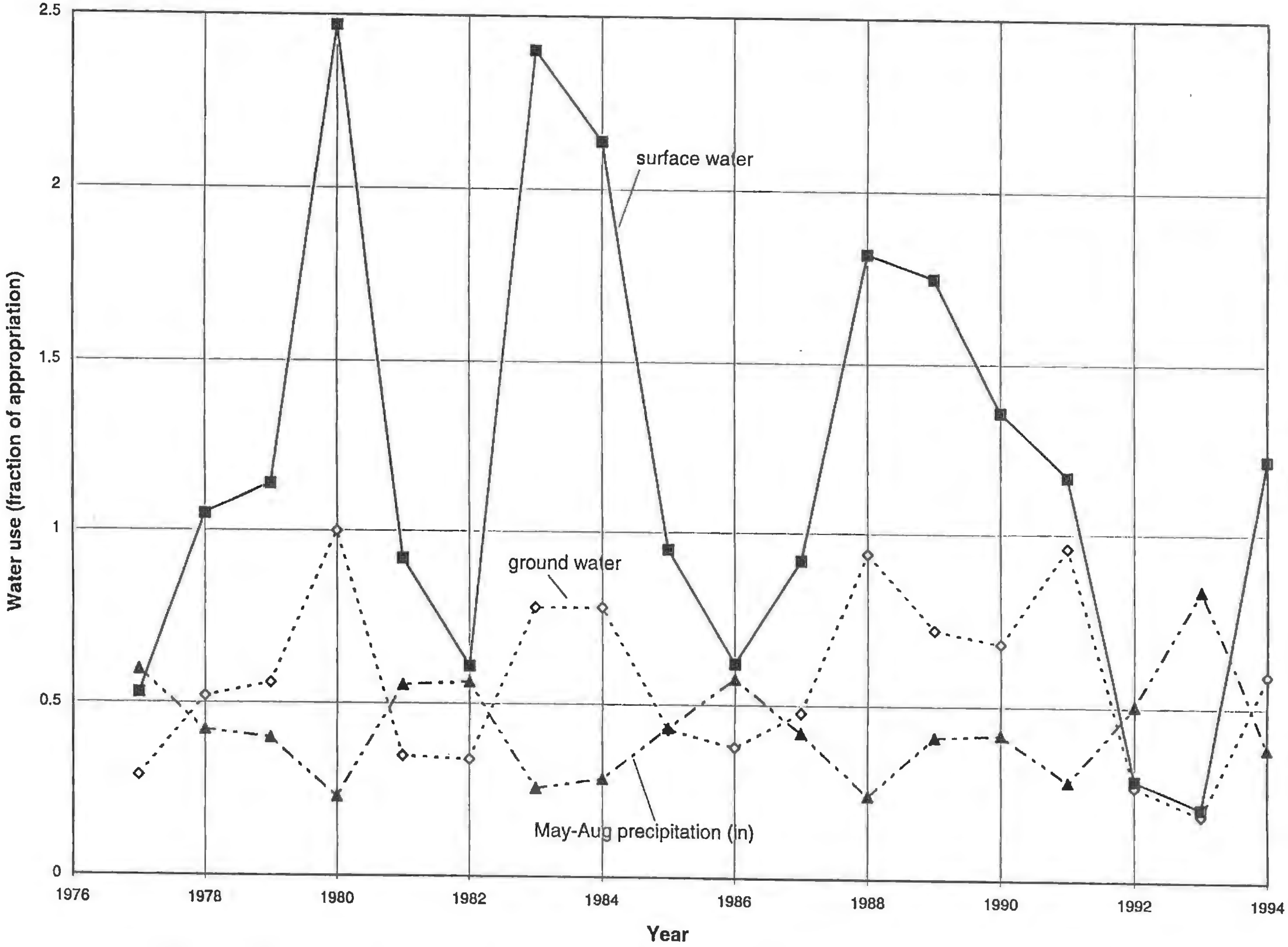


Figure 3.5. May-Aug precipitation (in) and surface and ground water use as a fraction of appropriation

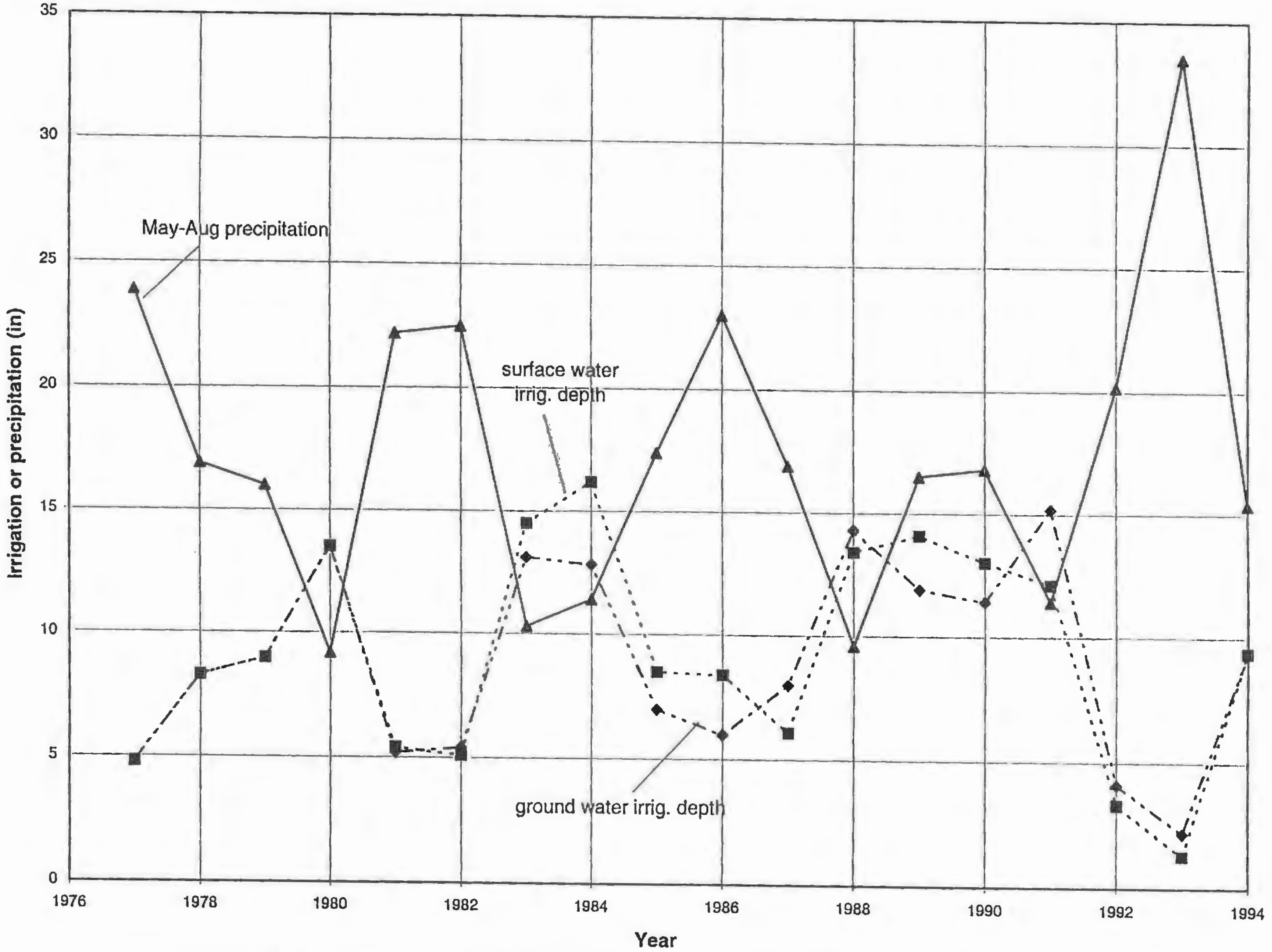


Figure 3.6. May-Aug precipitation (in) and surface and ground water use as depth of irrigation (in)

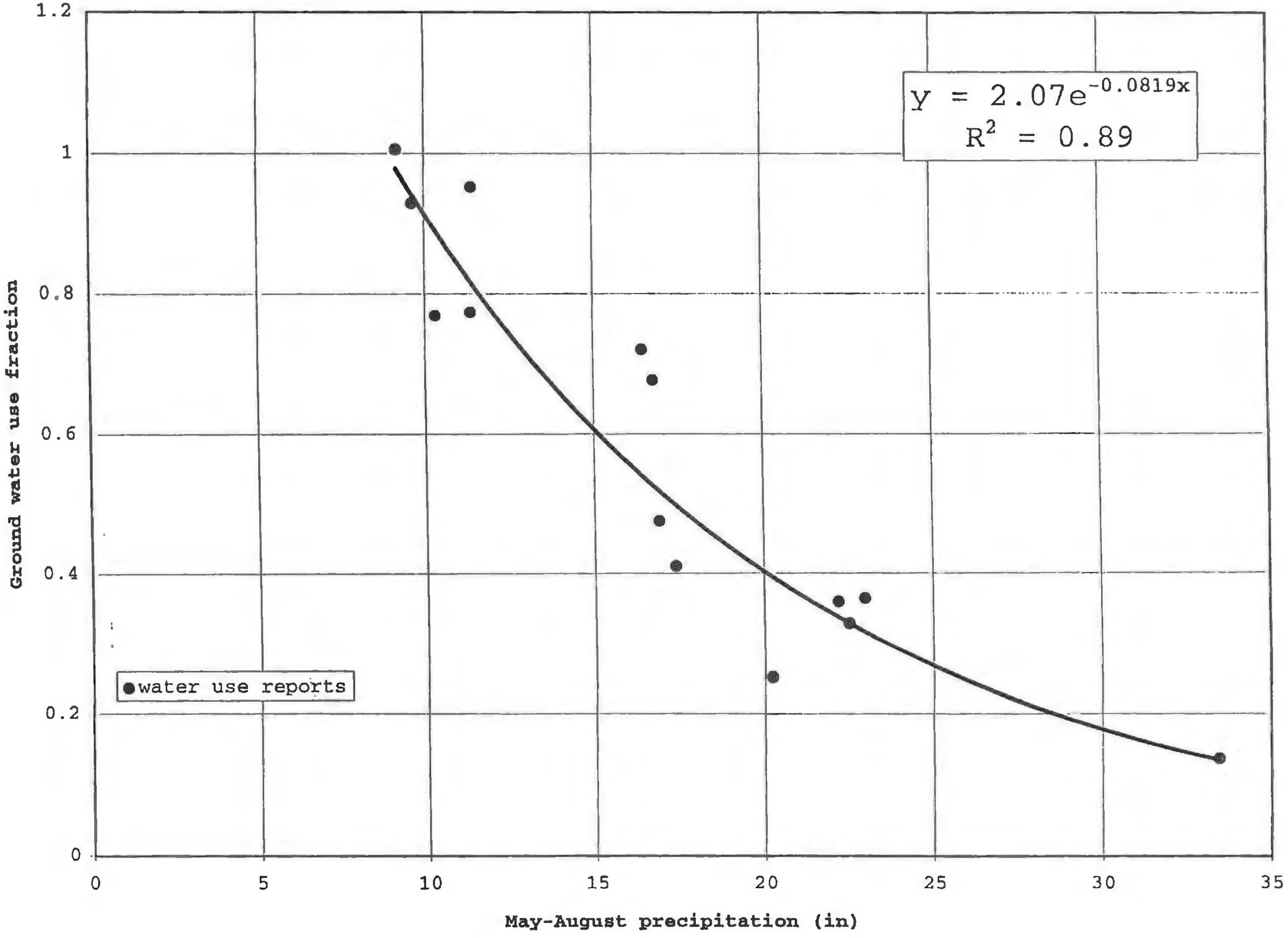


Figure 3.7. Ground-water use fraction versus precipitation.

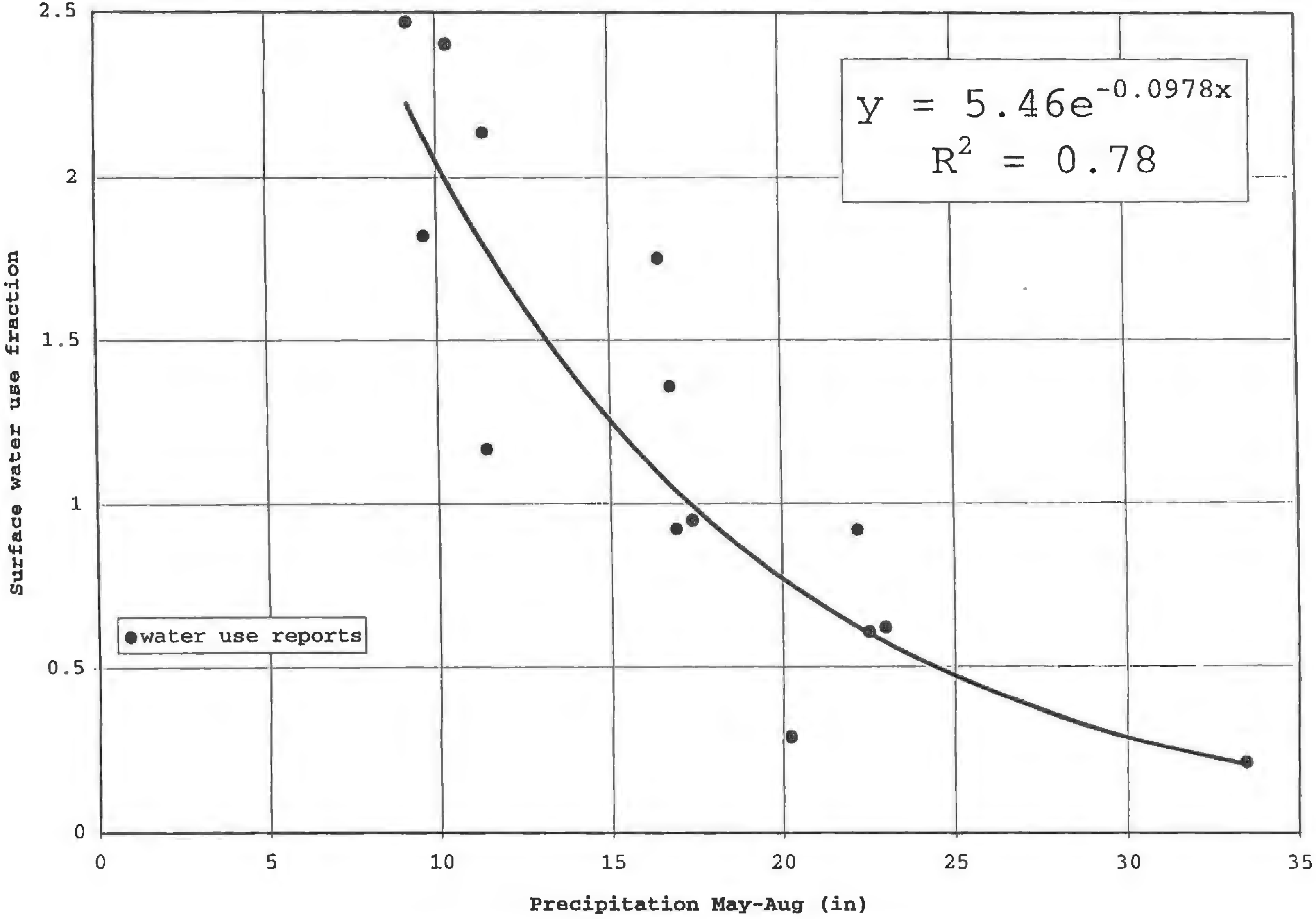


Figure 3.8. Surface-water use fraction versus precipitation.

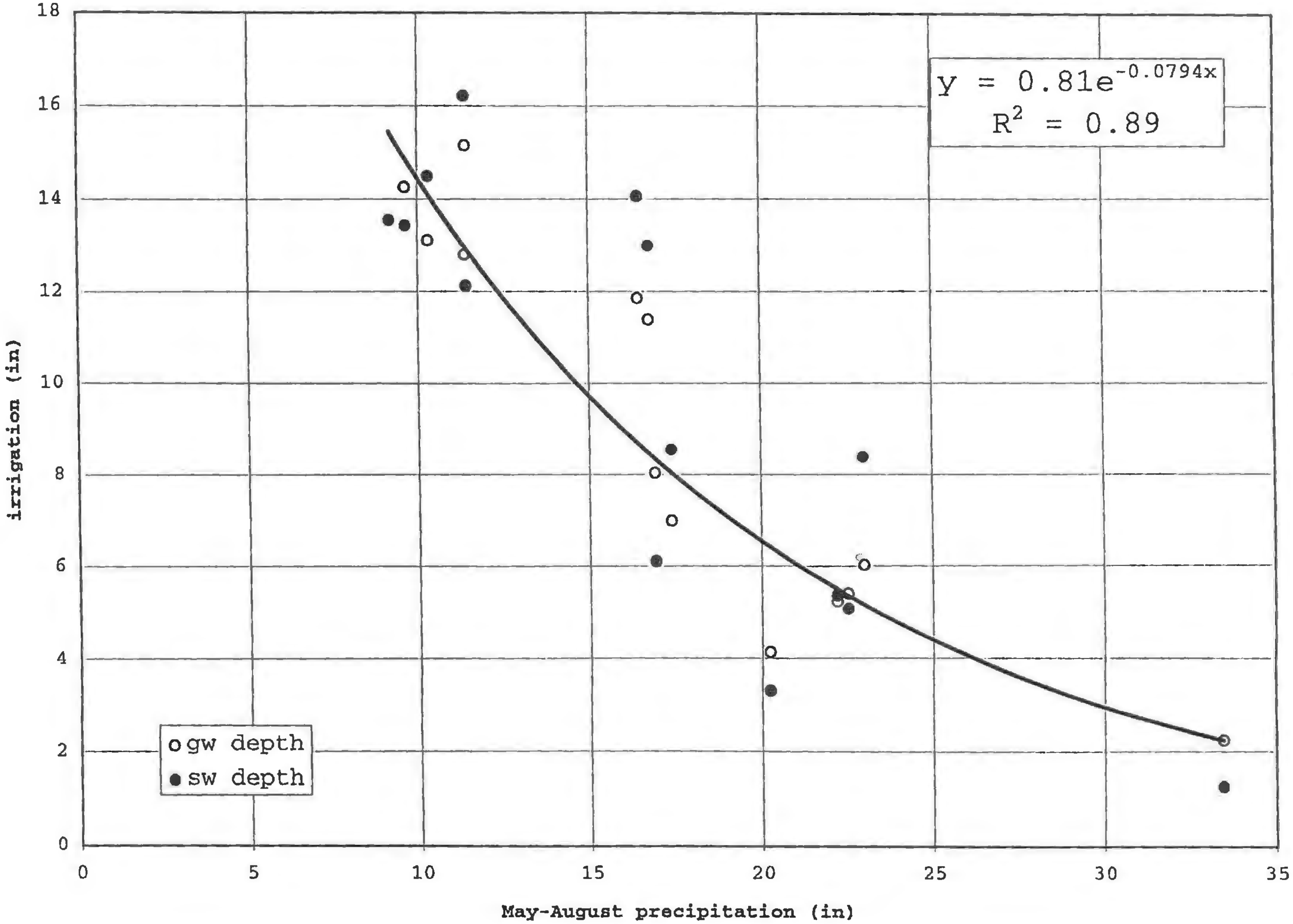


Figure 3.9. Depth of irrigation versus precipitation, combining ground and surface water use reports

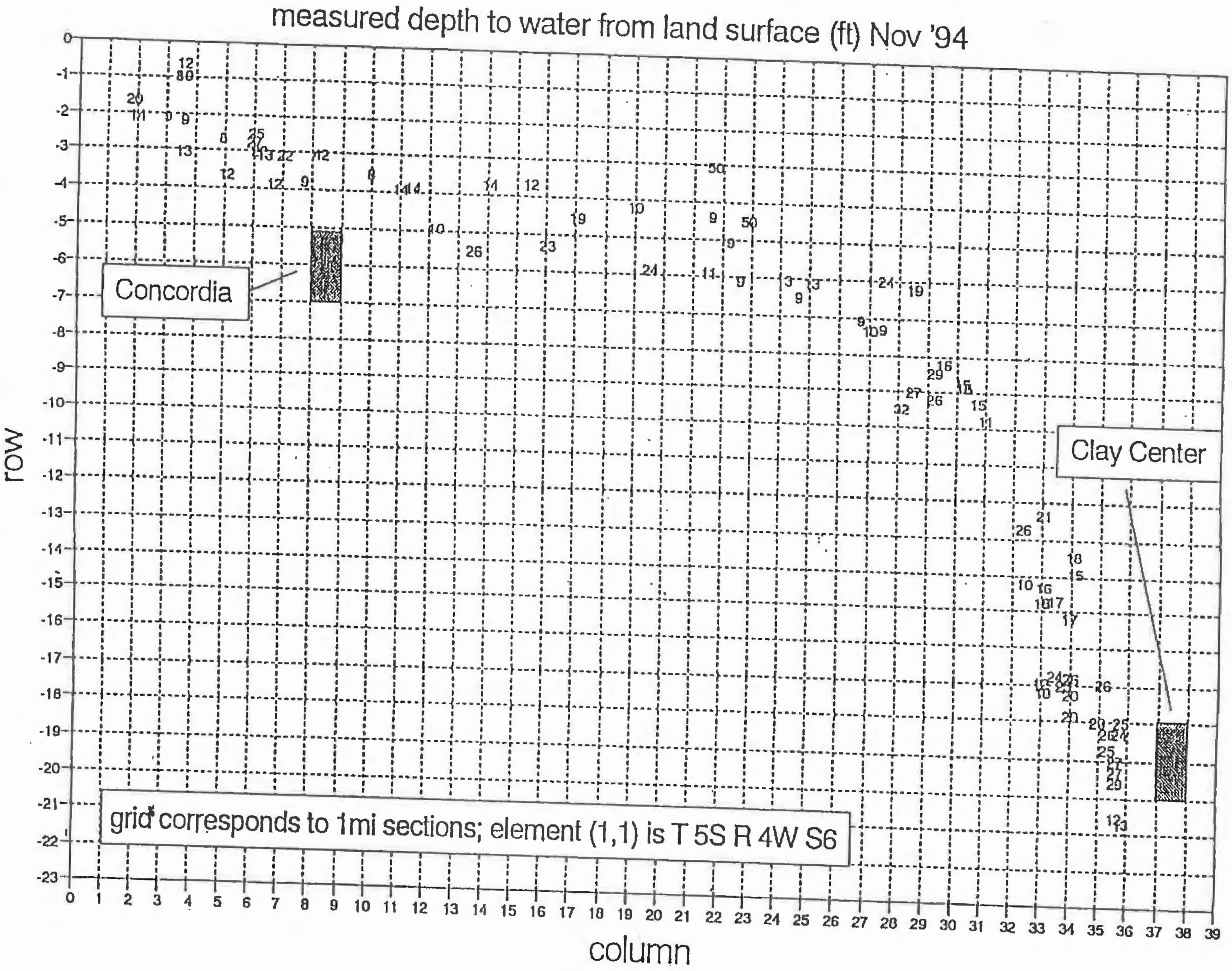


Figure 3.10. Location of wells and measured depth-to-water level during the November 1994 survey.

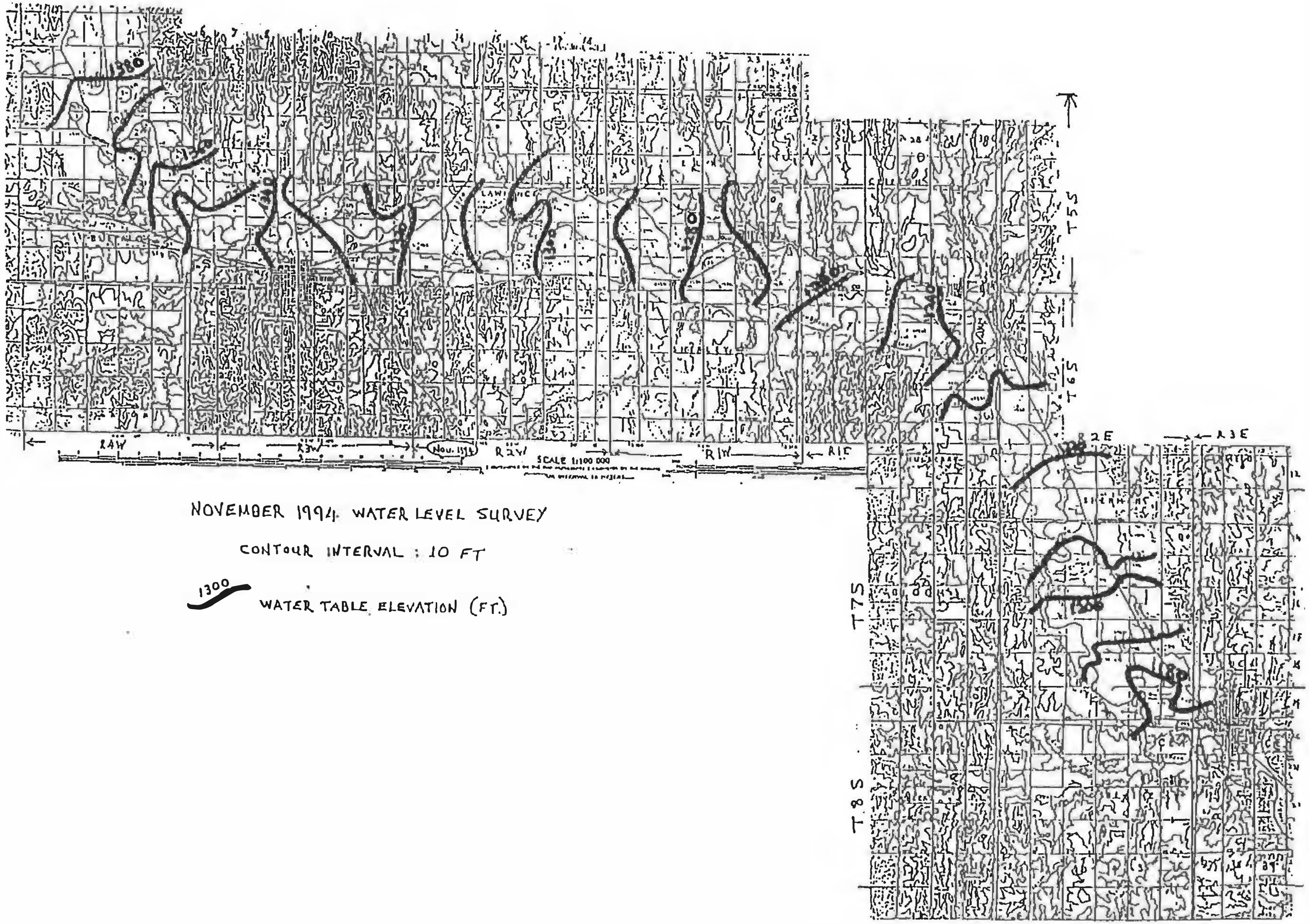


Figure 3.11. Ground-water level contours based on the November 1994 survey.

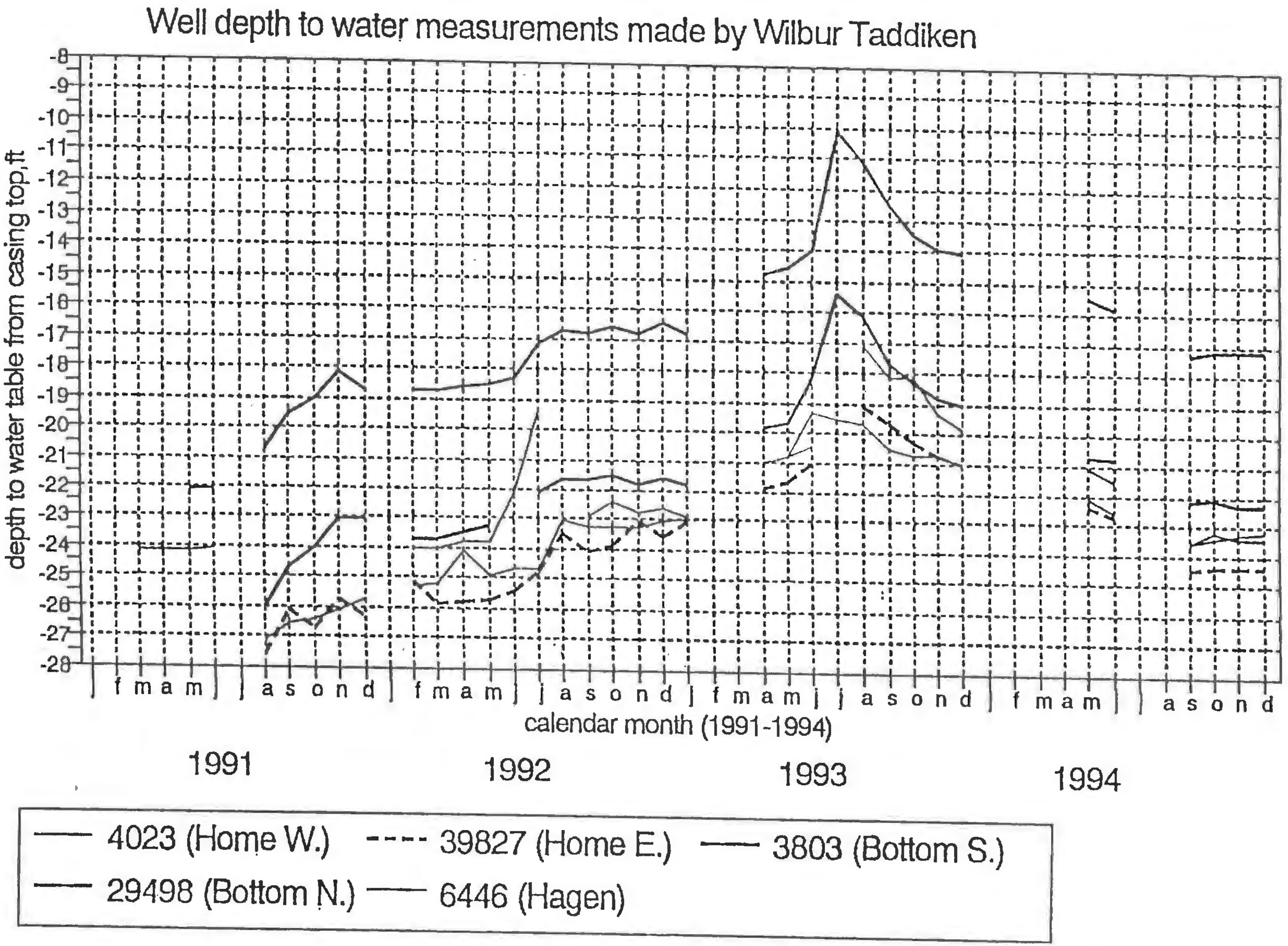


Figure 3.12. Depth to water level hydrograph at the Taddiken wells measured by W. Taddiken.

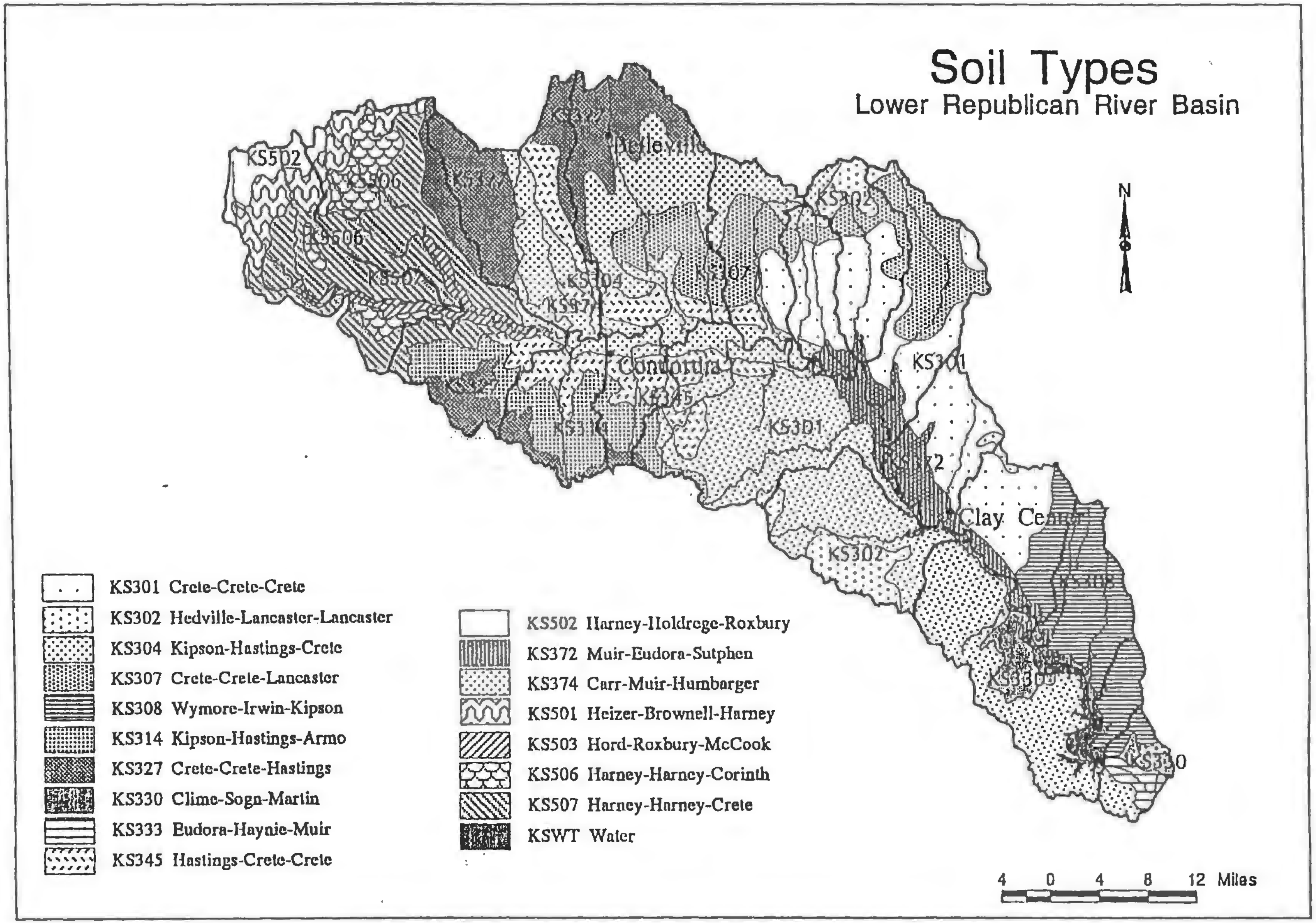


Figure 3.13. Soil associations for the Lower Republican River basin.

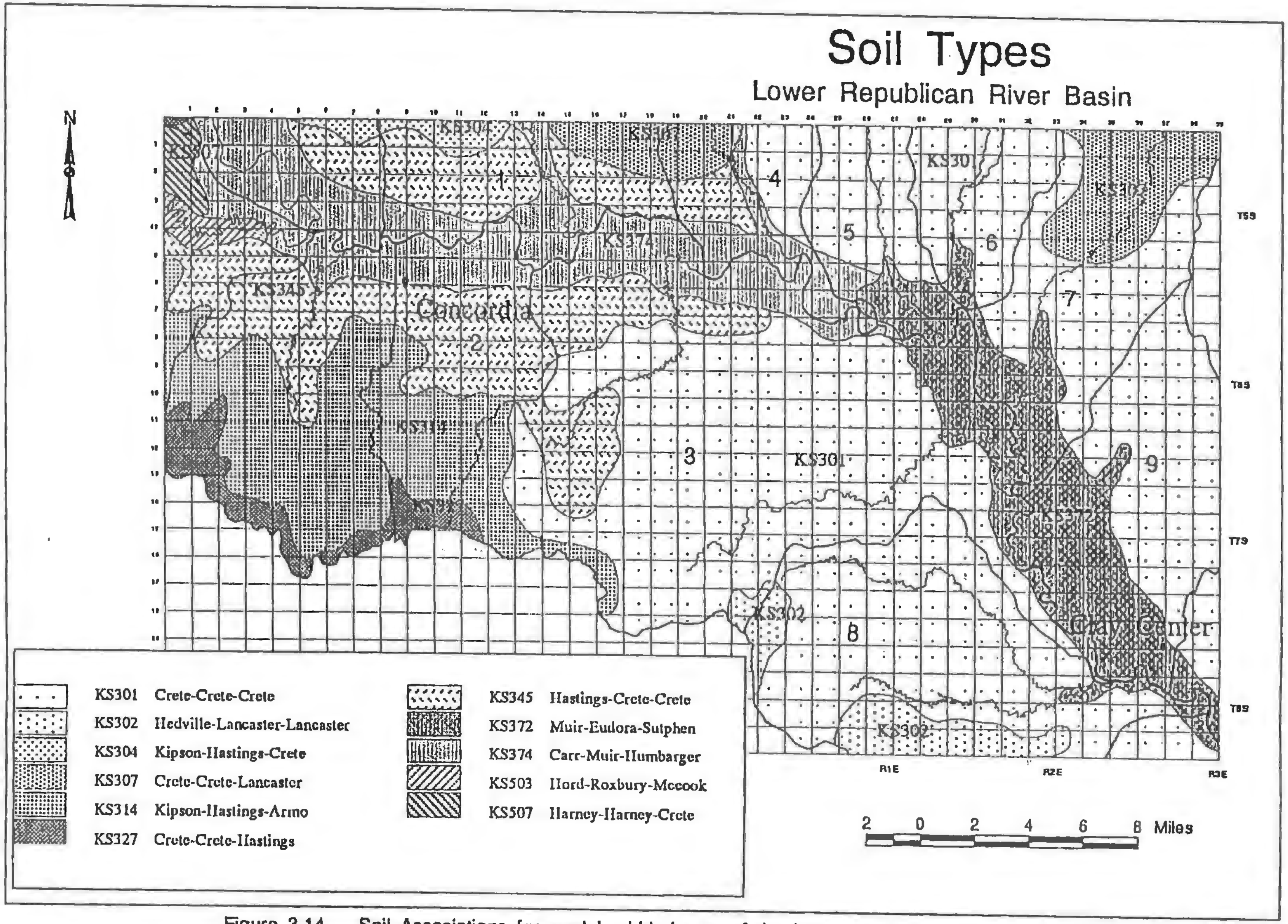


Figure 3.14. Soil Associations for model gridded area of the Lower Republican River basin from Concordia to Clay Center

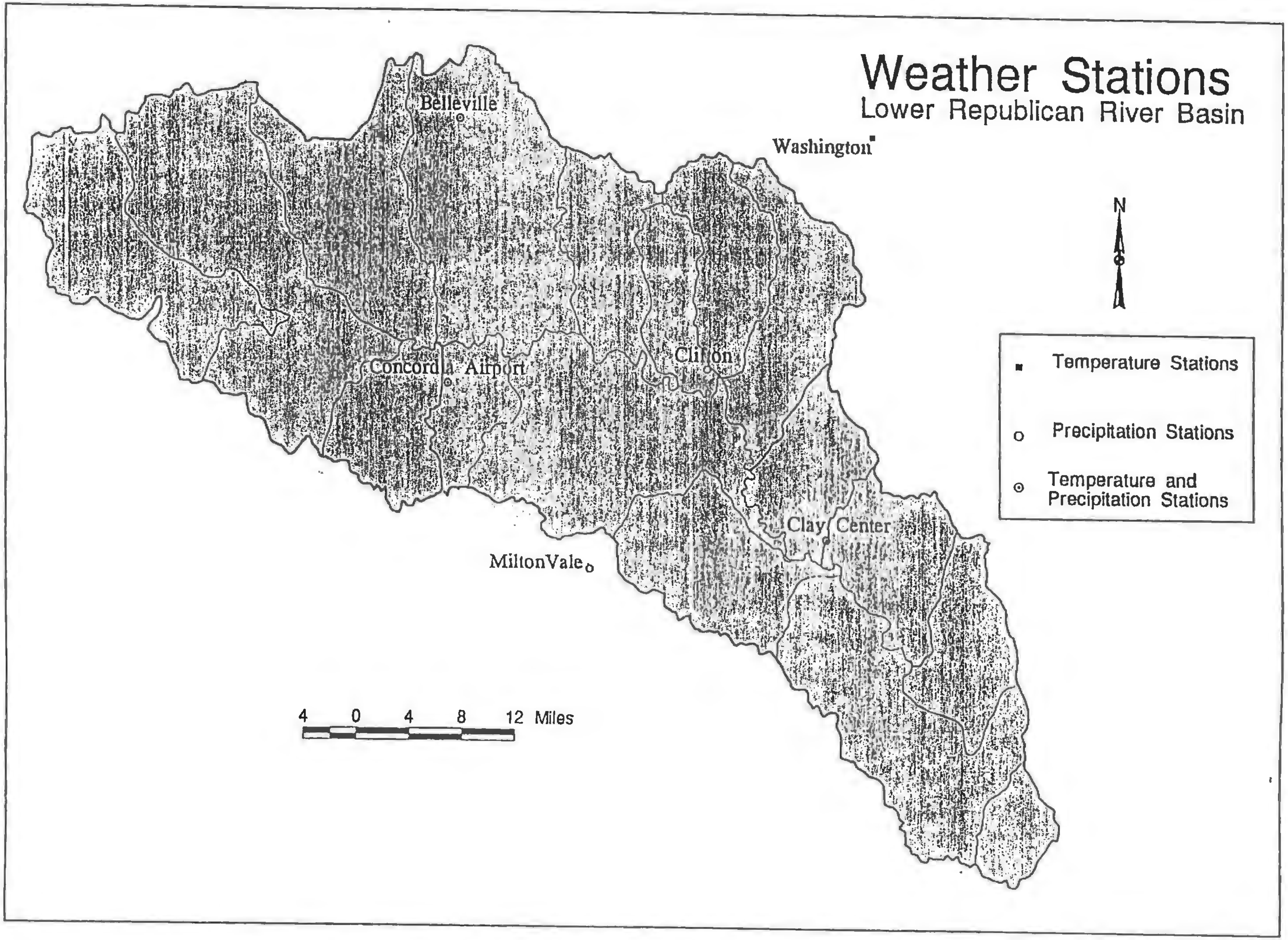


Figure 3.15. Climatic stations employed to characterize weather variables for the Lower Republican River basin.

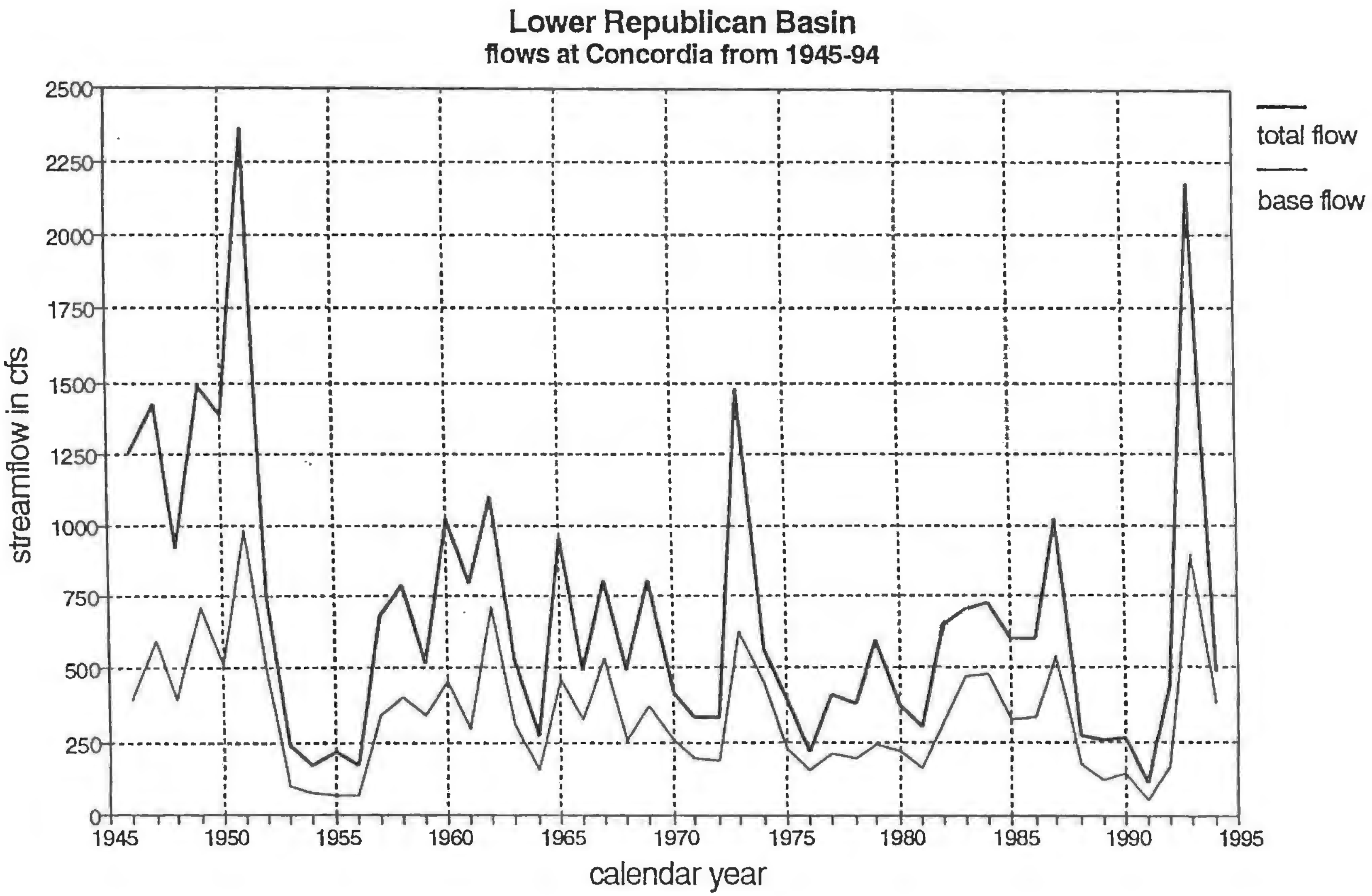


Figure 3.16a. 1946-1994 Republican River streamflow and baseflow at Concordia.

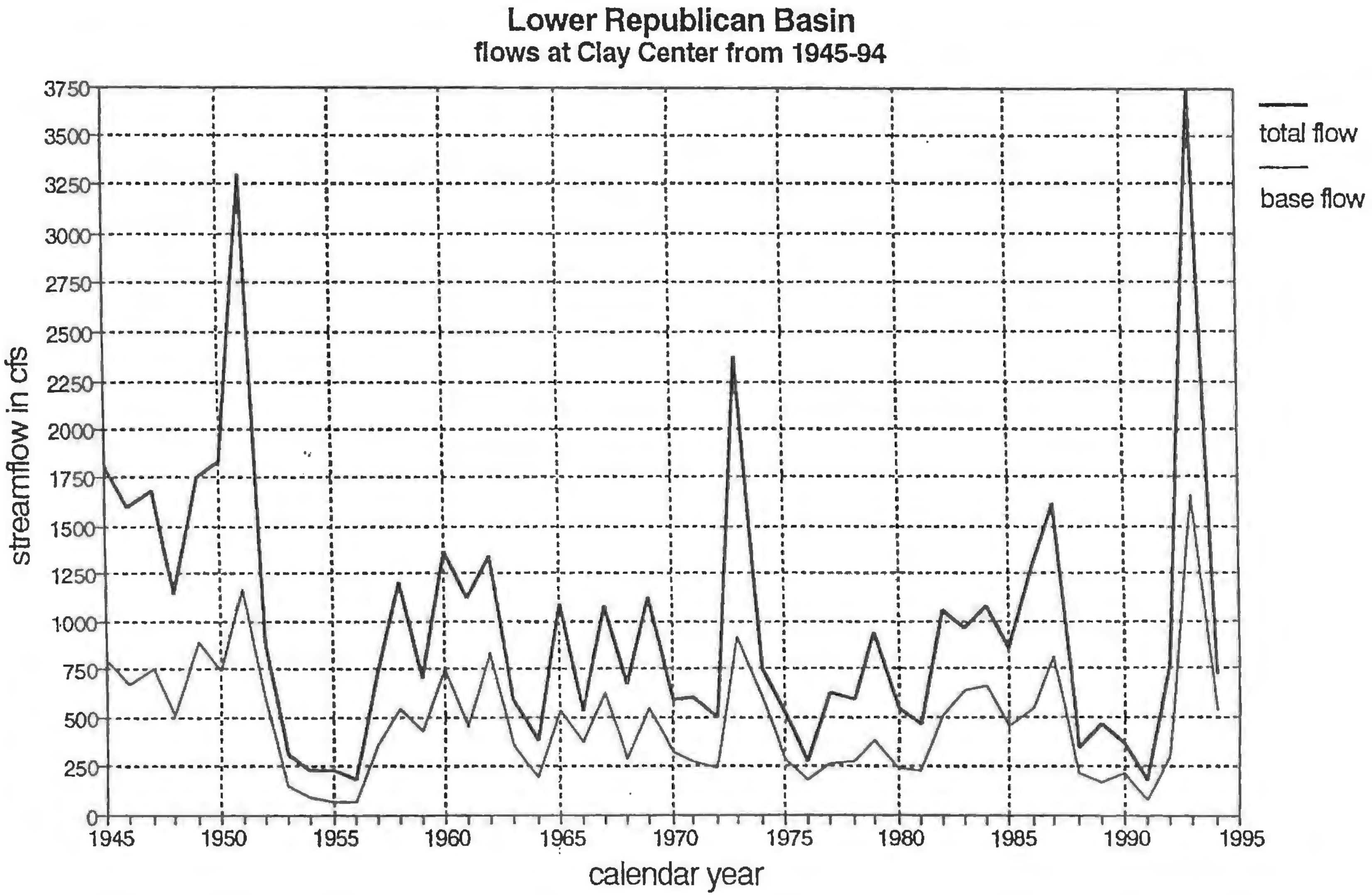


Figure 3.16b. 1946-1994 Republican River streamflow and baseflow at Clay Center.

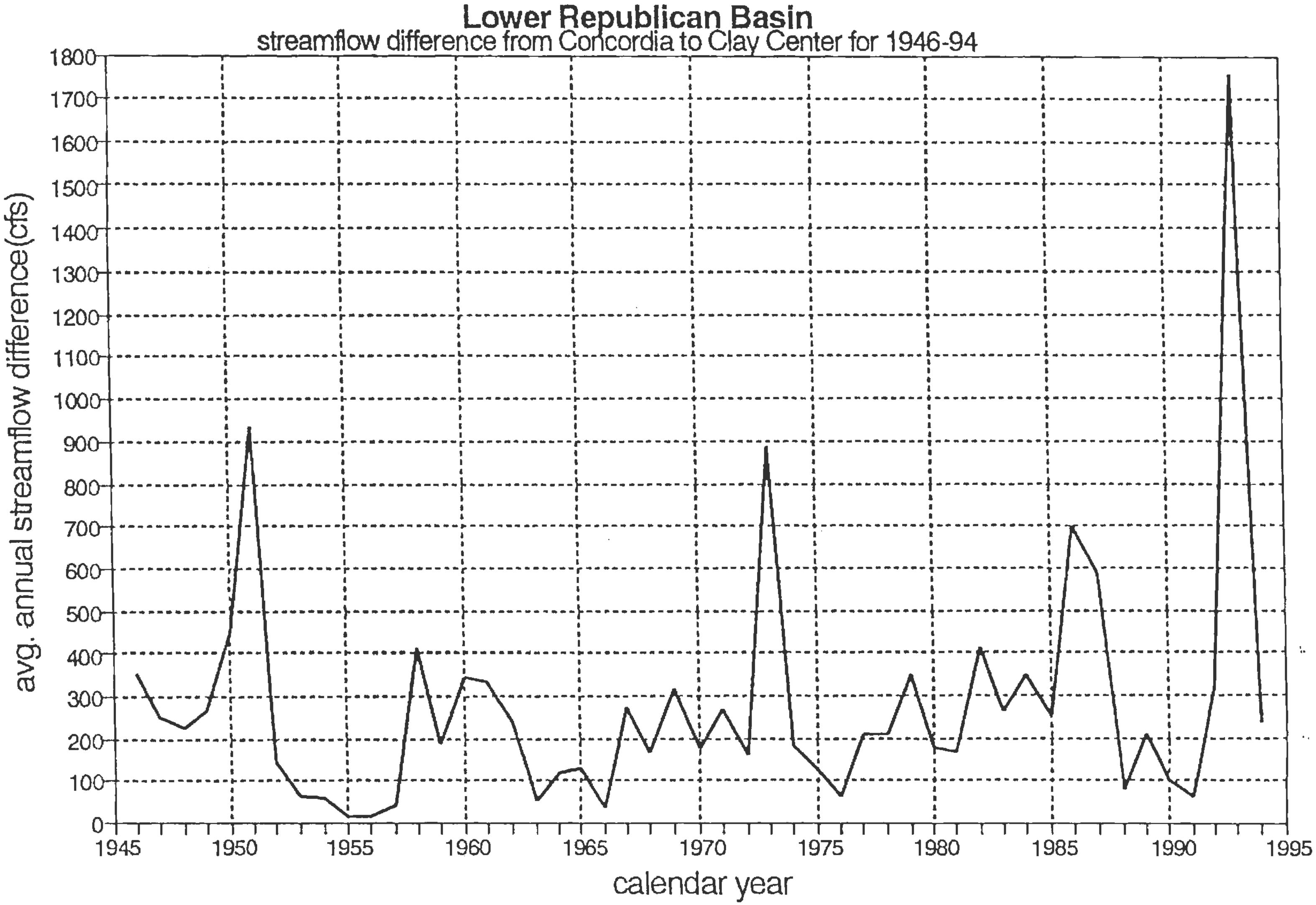


Figure 3.16c. 1946-1994 river yield between Concordia and Clay Center.

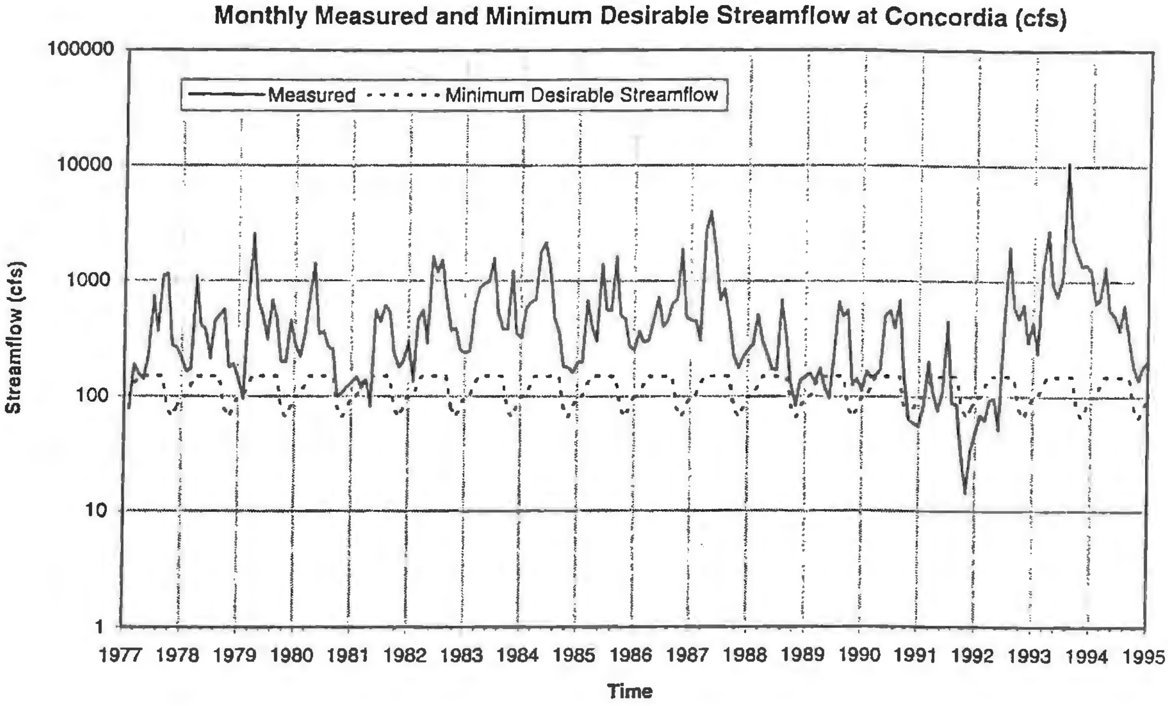


Figure 3.16d. Measured and minimum desirable streamflow at Concordia (cfs)

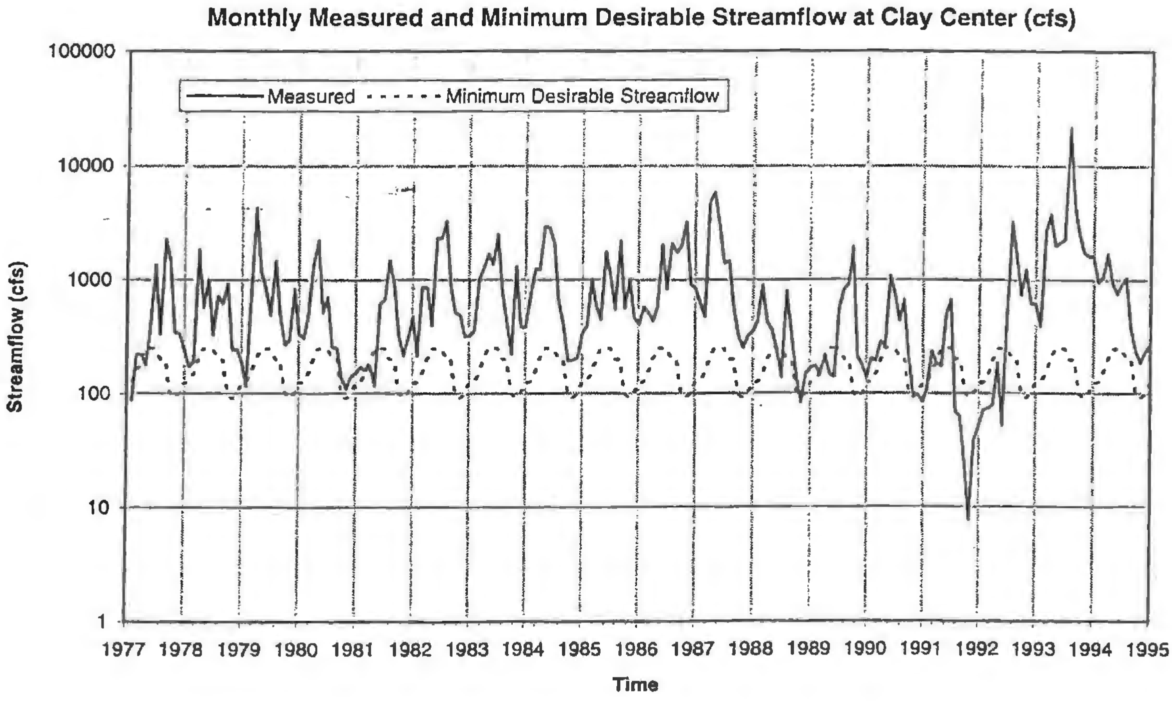


Figure 3.16e. Measured and minimum desirable streamflow at Clay Center (cfs)

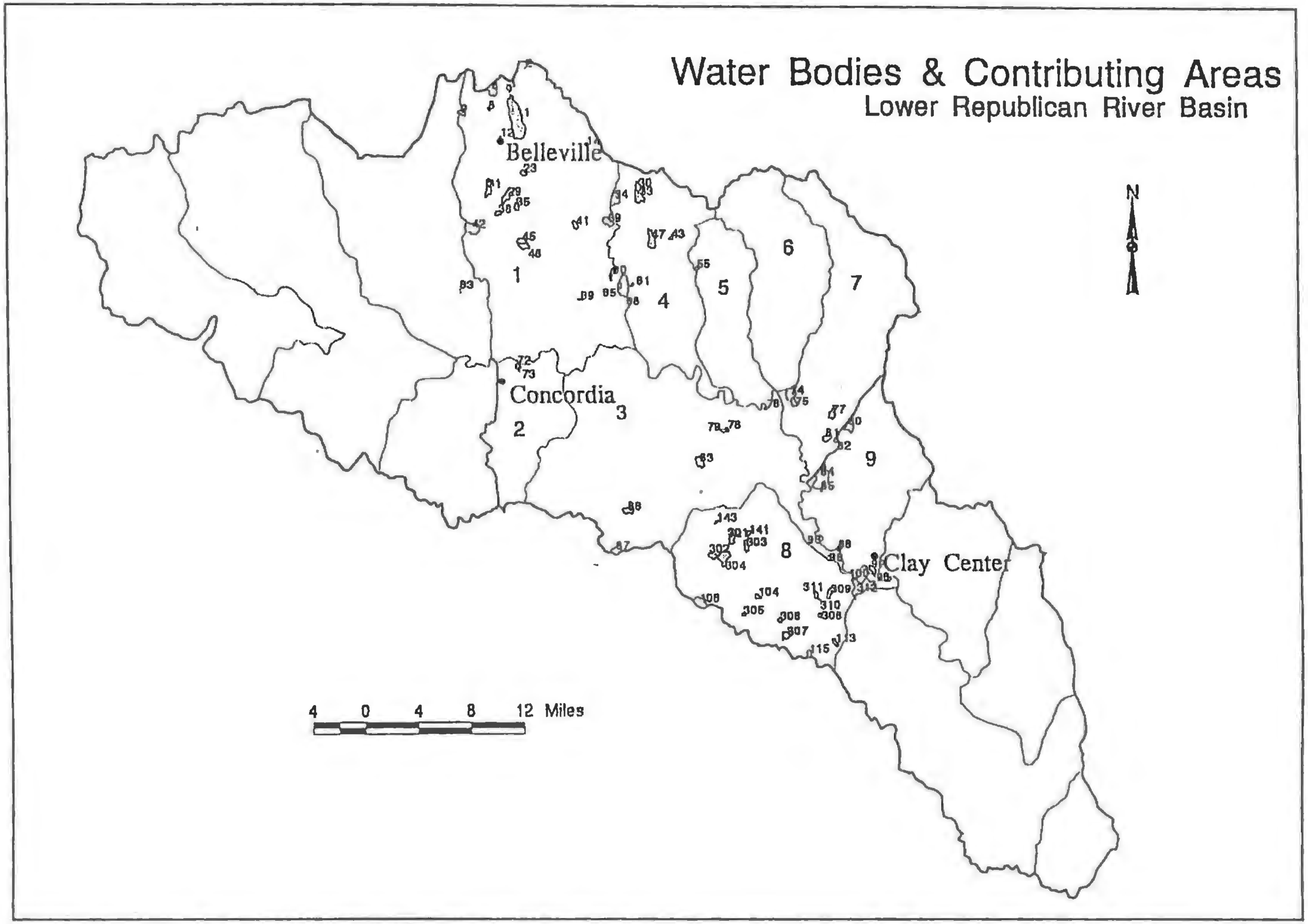


Figure 3.17. Pond drainage areas and pond identification numbers for Subbasins 1-9 of the Lower Republican River Basin between Concordia and Clay Center

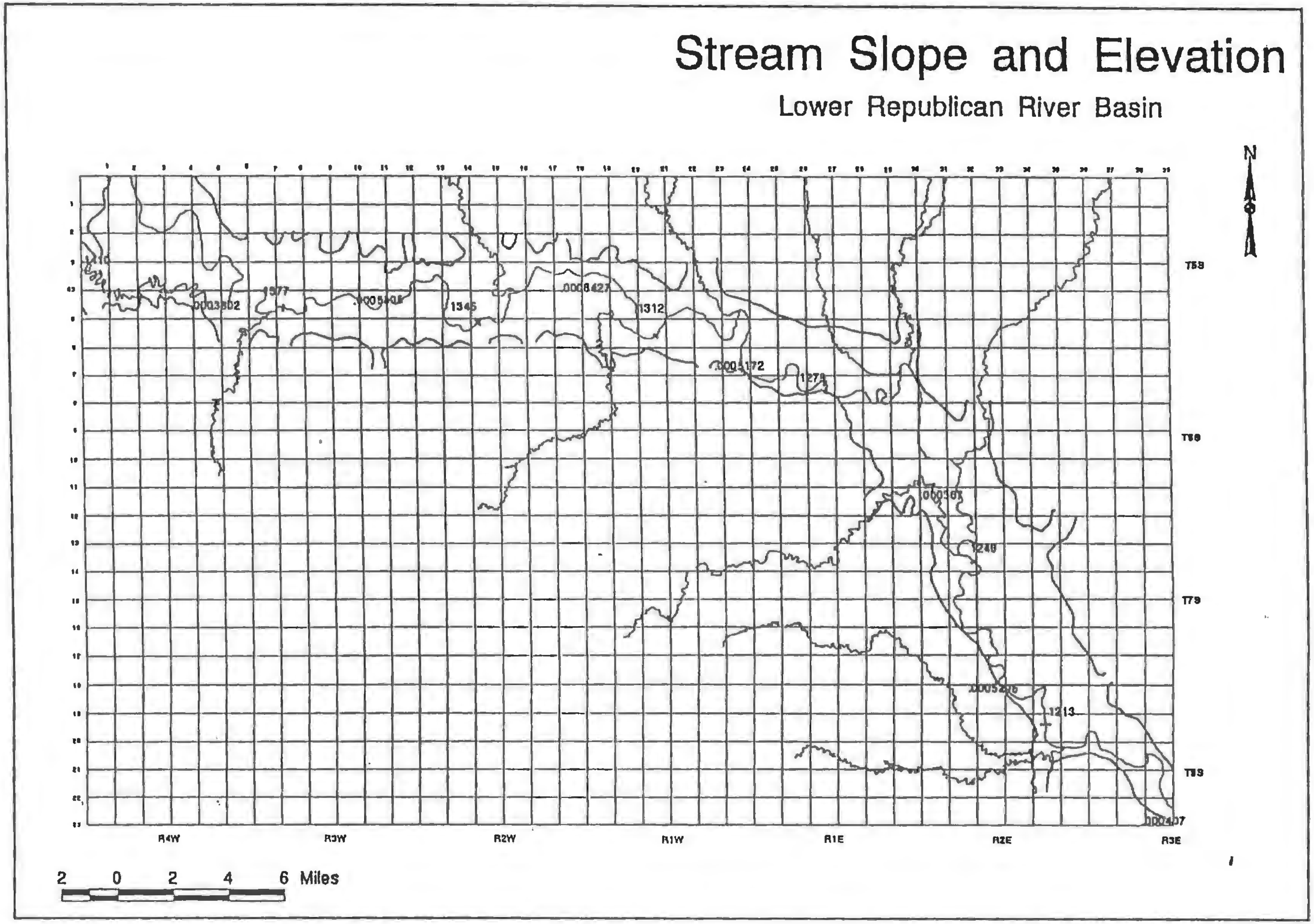


Figure 3.18. Model Grid together with Republican River elevations (in feet) and in-between slopes.

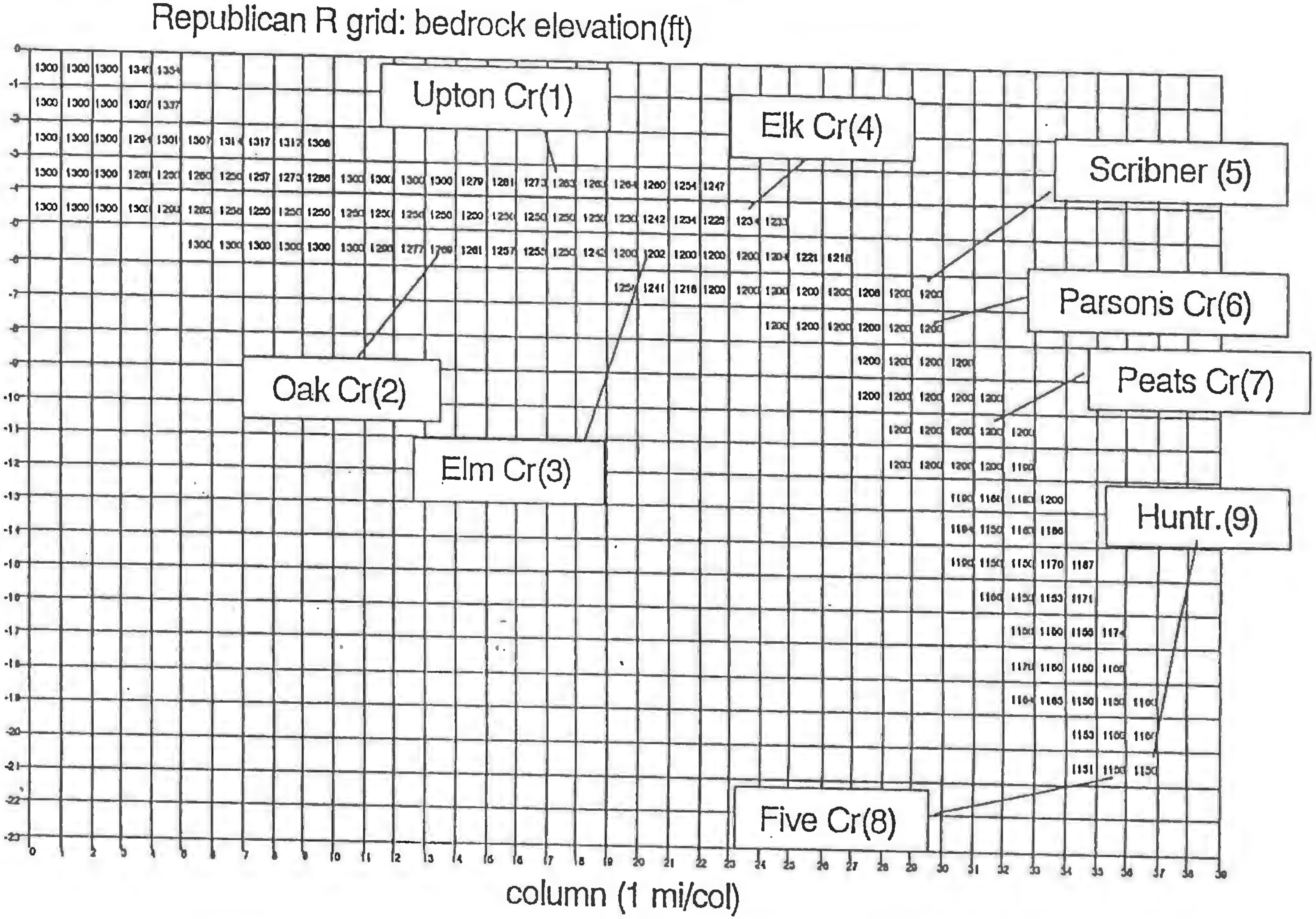


Figure 3.19. Grid bedrock elevation values employed (discretized from Dunlap, 1982).

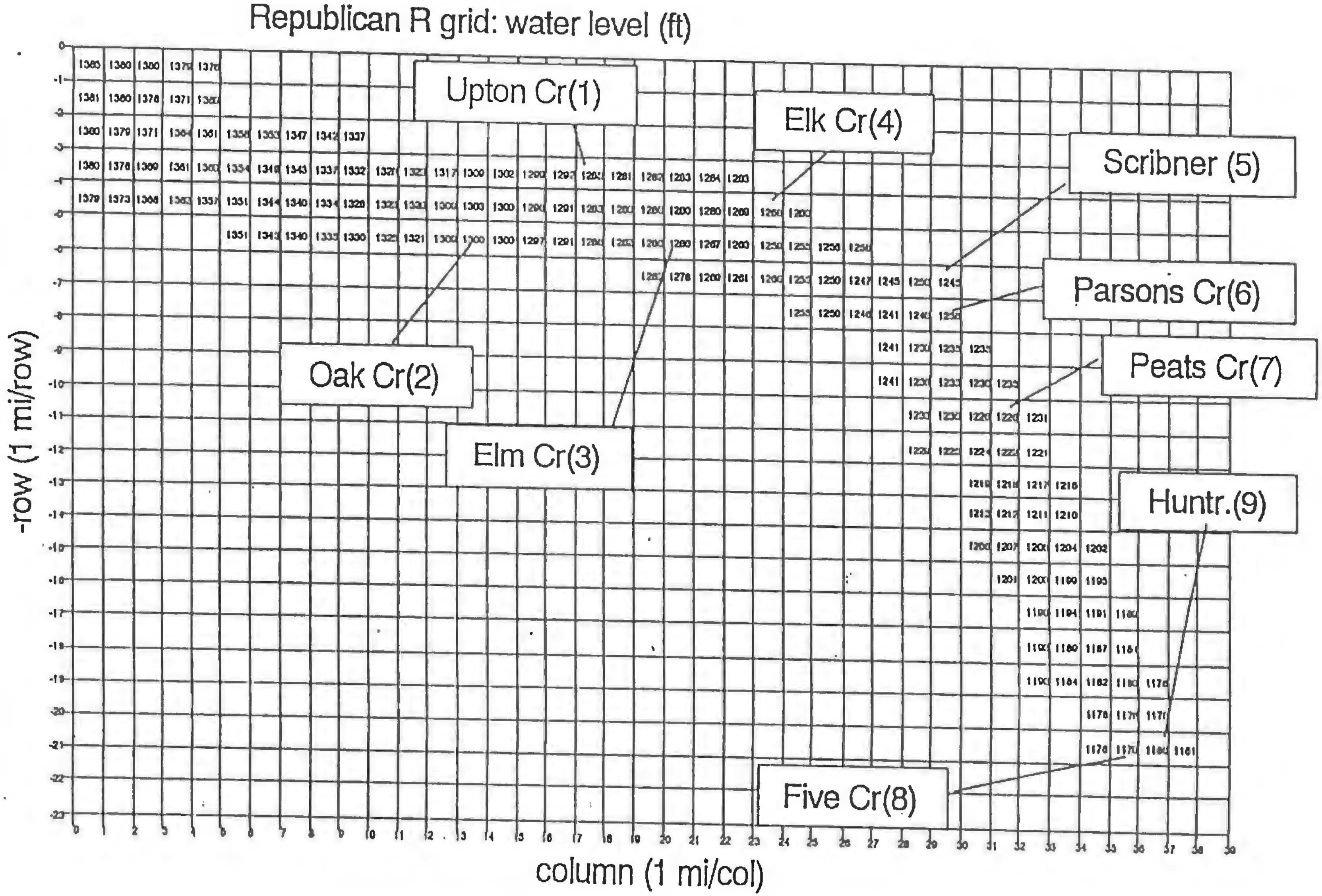
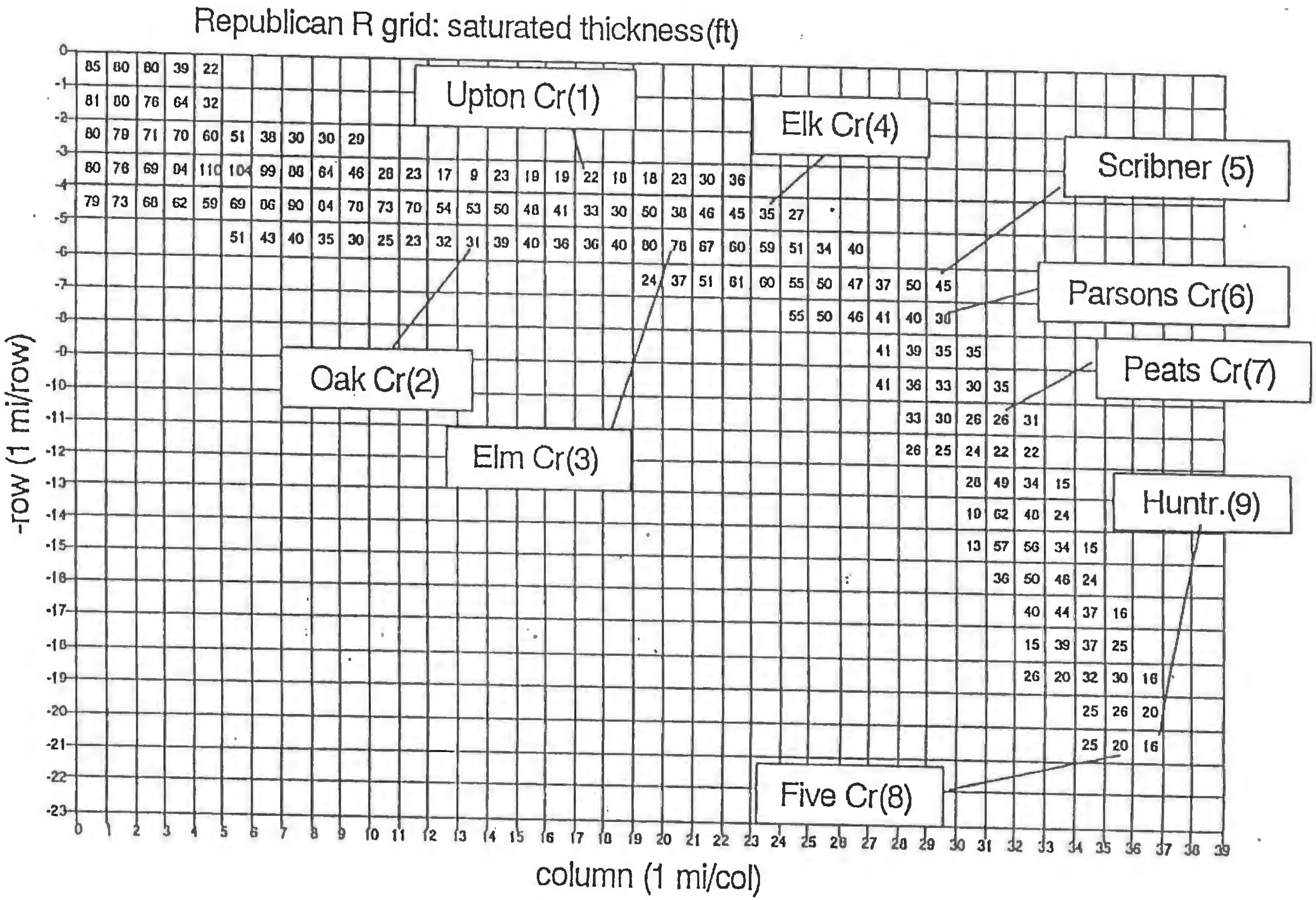


Figure 3.20. 1977 grid water table elevation values (discretized from Dunlap, 1982).



85	80	80	39	22																																	
81	80	76	64	32																																	
80	79	71	70	60	51	38	30	30	29																												
80	76	69	94	110	104	99	88	64	46	28	23	17	9	23	19	19	22	18	18	23	30	36															
79	73	68	62	59	69	86	90	84	78	73	70	54	53	50	48	41	33	30	50	38	46	45	35	27													
					51	43	40	35	30	25	23	32	31	39	40	36	36	40	80	78	67	60	59	51	34	40											
																			24	37	51	61	60	55	50	47	37	50	45							
																								55	50	46	41	40	30							
																											41	39	35	35						
																											41	36	33	30	35					
																												33	30	26	26	31				
																												26	25	24	22	22				
																														28	49	34	15			
																														10	62	48	24			
																														13	57	56	34	15		
																															36	50	46	24		
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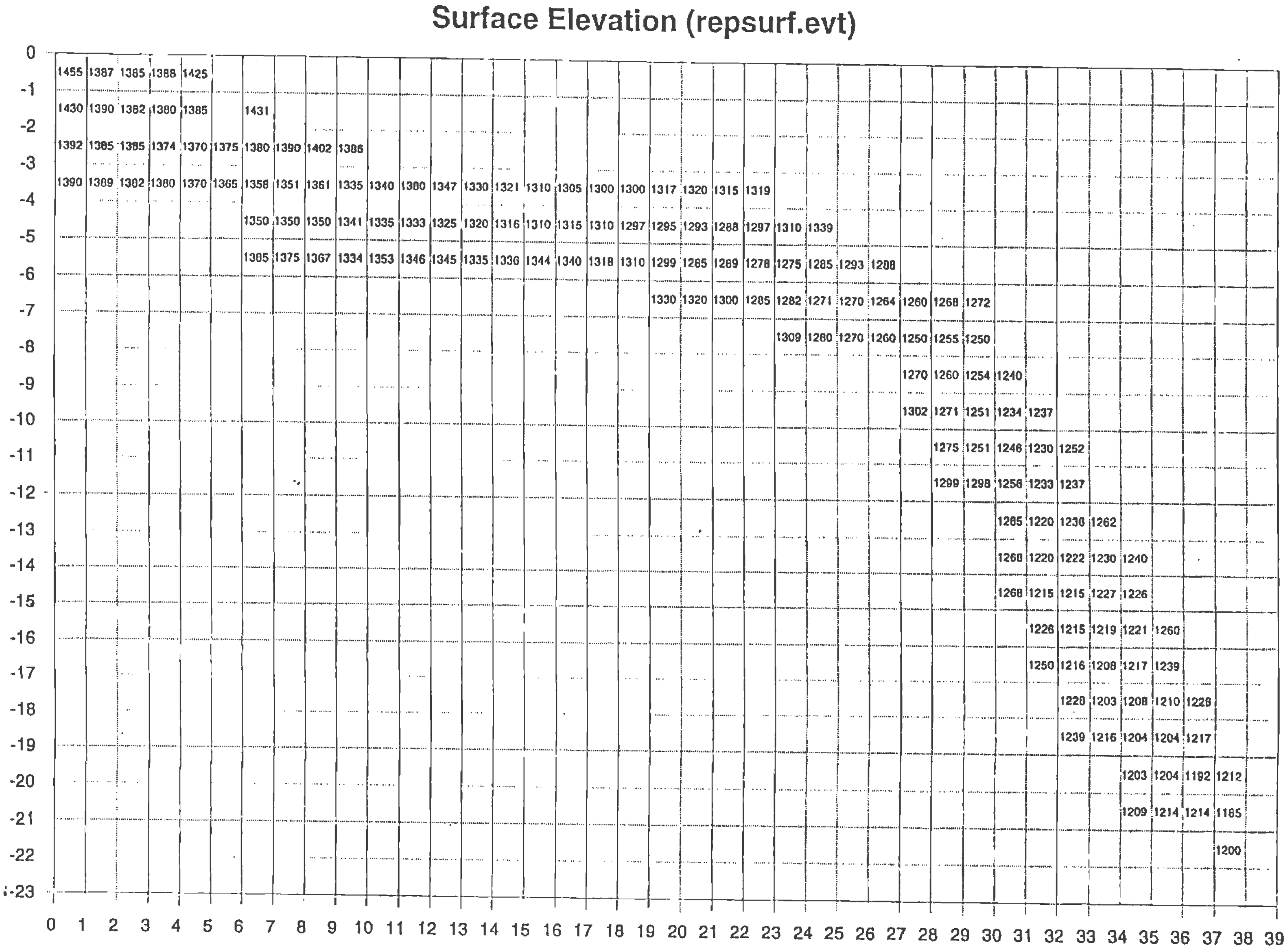
																																15	39	37	25	
																																26	20	32	30	16
																																		25	26	20
																																		25	20	16

Figure 3.21. 1977 grid saturated thickness values derived from Dunlap (1982).



1455	1387	1385	1388	1425																																	
1430	1390	1382	1380	1385		1431																															
1392	1385	1385	1374	1370	1375	1380	1390	1402	1386																												
1390	1389	1382	1380	1370	1365	1358	1351	1361	1335	1340	1380	1347	1330	1321	1310	1305	1300	1300	1317	1320	1315	1319															
						1350	1350	1350	1341	1335	1333	1325	1320	1316	1310	1315	1310	1297	1295	1293	1288	1297	1310	1339													
						1385	1375	1367	1334	1353	1346	1345	1335	1336	1344	1340	1318	1310	1299	1285	1289	1278	1275	1285	1293	1288											
																			1330	1320	1300	1285	1282	1271	1270	1264	1260	1268	1272								
																							1309	1280	1270	1260	1250	1255	1250								
																											1270	1260	1254	1240							
																											1302	1271	1251	1234	1237						
																												1275	1251	1246	1230	1252					
																												1299	1298	1256	1233	1237					
																														1285	1220	1236	1262				
																														1260	1220	1222	1230	1240			
																														1268	1215	1215	1227	1226			
																															1226	1215	1219	1221	1260		
																															1250	1216	1208	1217	1239		
																																1220	1203	1208	1210	1228	
																																1239	1216	1204	1204	1217	
																																		1203	1204	1192	1212
																																		1209	1214	1214	1185
																																					1200

Figure 3.22. Grid land surface elevation values discretized from 7.5-minute USGS topographic maps.

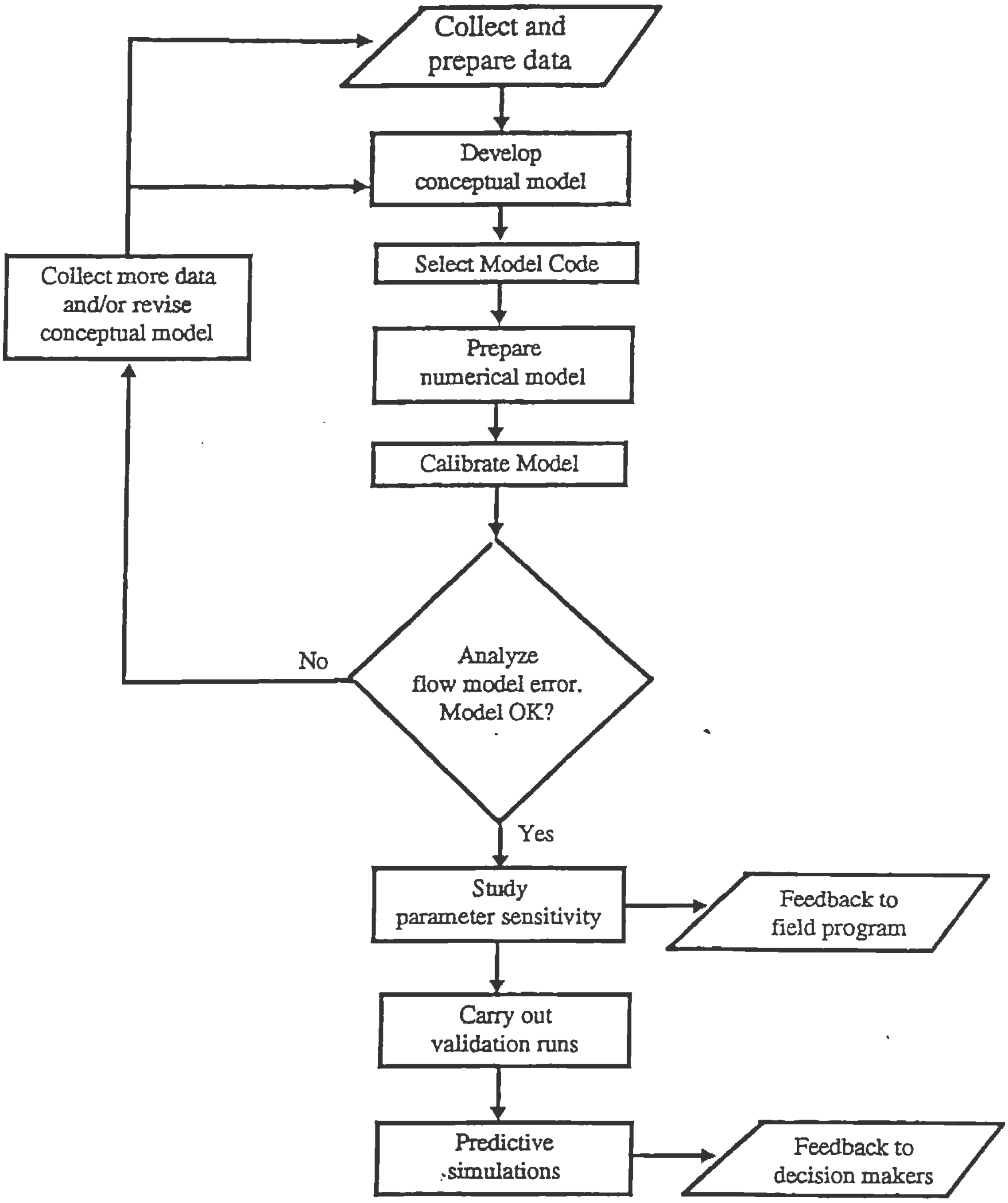


Fig. 4.1. Modeling process flow chart

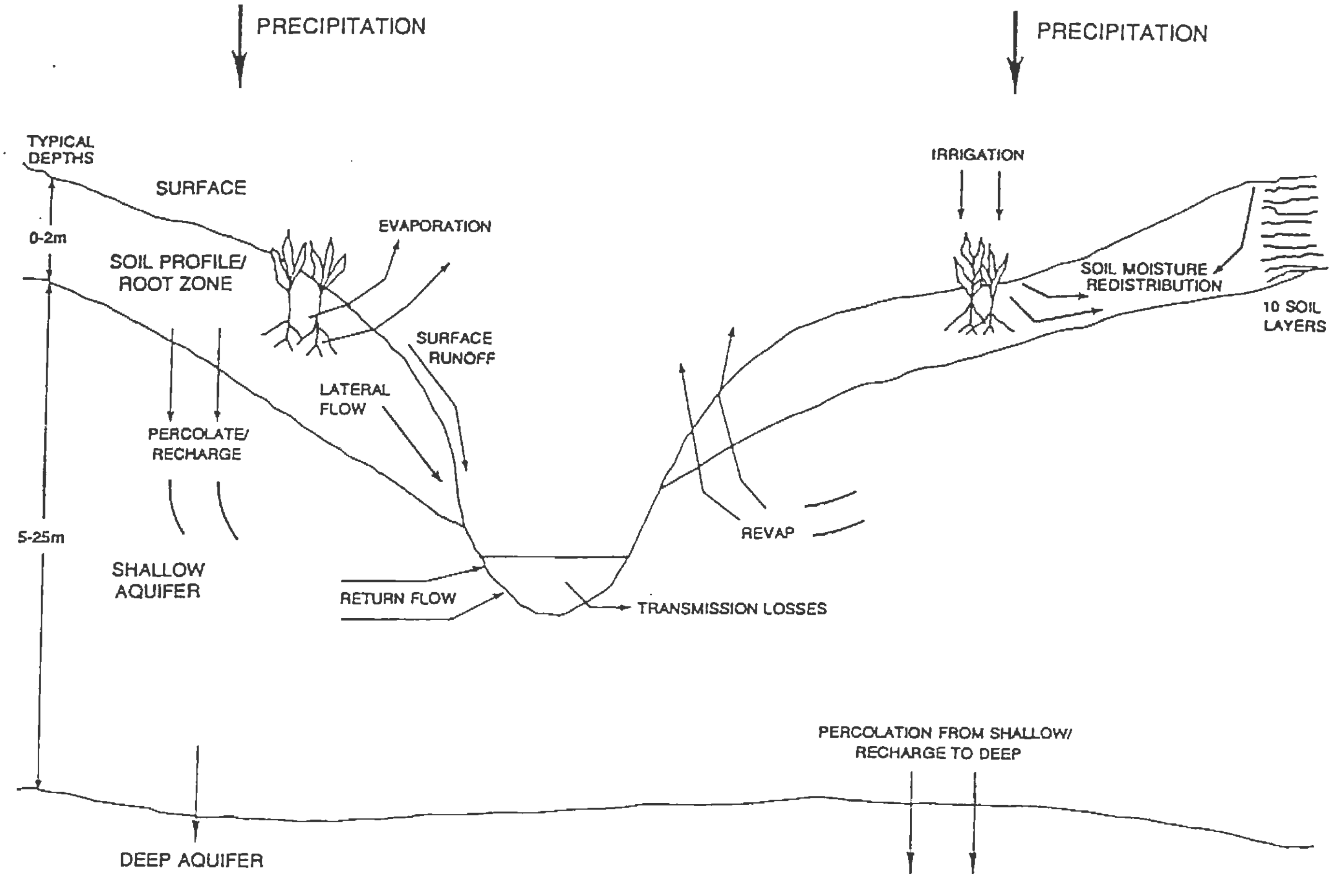


Figure 5.1. Hydrologic components modelled by SWAT.

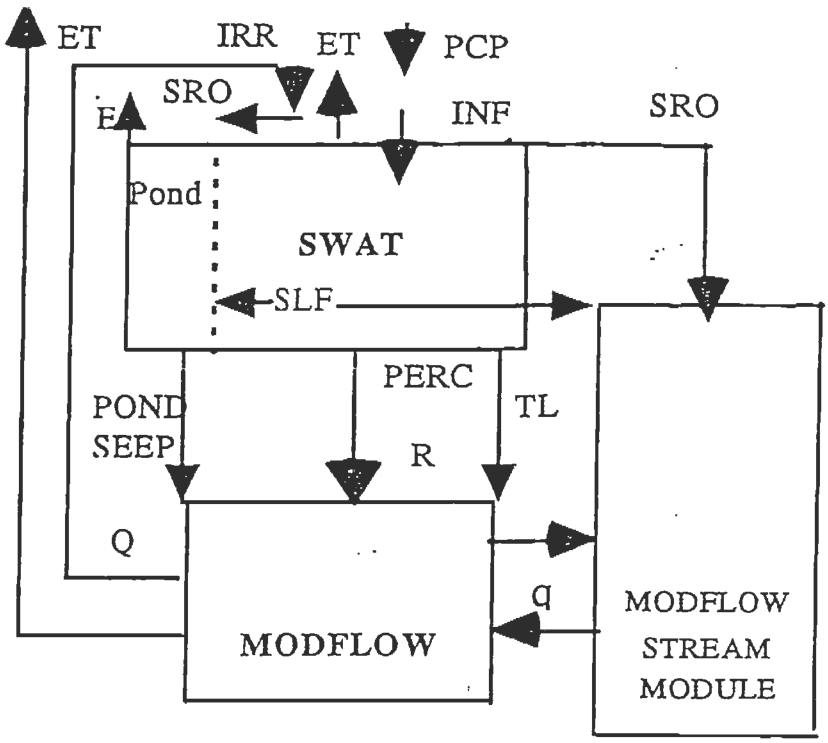


Fig. 5.2 Schematic block diagram of SWAT/MODFLOW linkages.

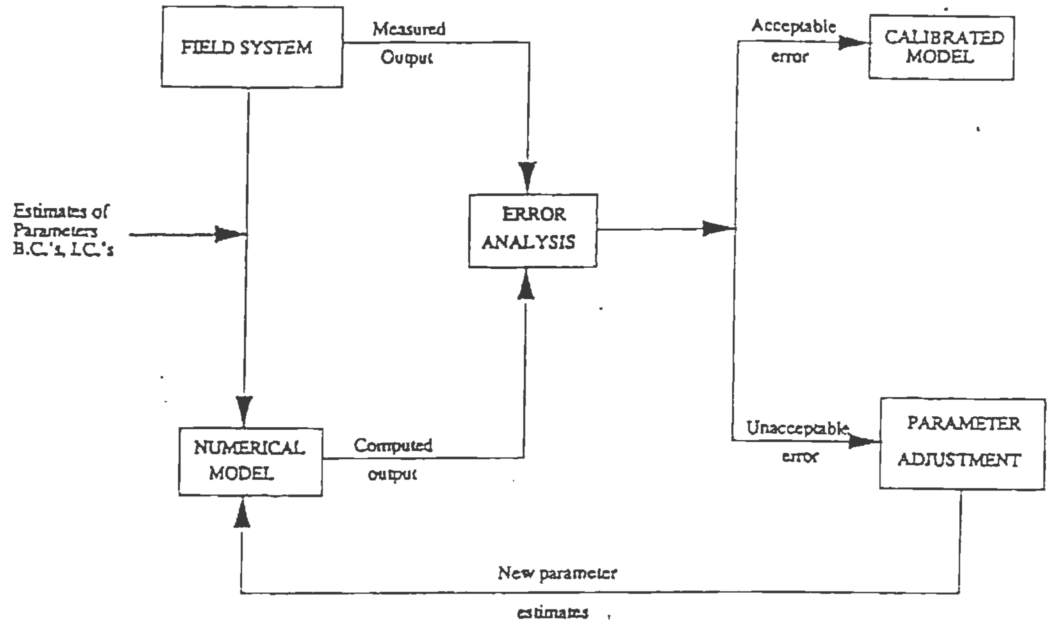


Figure 7.0. Trial-and-error calibration procedure.

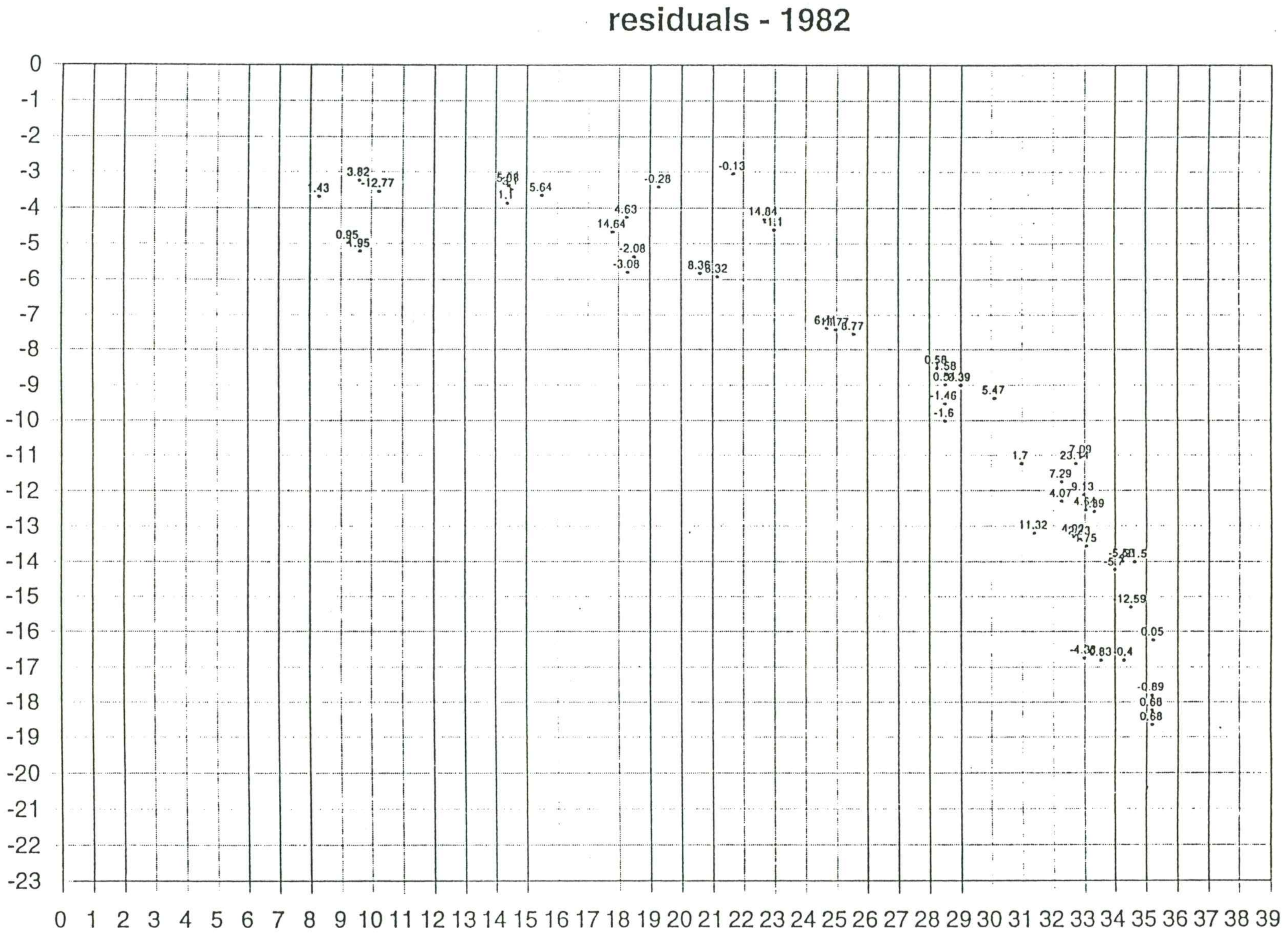


Figure 7.1. Spatial distribution of 1982 residuals (measured minus simulated water levels) in ft.

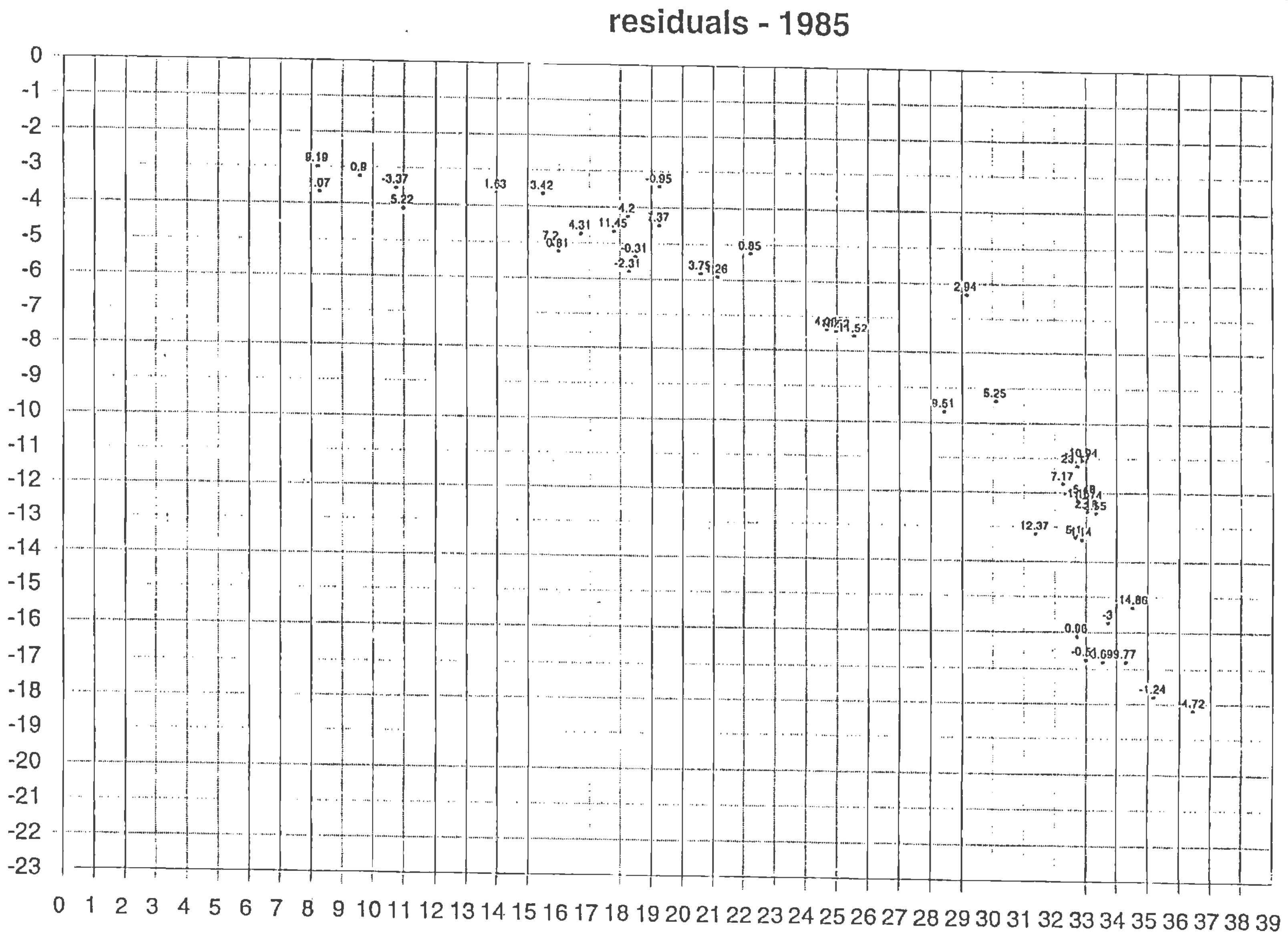


Figure 7.2. Spatial distribution of 1985 residuals (measured minus simulated water levels) in ft.

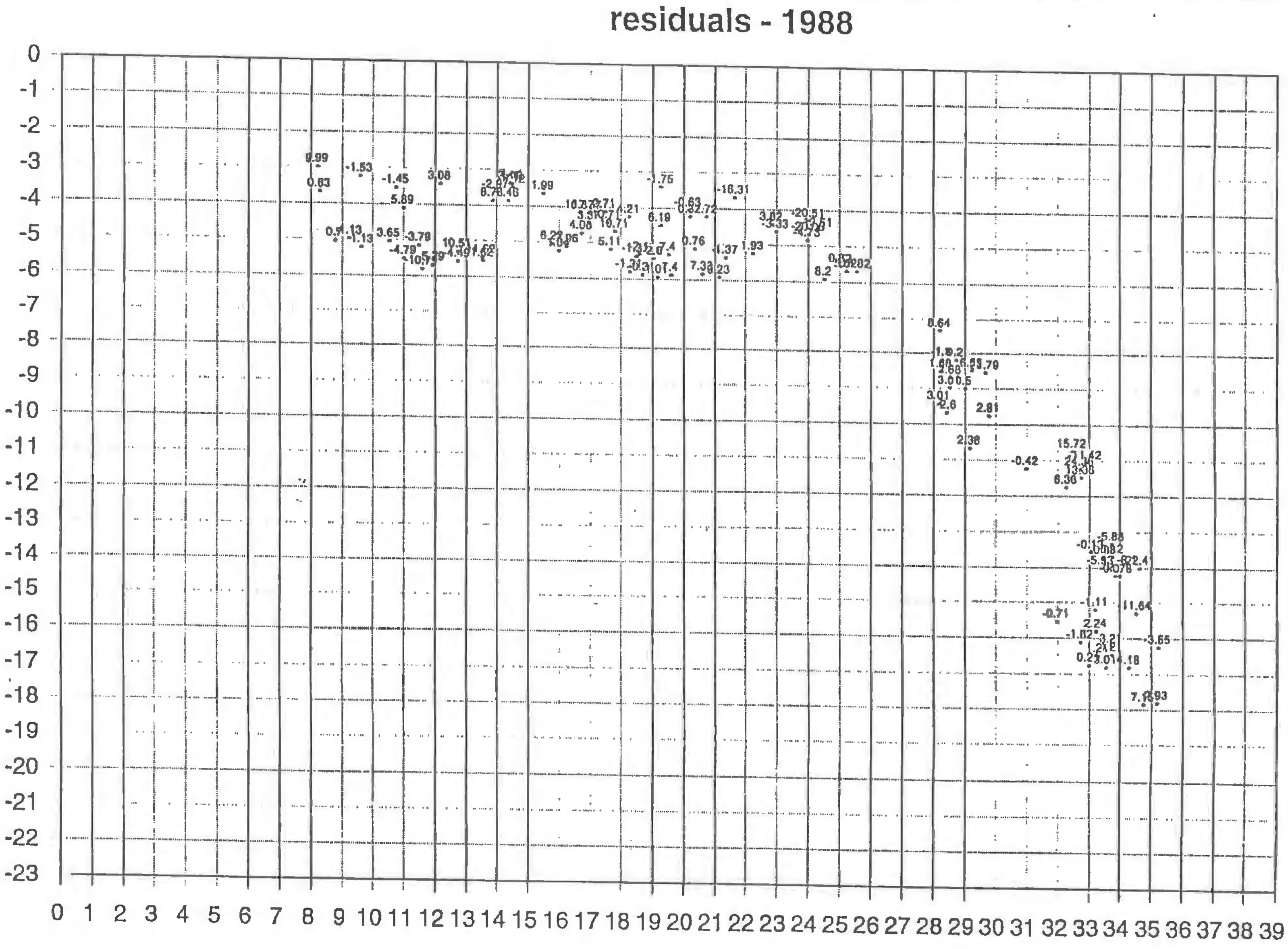


Figure 7.3. Spatial distribution of 1988 residuals (measured minus simulated water levels) in ft.

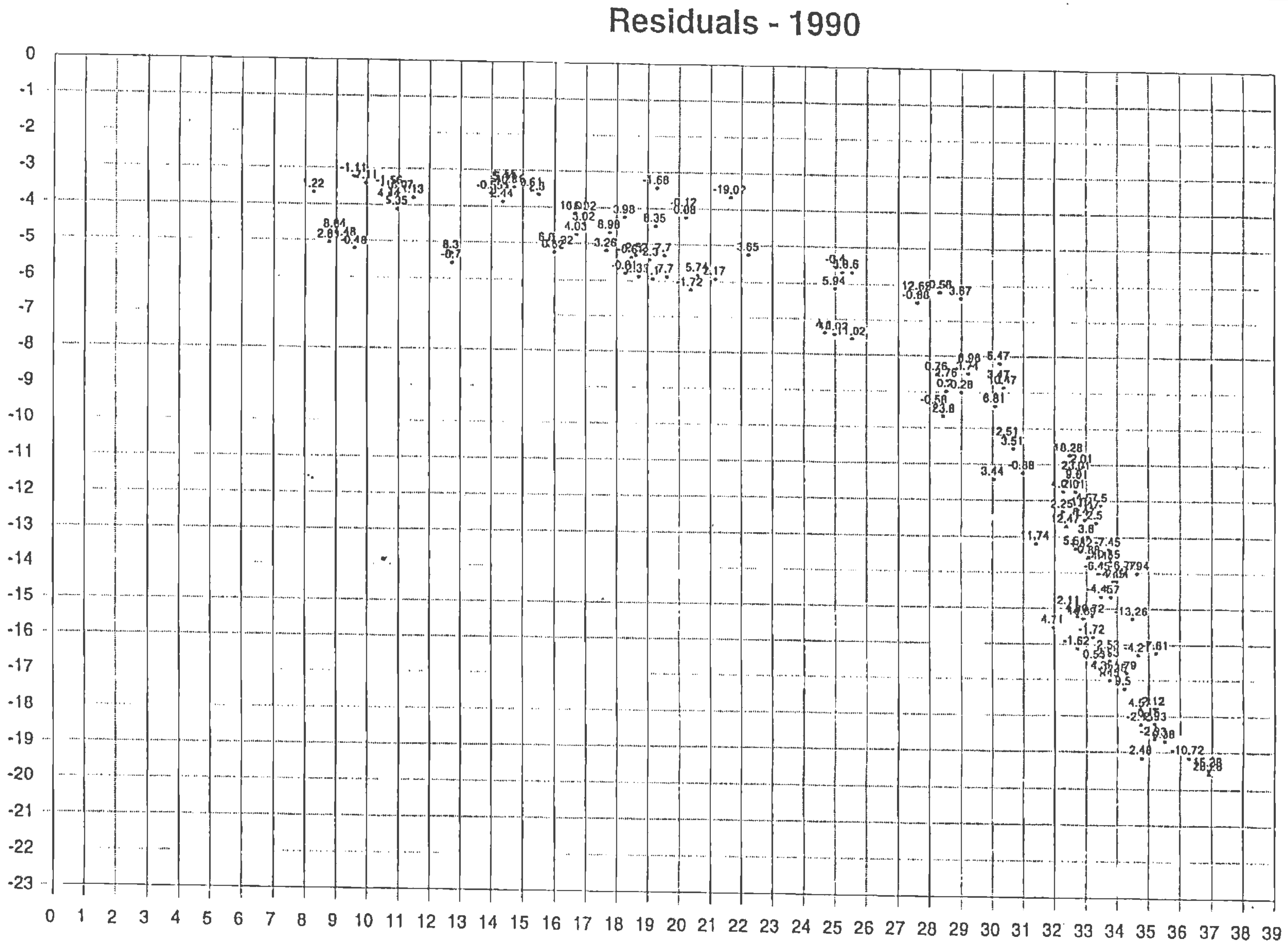


Figure 7.4. Spatial distribution of 1990 residuals (measured minus simulated water levels) in ft.

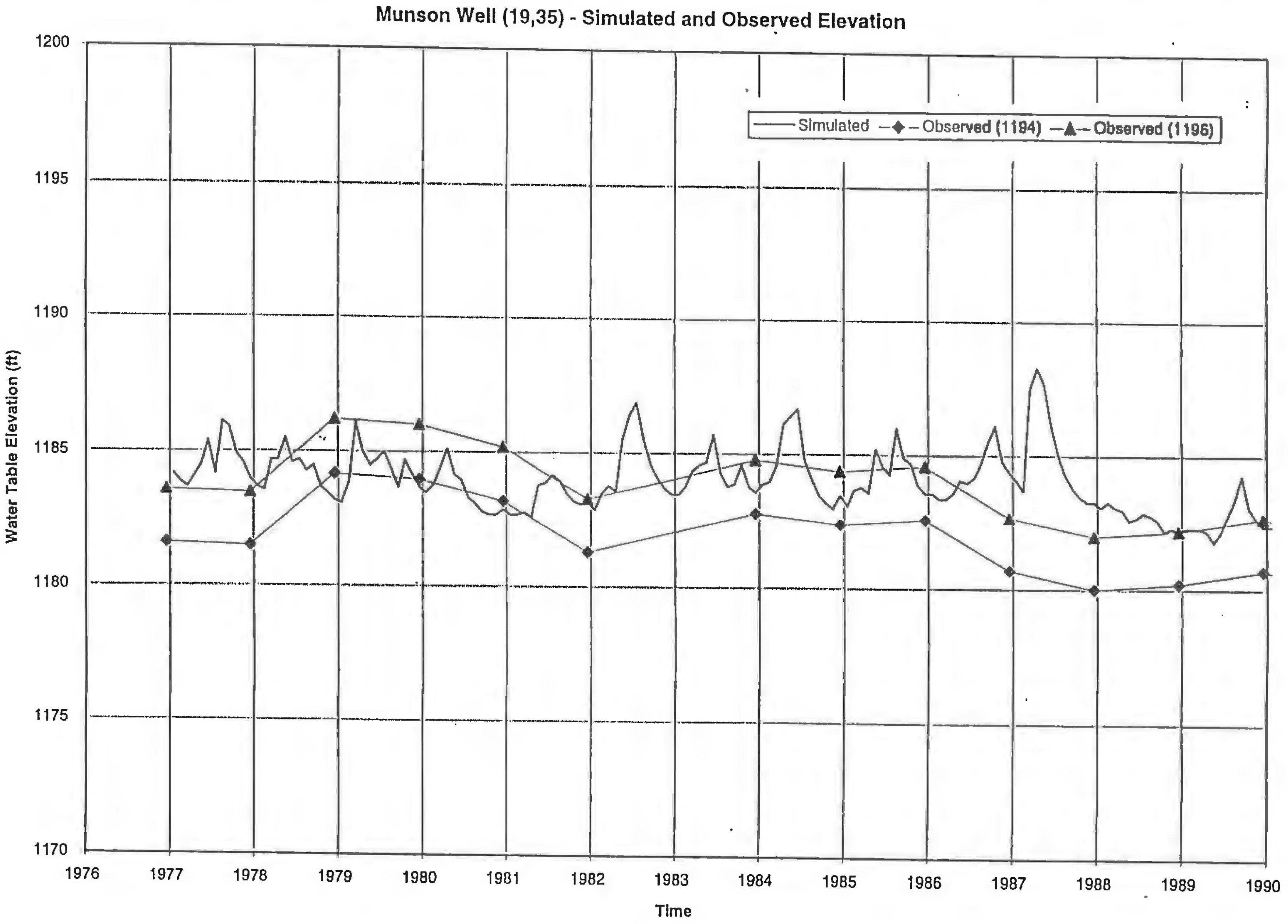


Figure 7.5. 1977-1990 measured (based on two land surface elevation estimates) and simulated water table hydrograph (in ft) for a well located in Twp. 8S, R2E, S2cca, reported in Munson (1991).

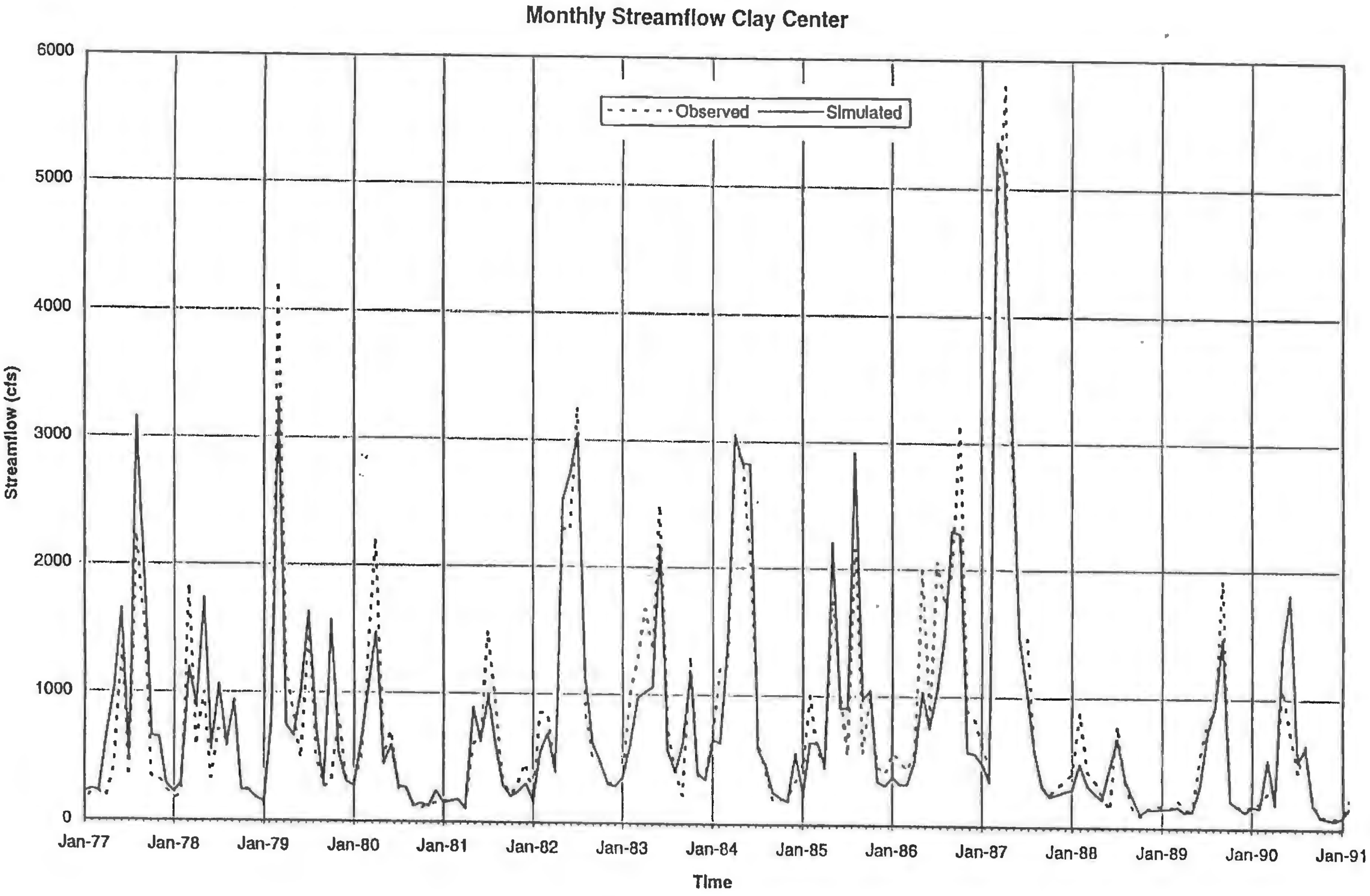


Figure 7.6a. 1977-1990 measured and simulated monthly streamflows (in cfs) at Clay Center displayed on arithmetic scale.

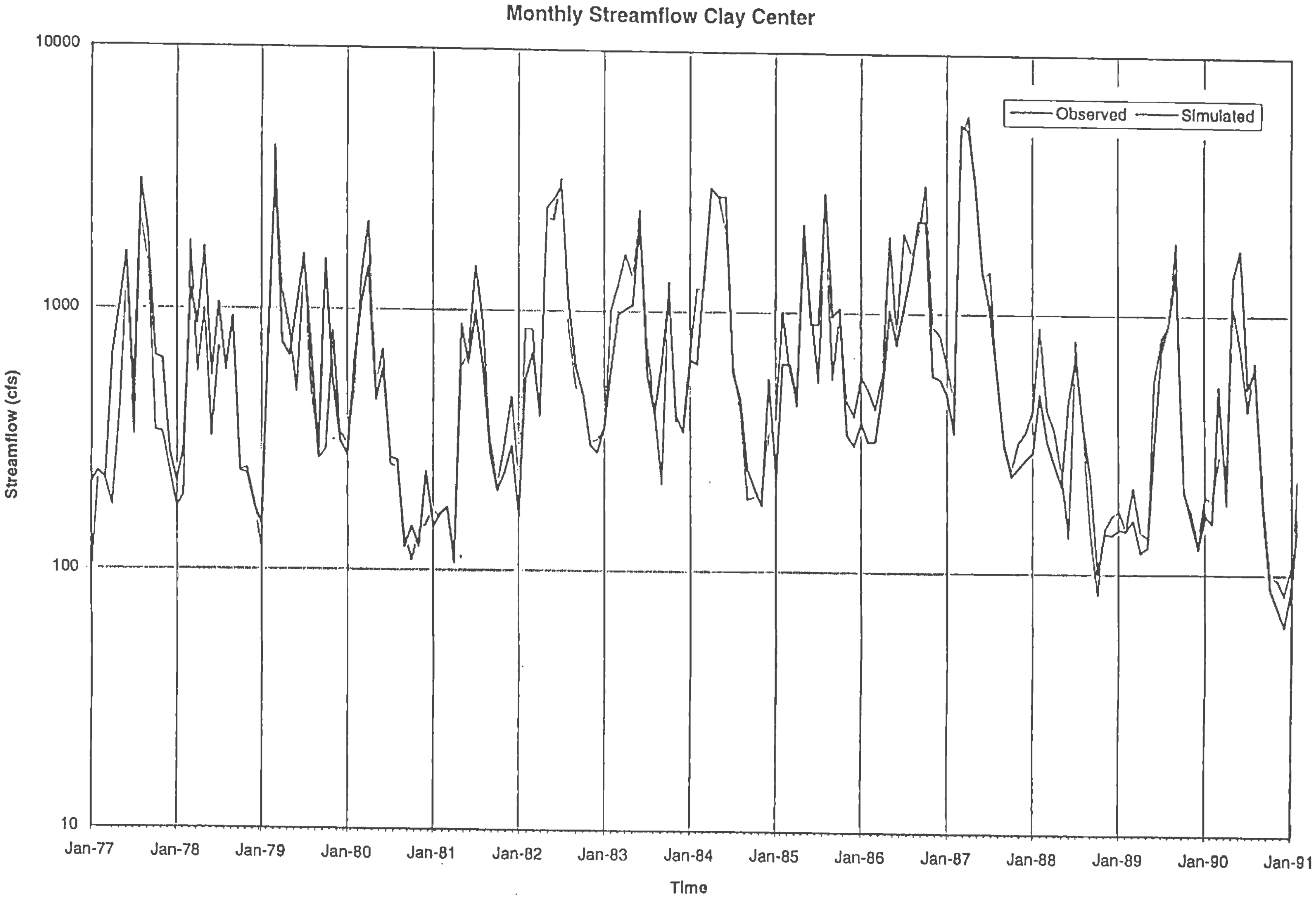


Figure 7.6b. 1977-1990 measured and simulated monthly streamflows (in cfs) at Clay Center displayed on logarithmic scale.

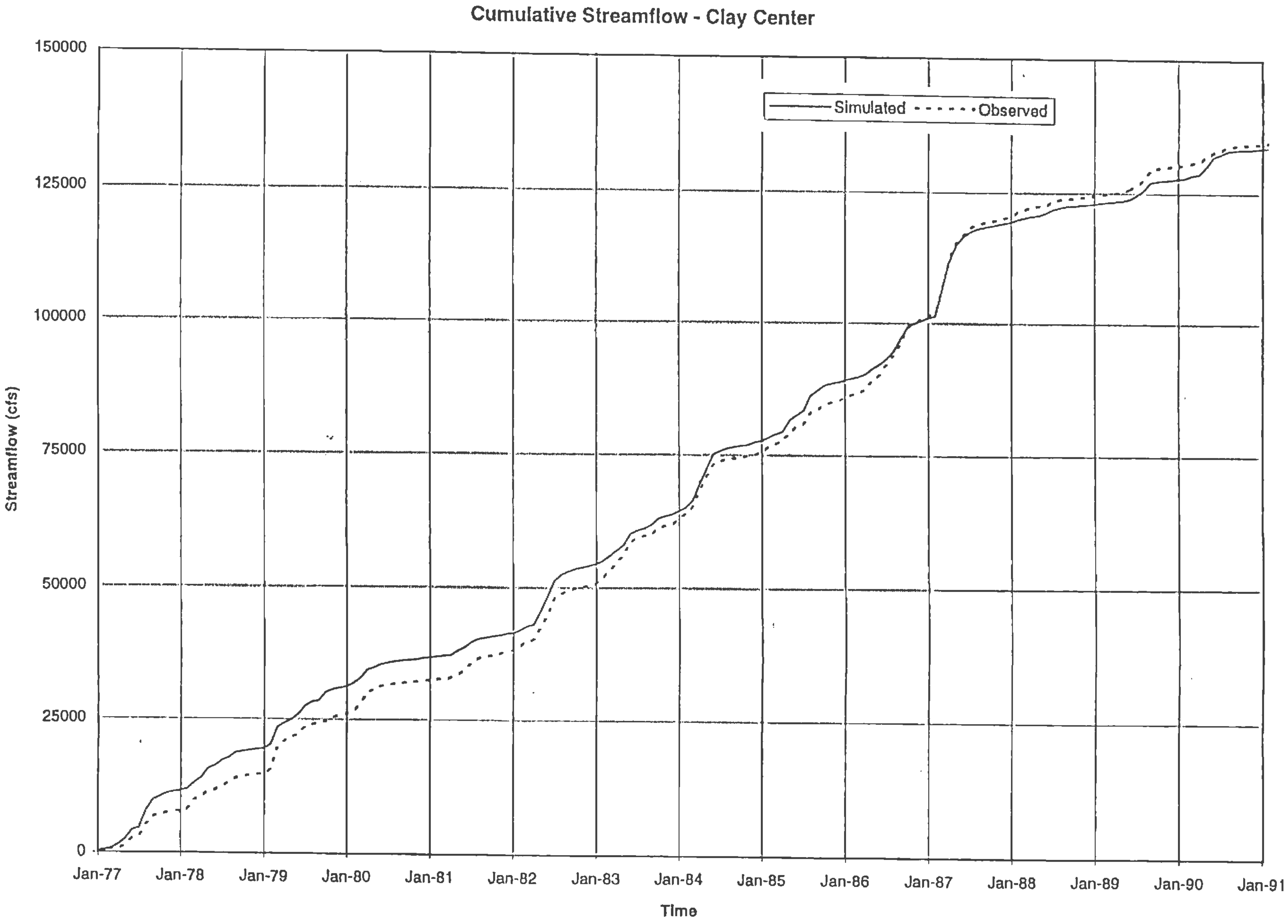


Figure 7.7. 1977-1990 measured and simulated cumulative monthly streamflow (in cfs) at Clay Center.

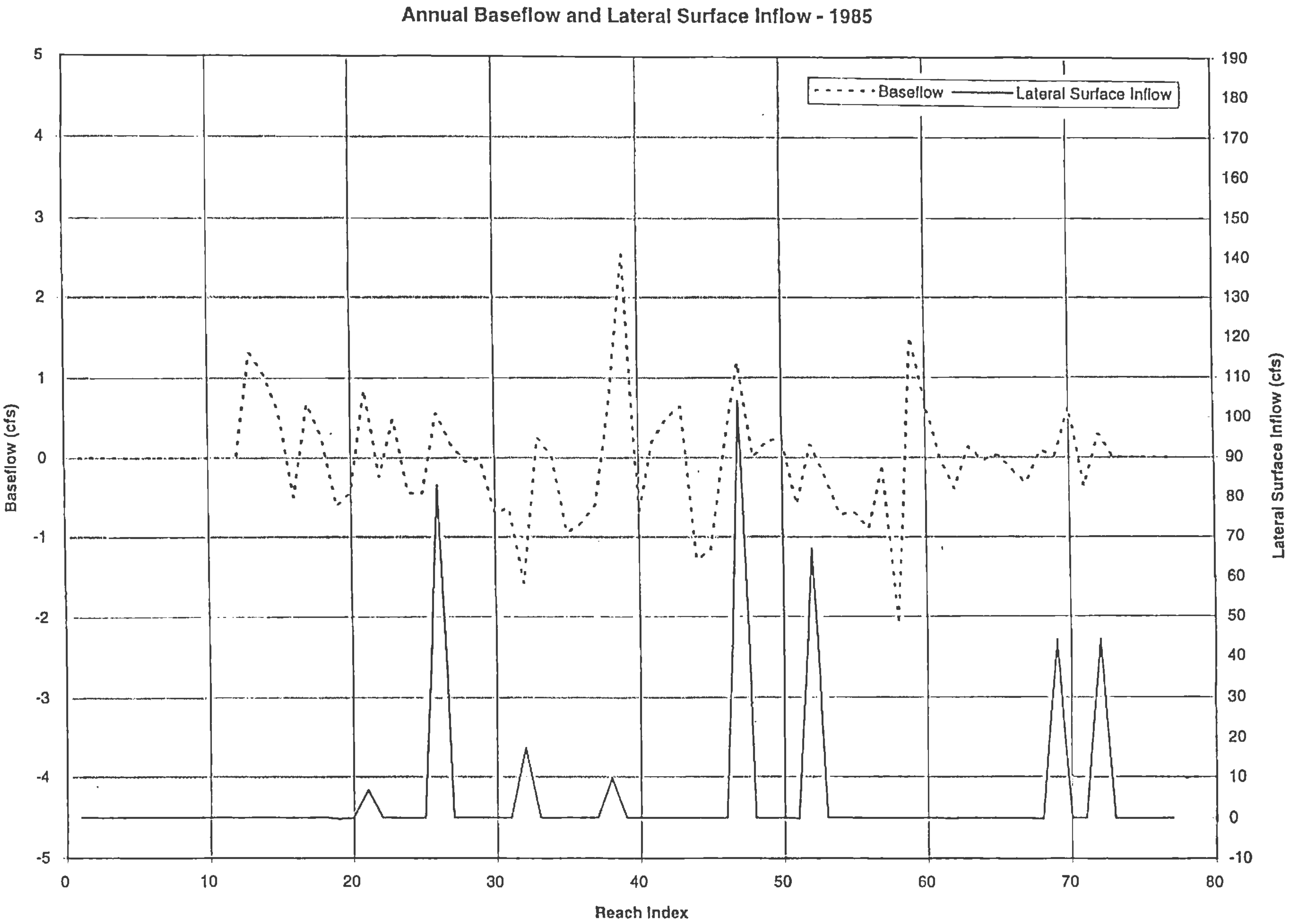


Figure 7.8. Stream leakage losses (negative values) and gains (baseflow; positive values), and lateral inflows to the Republican River from each subbasin from Concordia to Clay Center for 1985. All values in cfs.

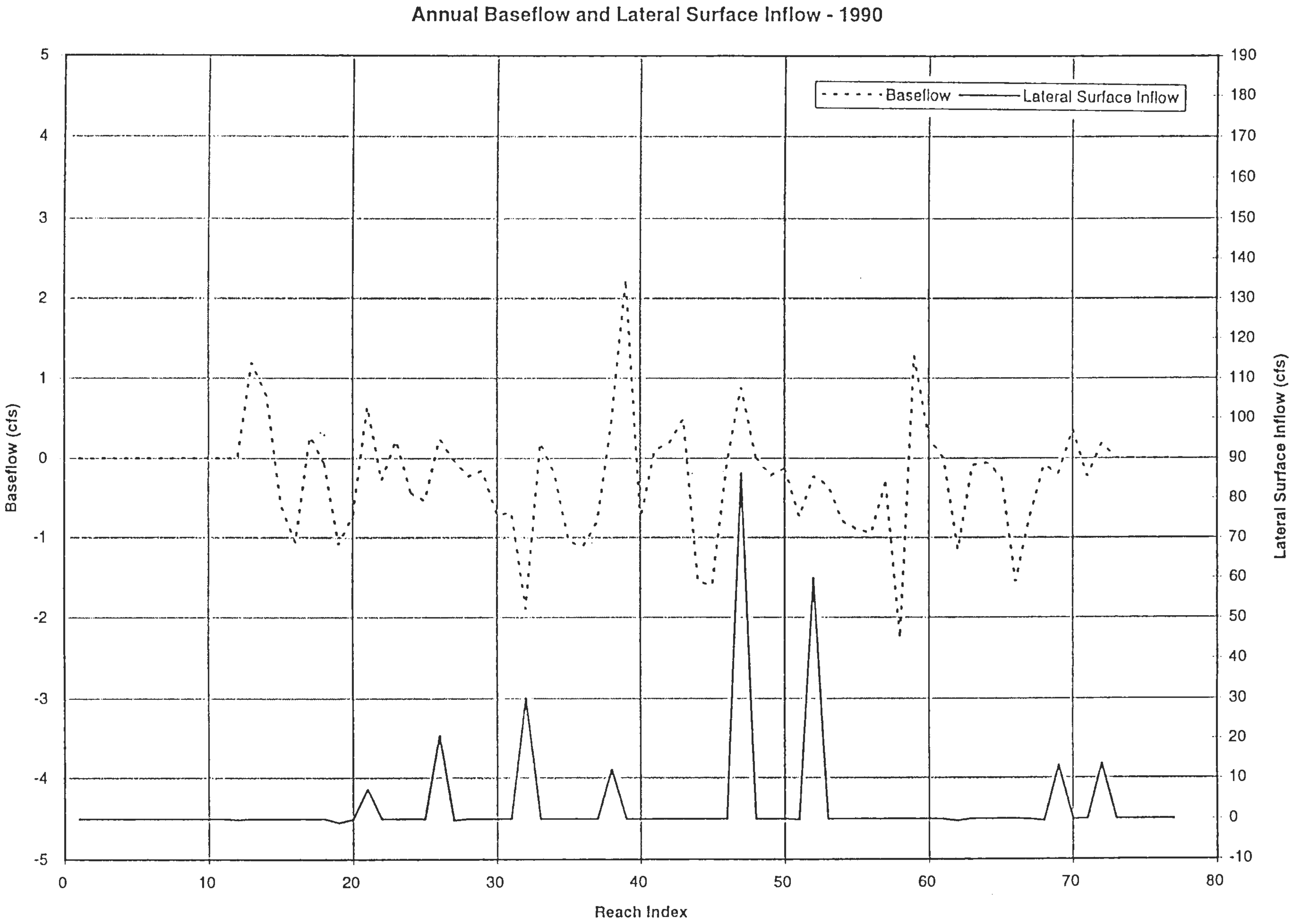


Figure 7.9. Stream leakage losses (negative values) and gains (baseflow; positive values), and lateral inflows to the Republican River from each subbasin from Concordia to Clay Center for 1990. All values in cfs.

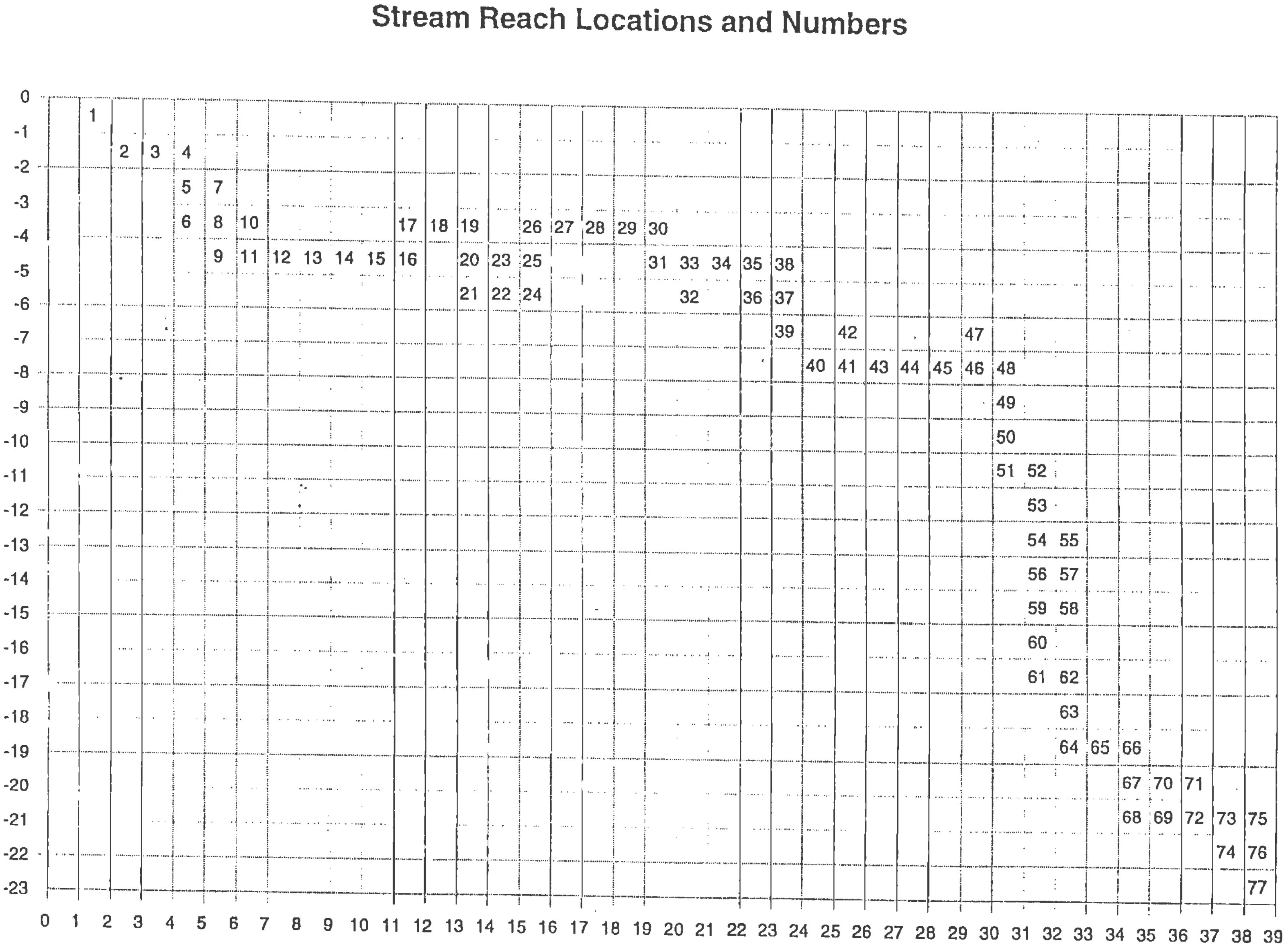


Figure 7.10. Republican River reach numbers employed in the model.

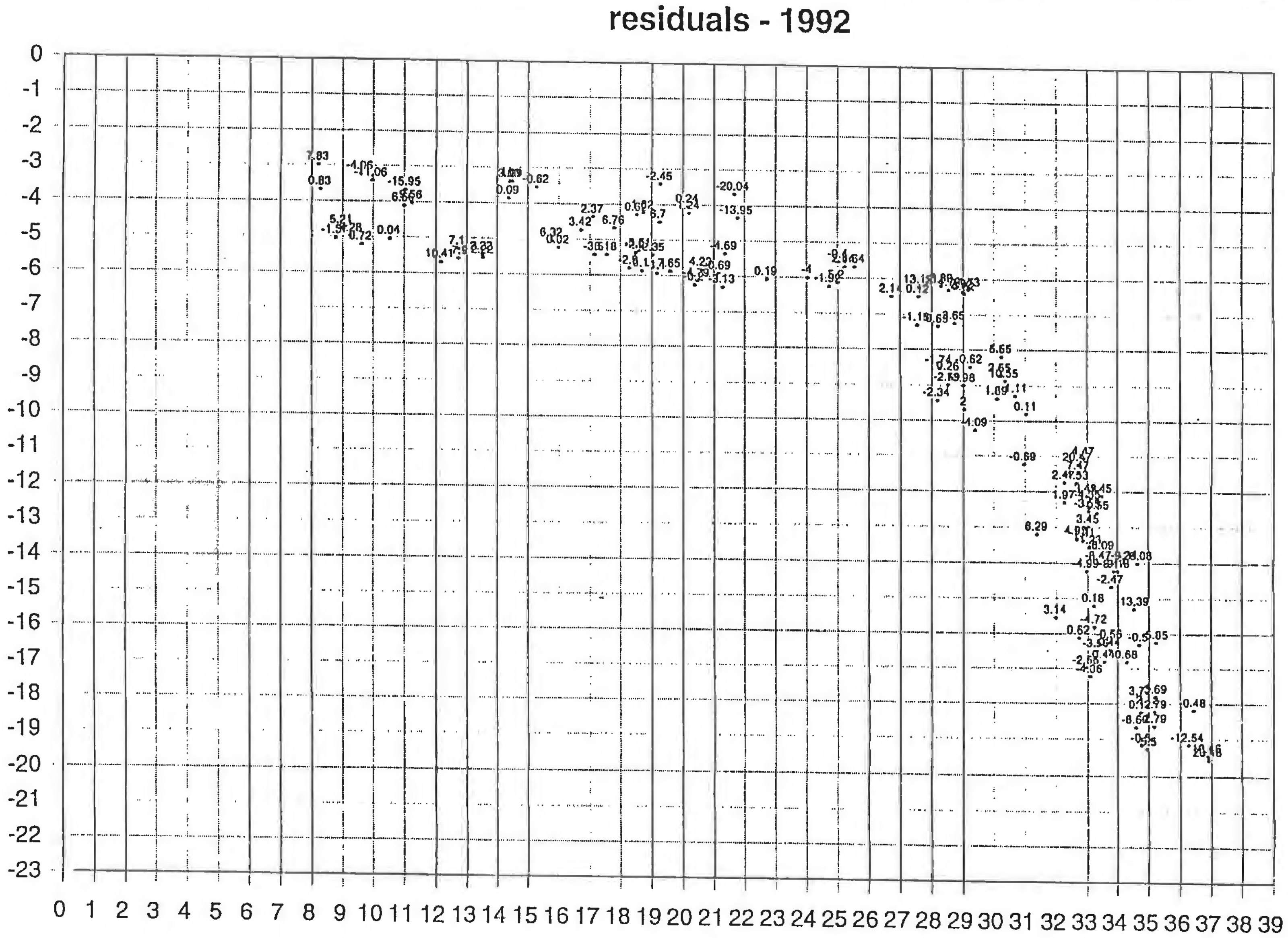


Figure 8.1. Spatial distribution of 1992 residuals (measured minus simulated water levels) in ft.

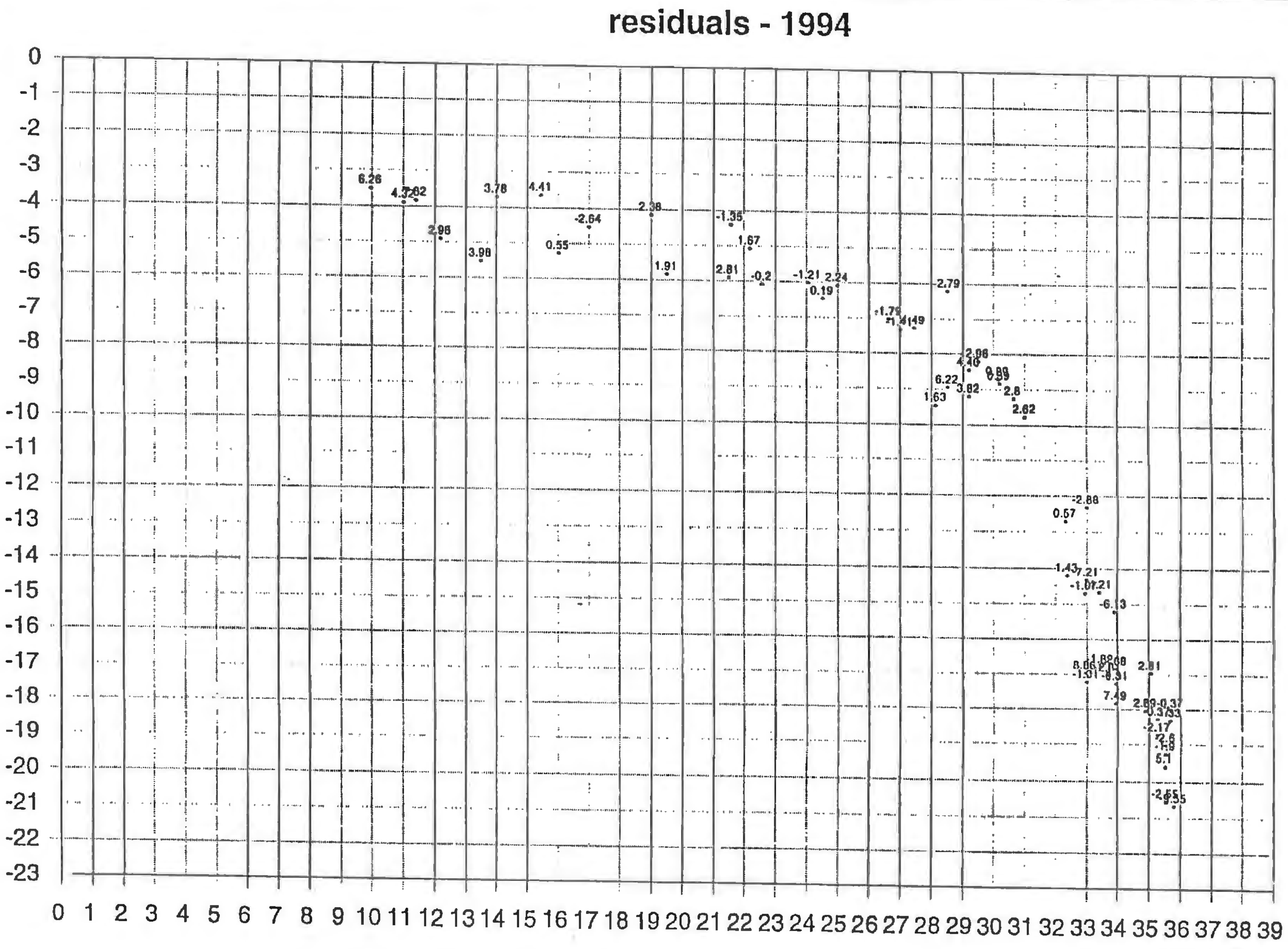


Figure 8.2. Spatial distribution of 1994 residuals (measured minus simulated water levels) in ft.

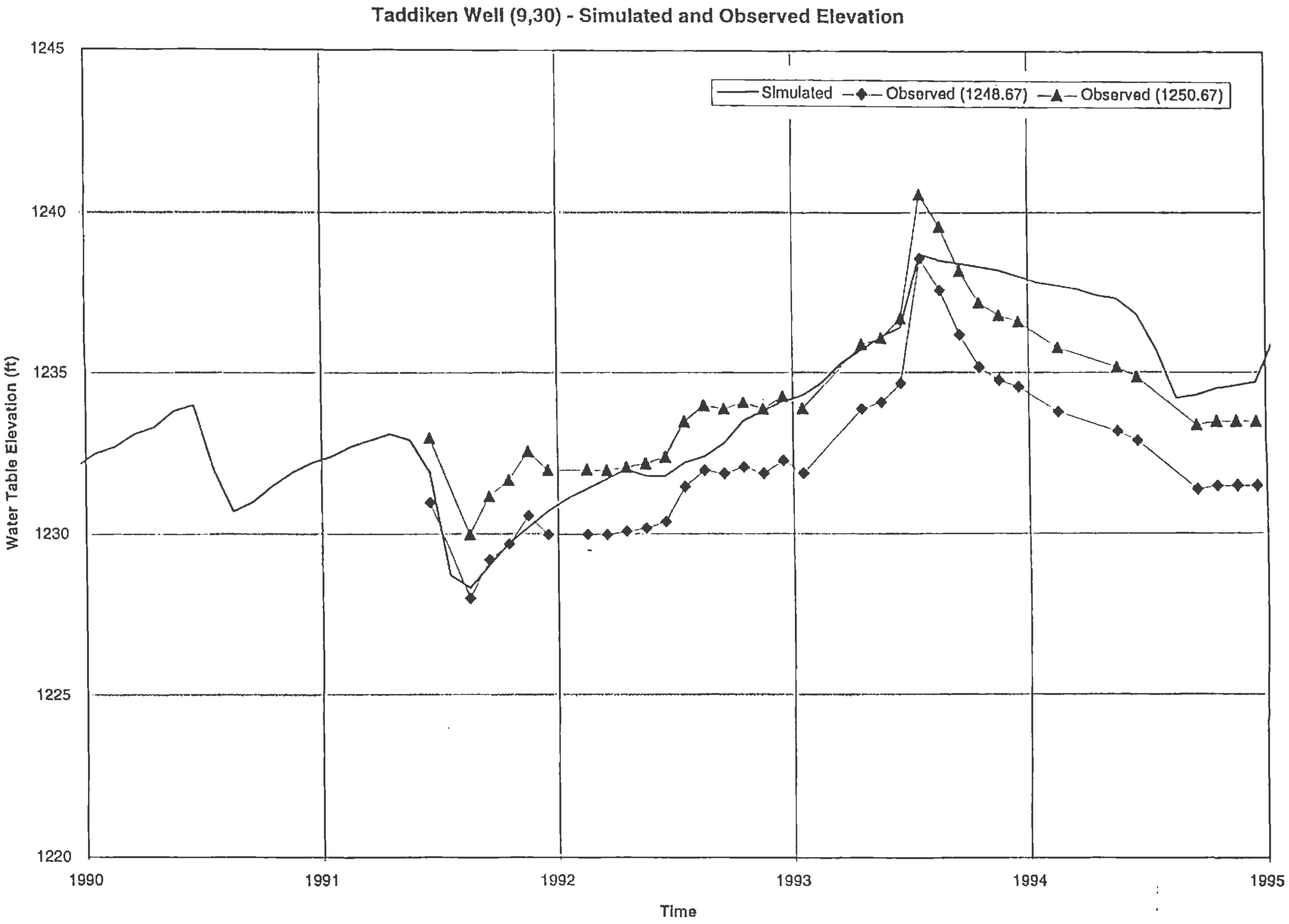


Figure 8.3. 1991-1994 measured (based on two land surface elevation estimates) and simulated water table hydrograph (in ft) for the Taddiken well located in Twp 6S, R1E, S13bcc.

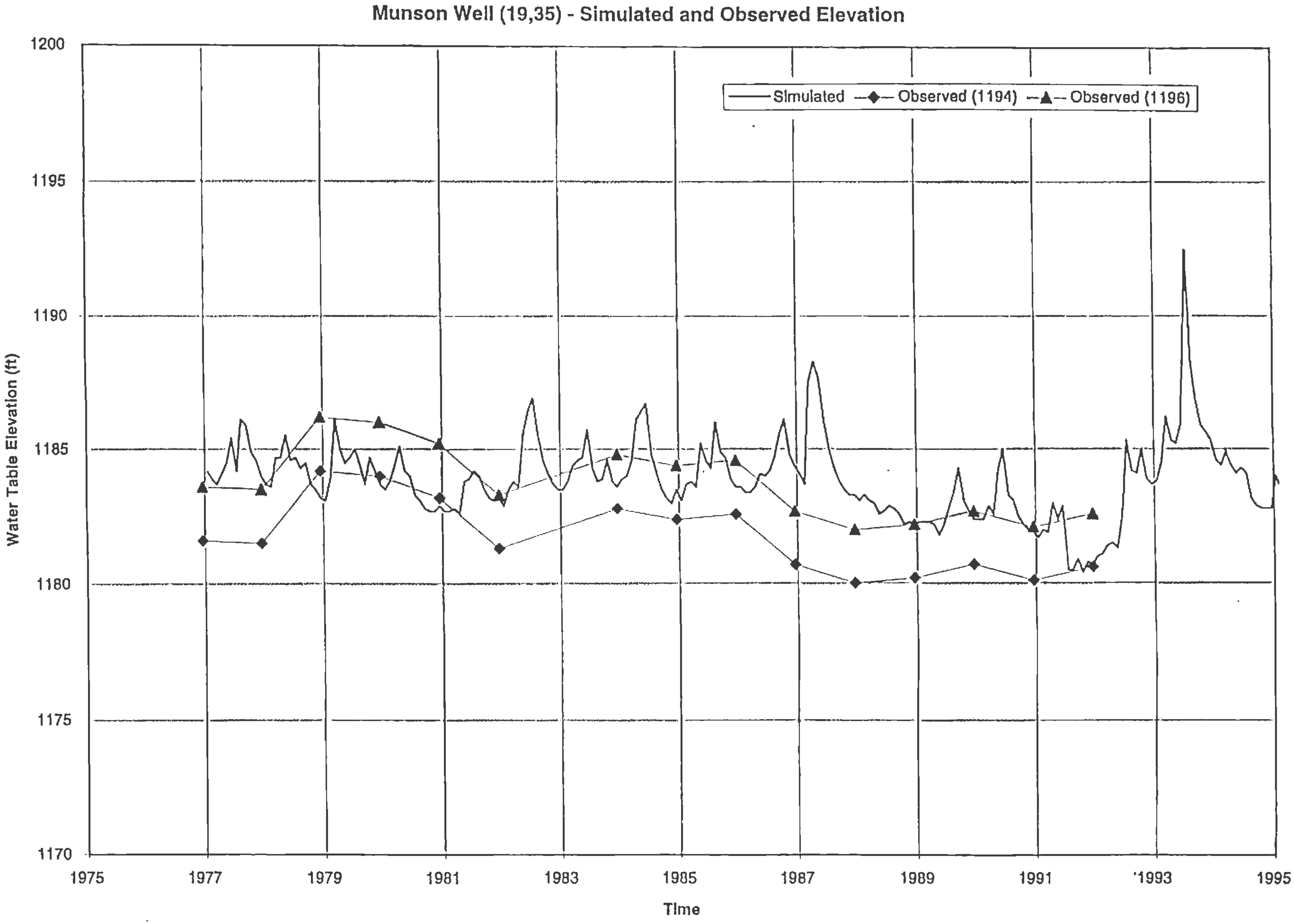


Figure 8.4. 1977-1991 measured (based on two land surface elevation estimates) and simulated water table hydrograph (in ft) for a well located in Twp 8S, R2E, S2cca, reported in Munson (1991).

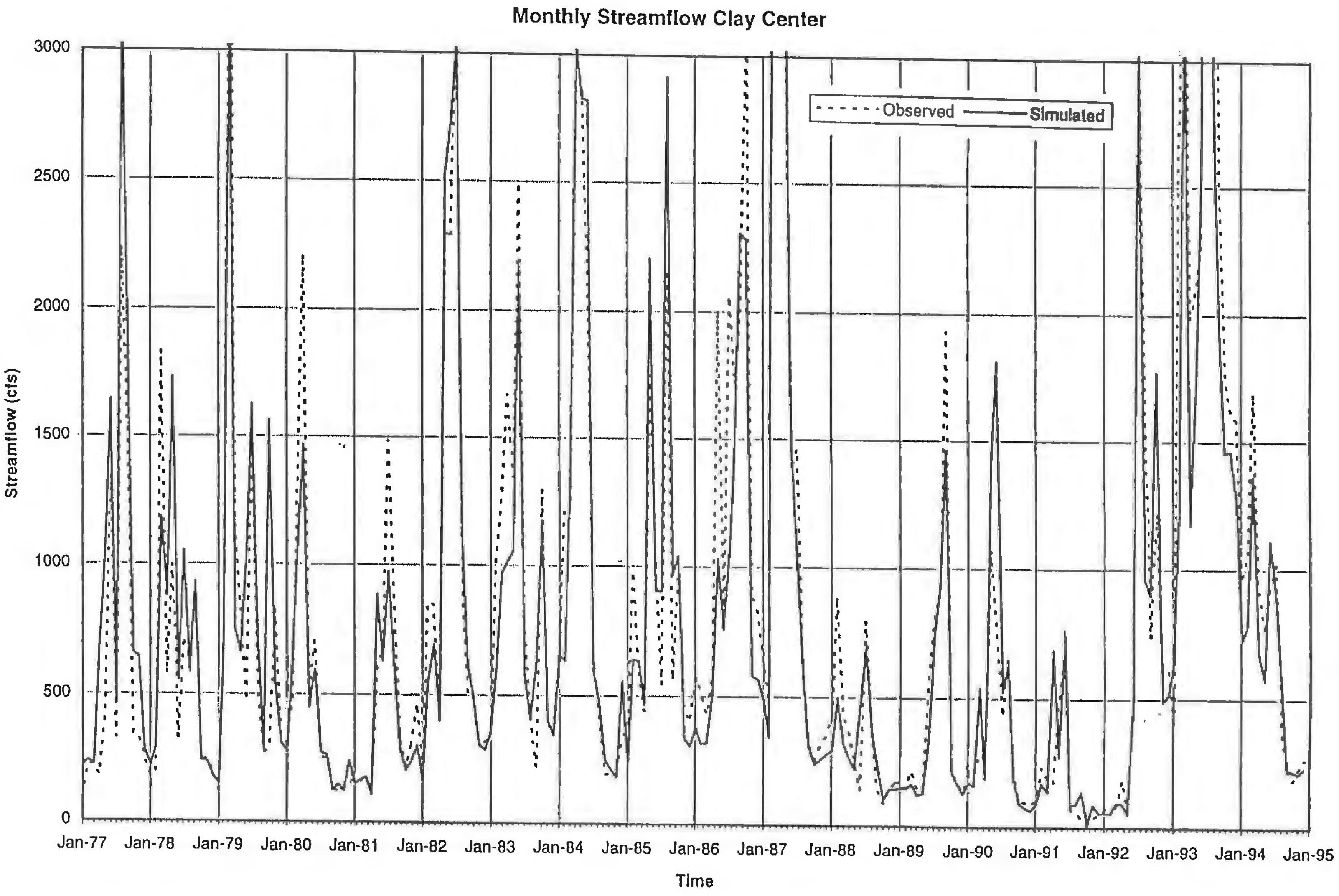


Figure 8.5a. 1977-1994 measured and simulated monthly streamflows (in cfs) at Clay Center displayed on arithmetic scale.

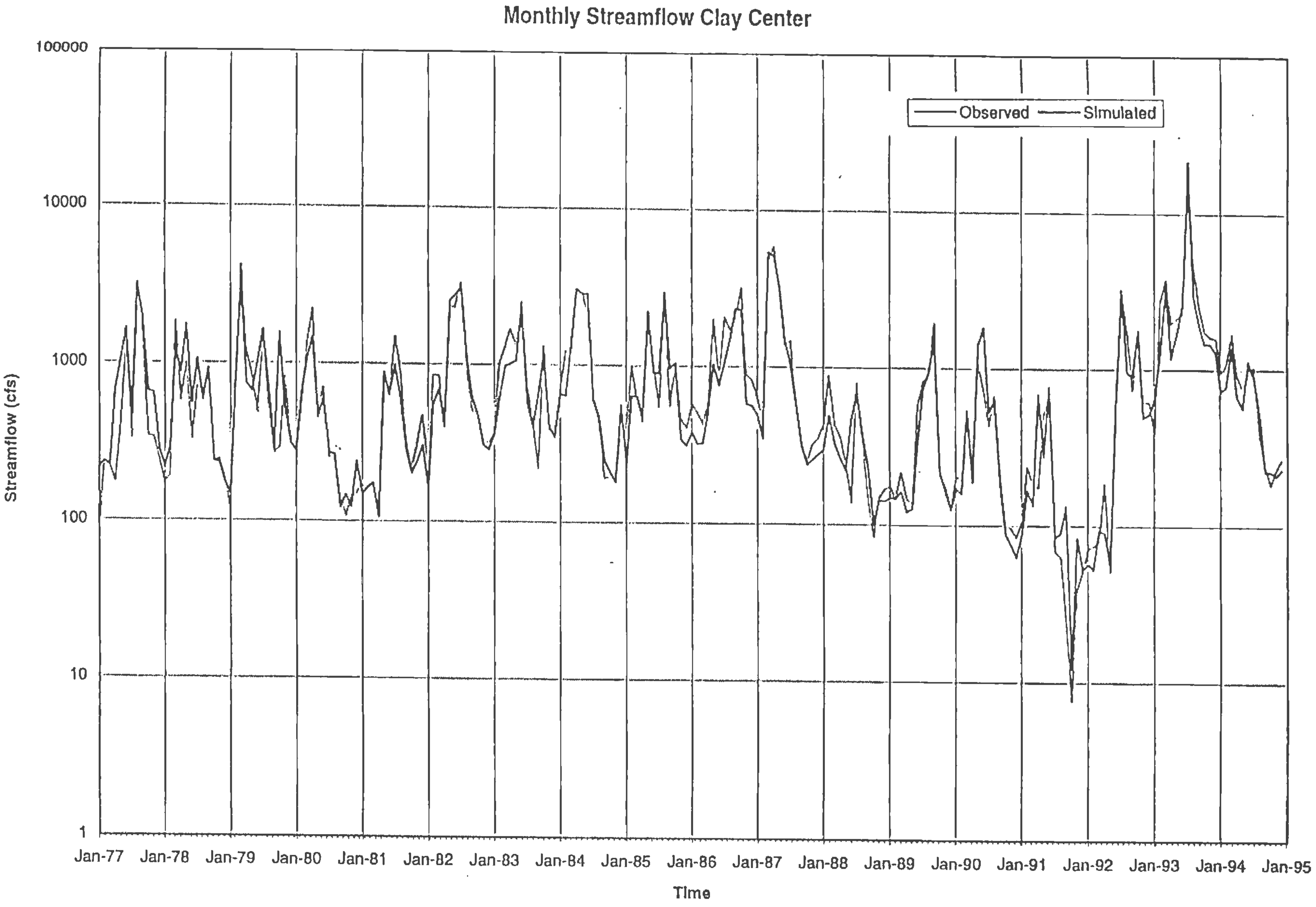


Figure 8.5b. 1977-1994 measured and simulated monthly streamflows (in cfs) at Clay Center displayed on logarithmic scale.

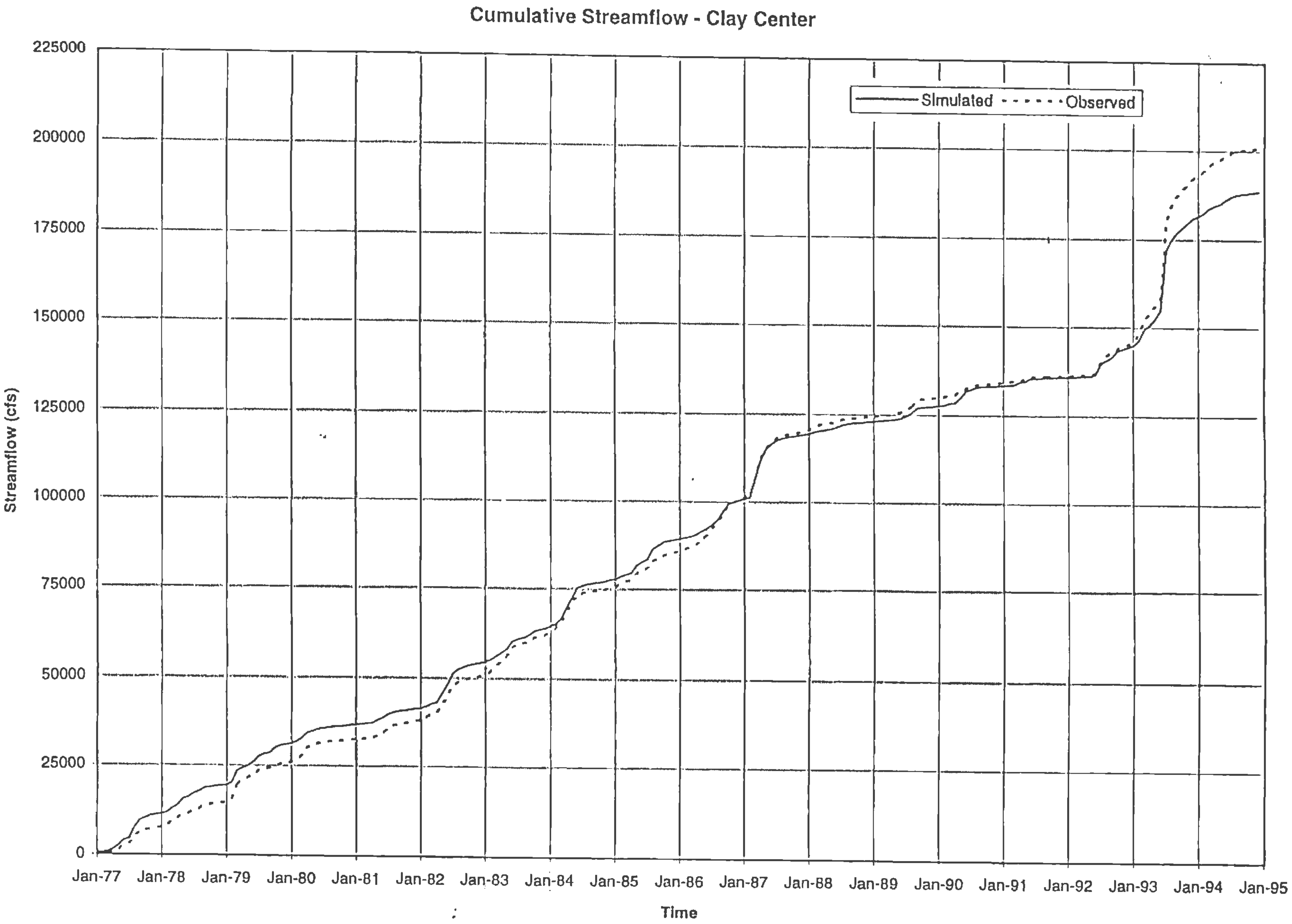
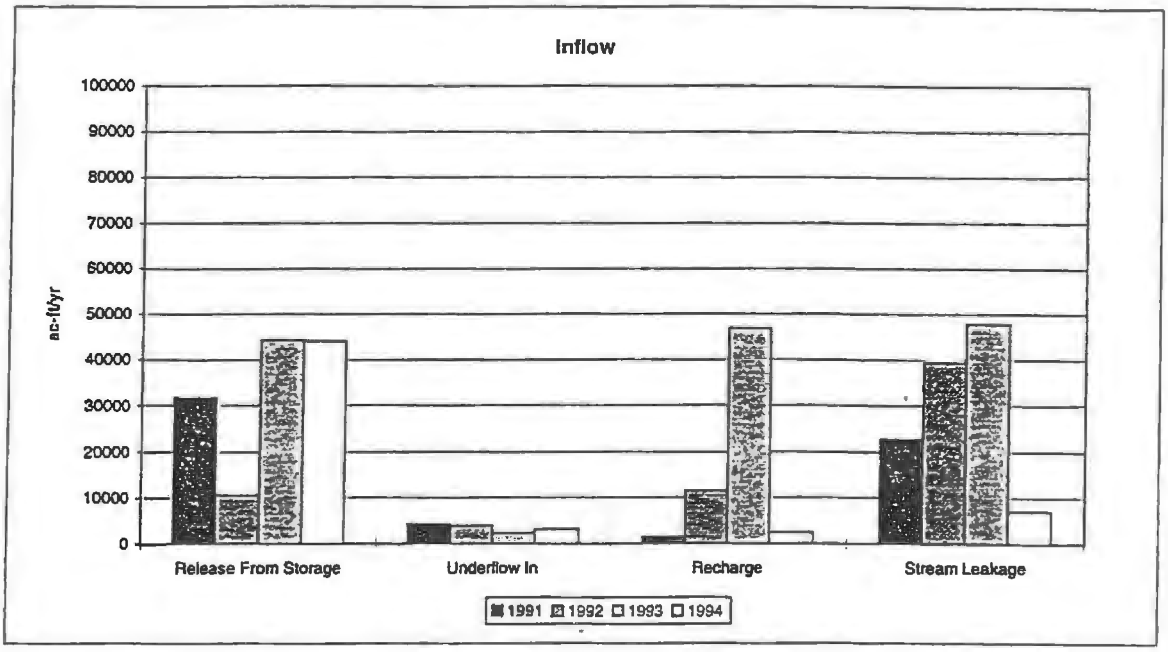


Figure 8.6. 1977-1994 measured and simulated cumulative monthly streamflows (in cfs) at Clay Center.



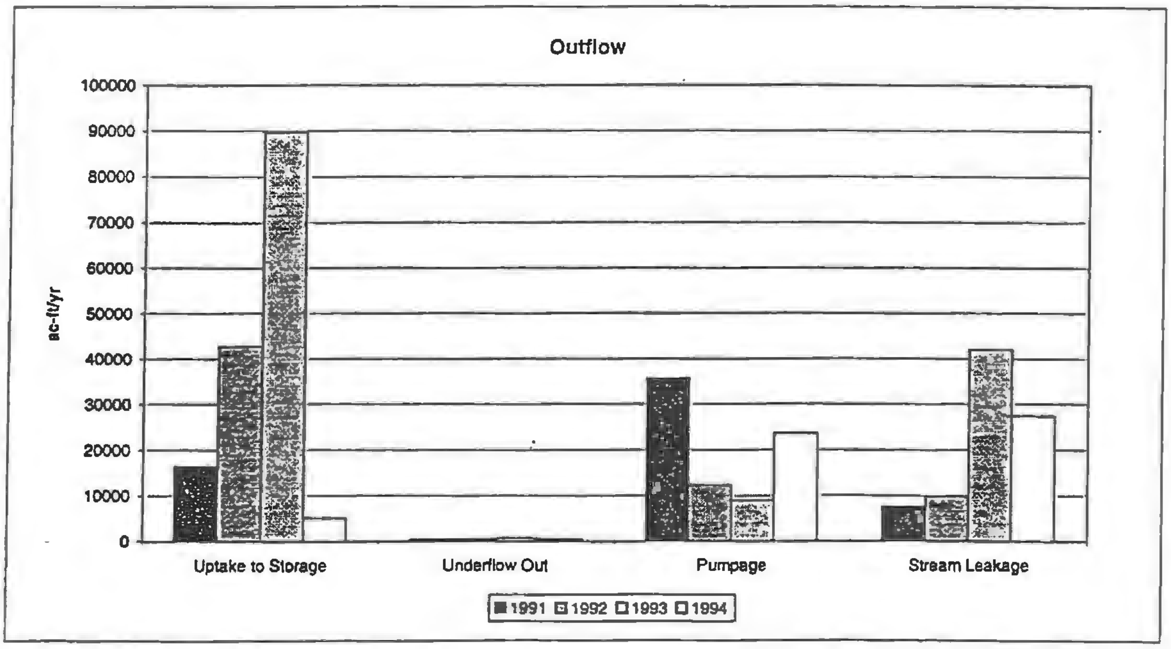


Figure 8.7. Histogram of water budget components for the years 1991 through 1994 in ac-ft/yr.

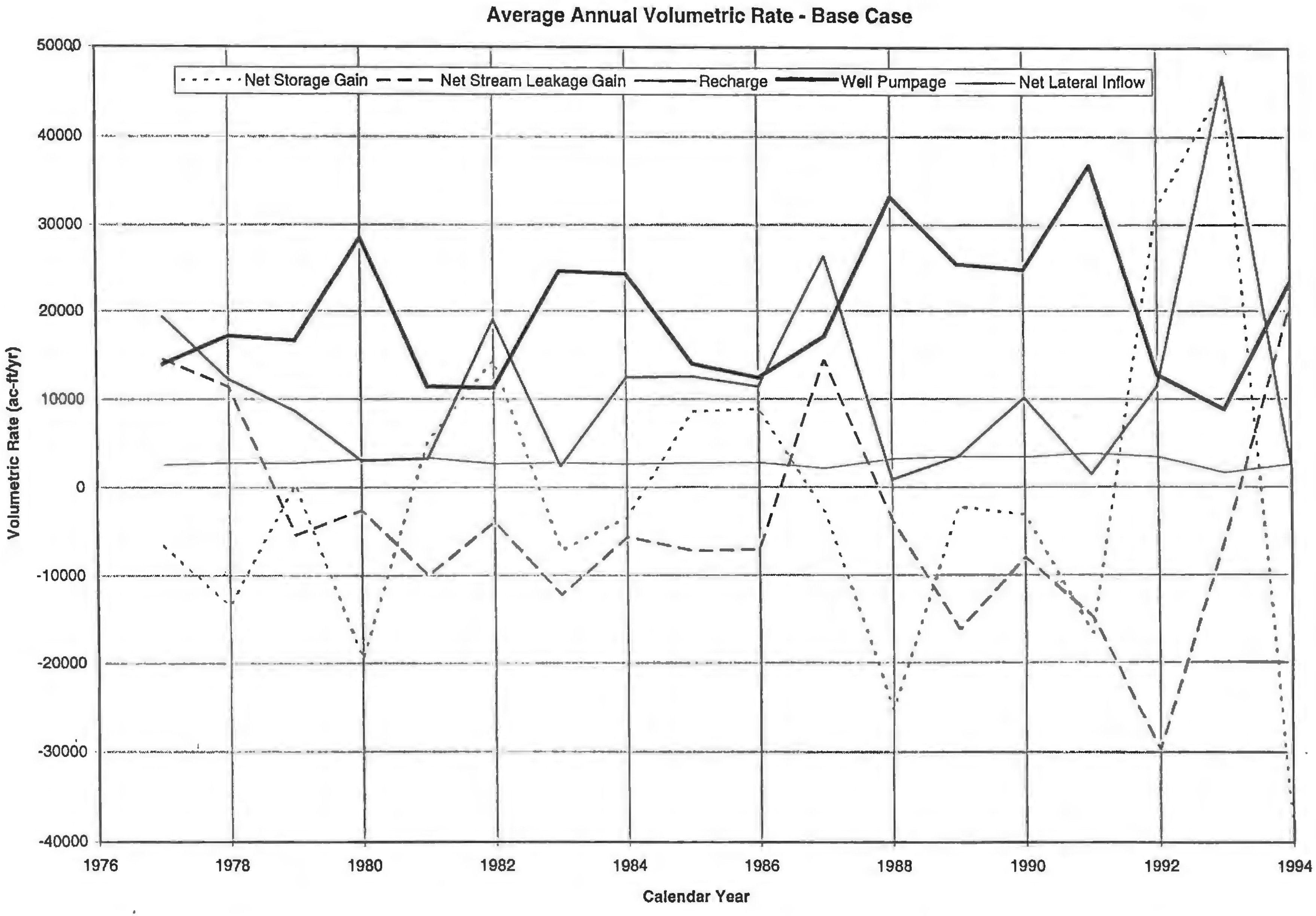


Figure 8.8. Annual time distribution of water budget components during the 1977-1994 period in ac-ft/yr.

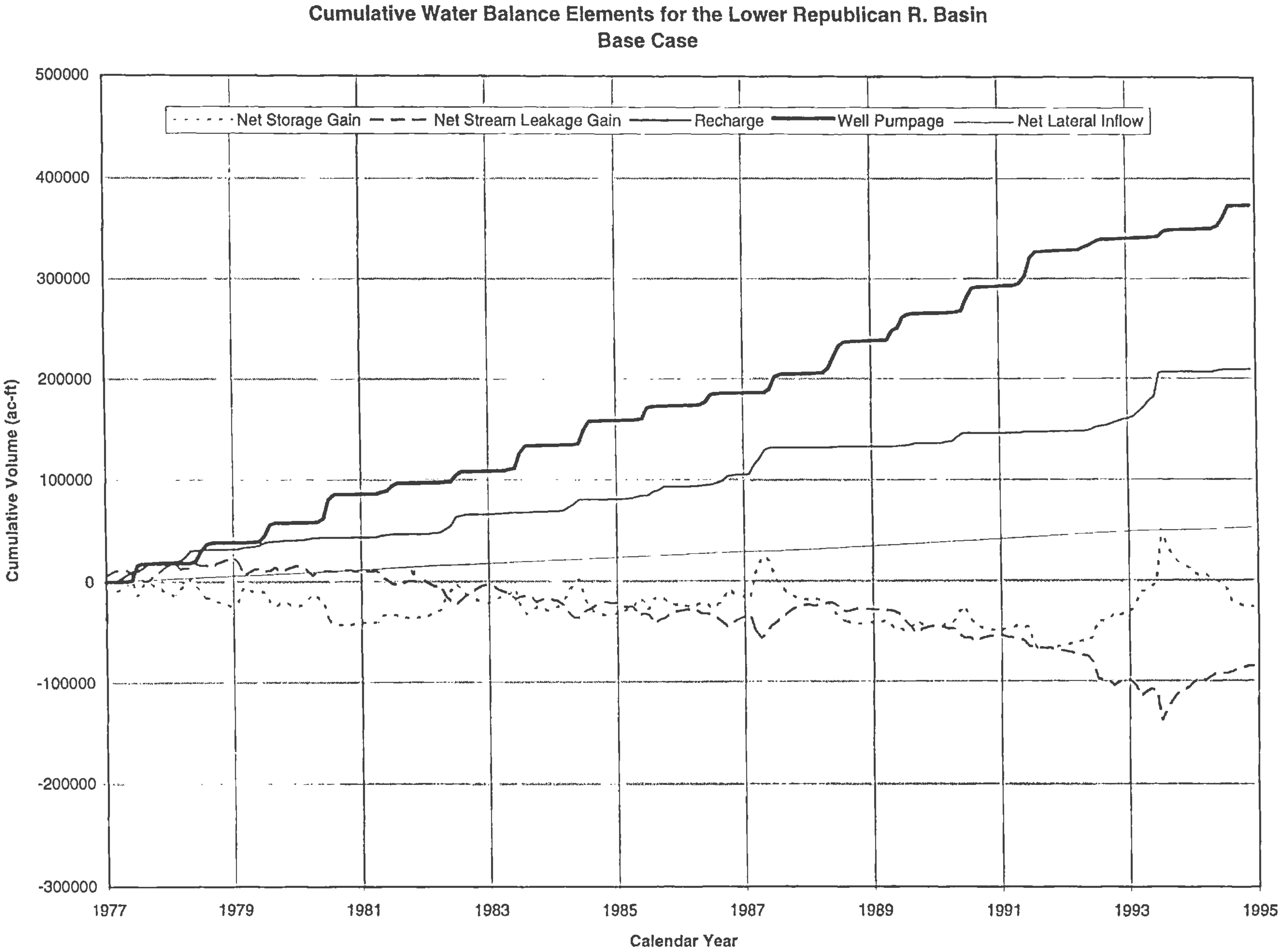


Figure 8.9. Cumulative monthly water budget components during the 1977-1994 period in ac-ft.

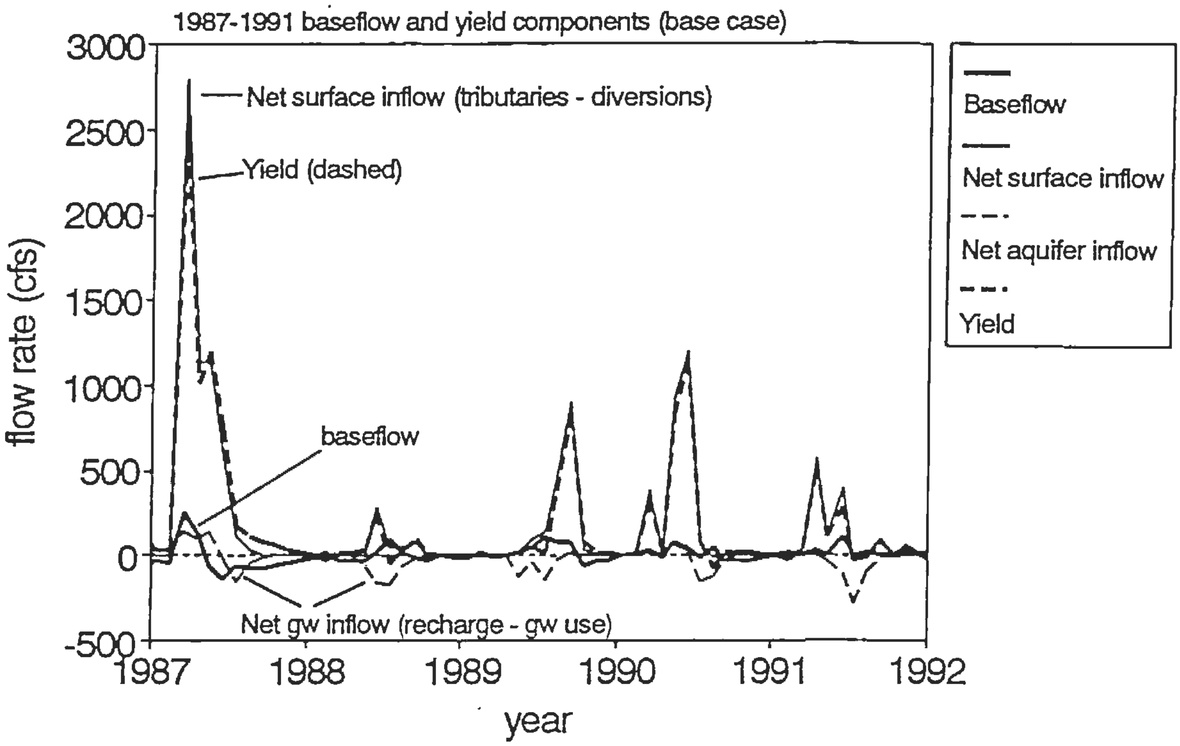


Figure 8.10 Hydrologic components for the period 1987-1992 based on the calibrated model (base case)

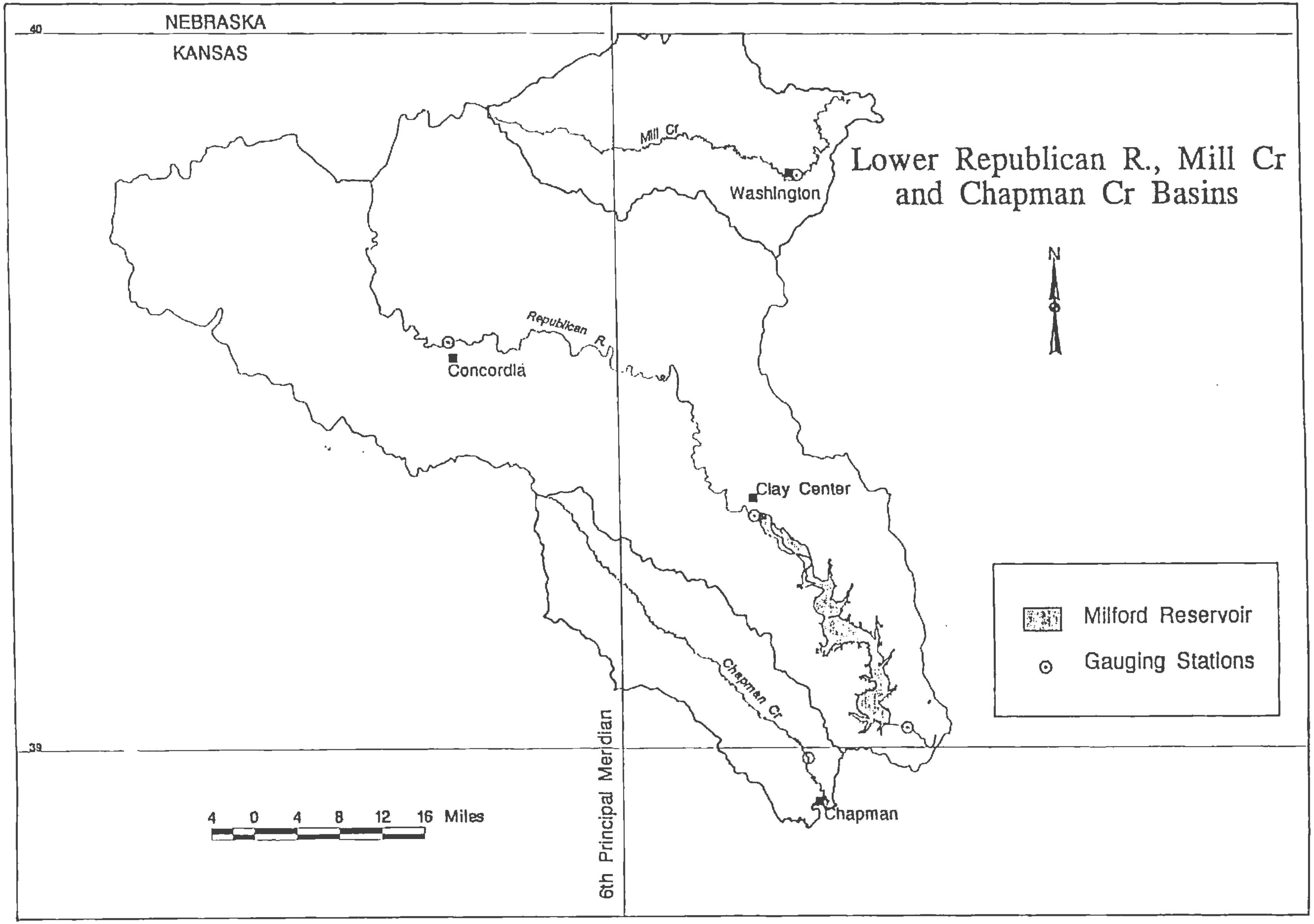


Figure 8.11. Neighboring watersheds of Mill Creek and Chapman Creek

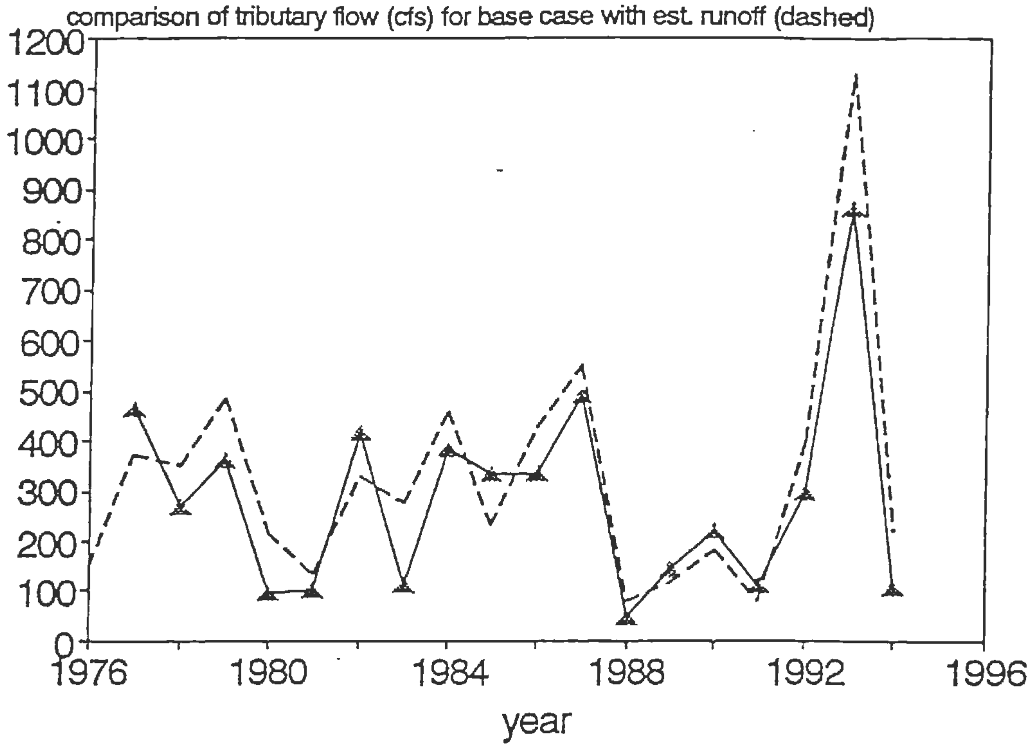


Figure 8.12 Comparison of tributary flow in the Lower Republican River basin with the average runoff from Mill Creek and Chapman Creek

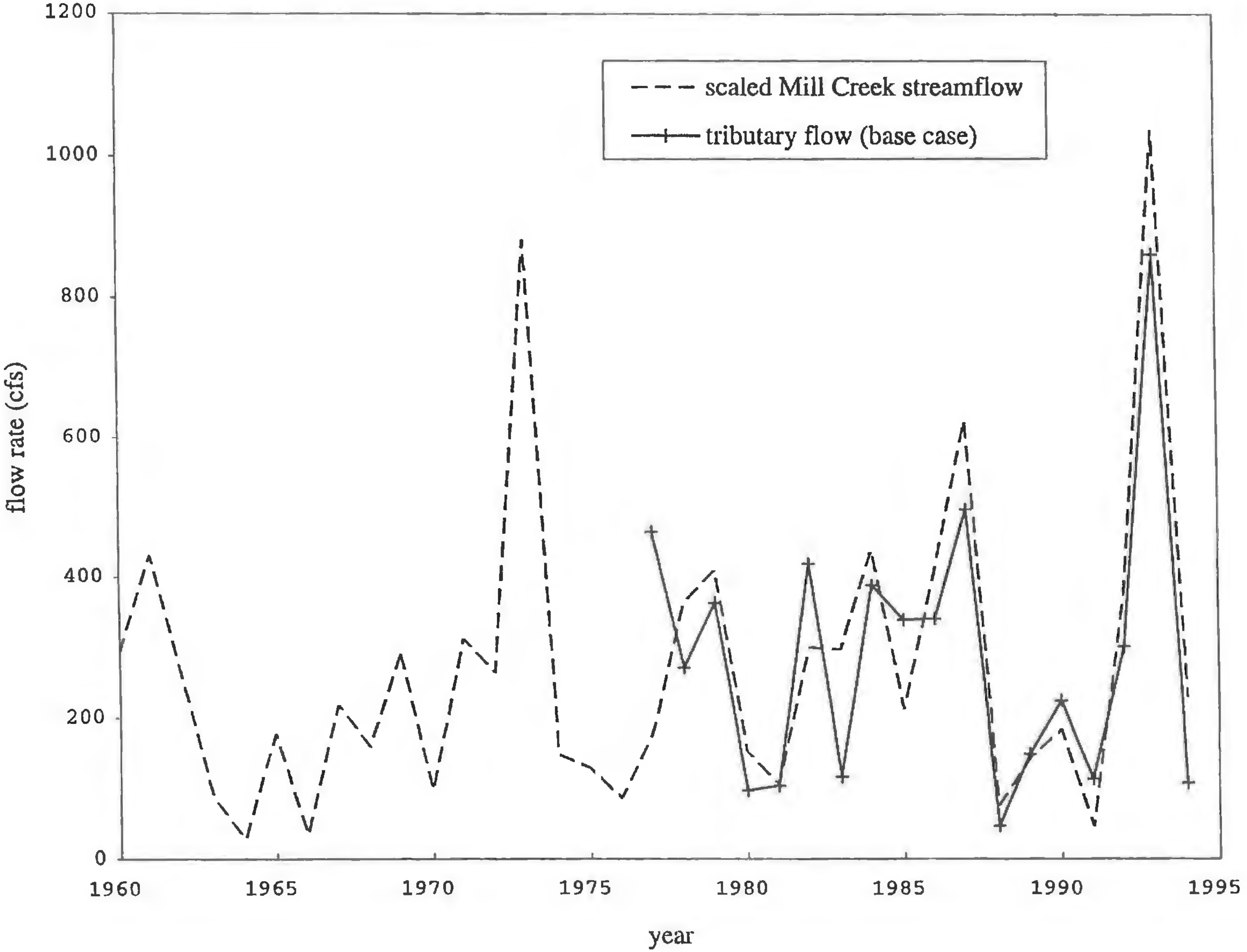


Figure 8.12a. Comparison of tributary flow for base case with runoff based on Mill Creek streamflow.

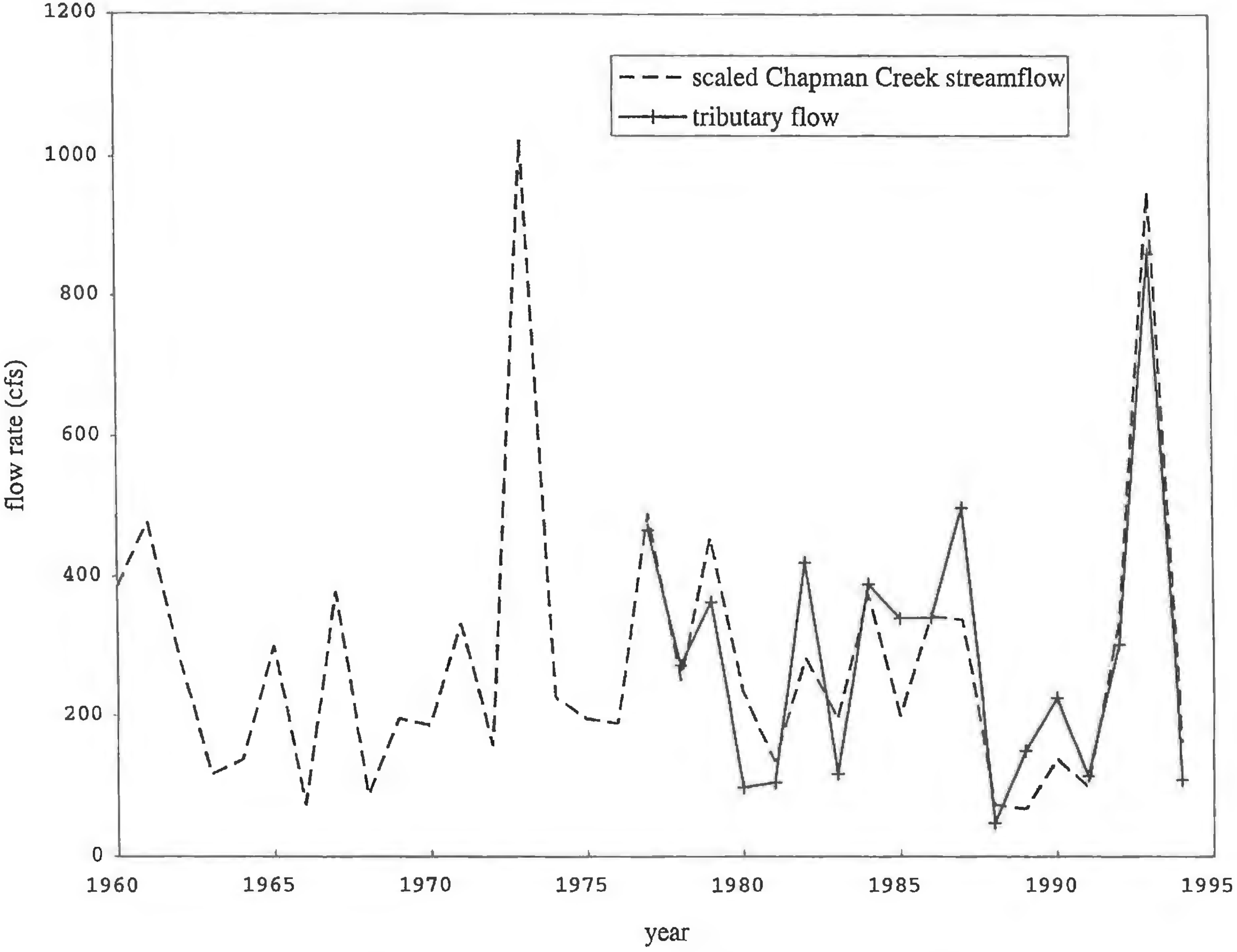


Figure 8.12b. Comparison of tributary flow for base case with runoff based on Chapman Creek streamflow.

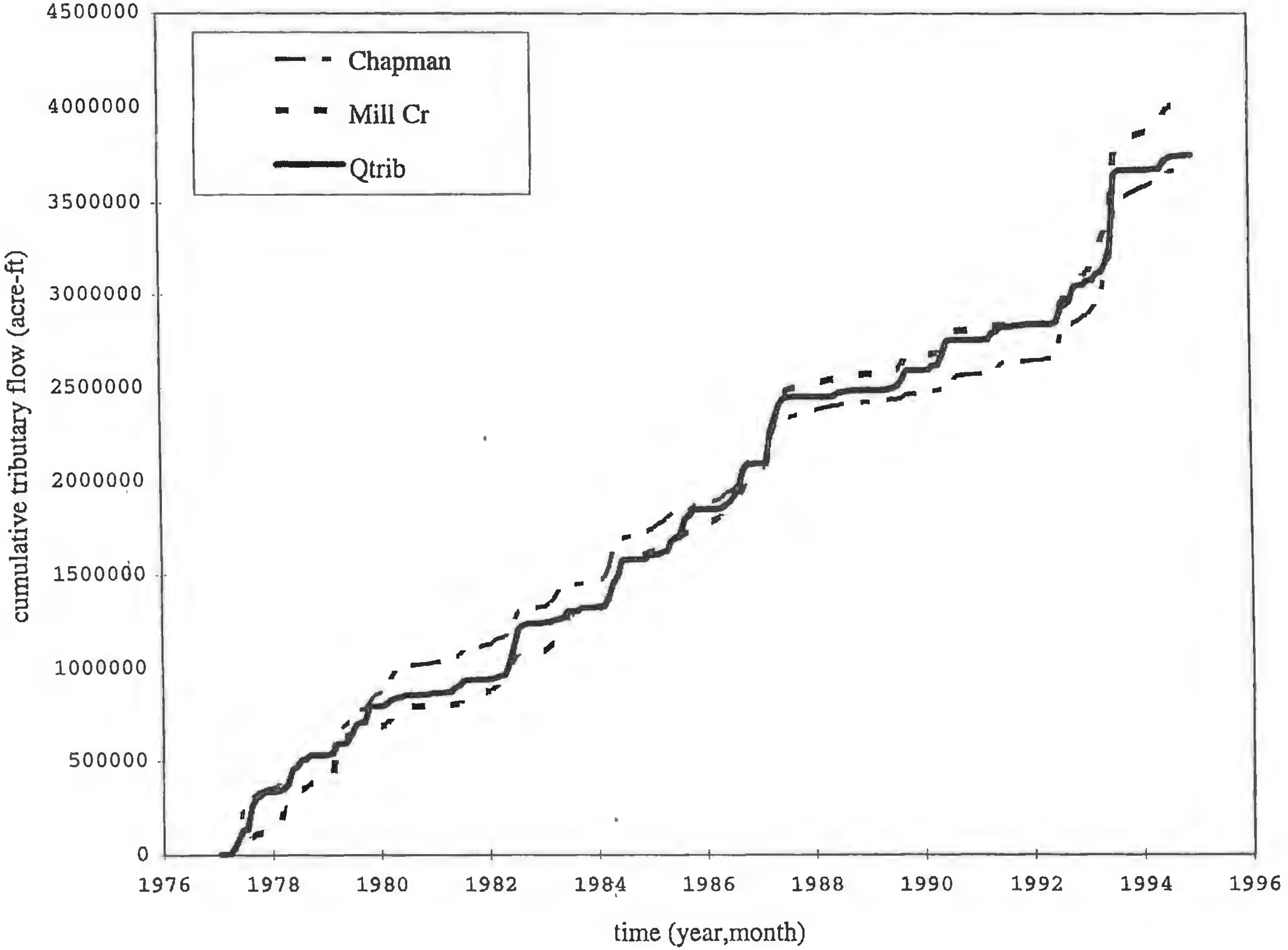


Figure 8.12c. Simulated tributary flow and runoff based on Chapman and Mill Creeks.

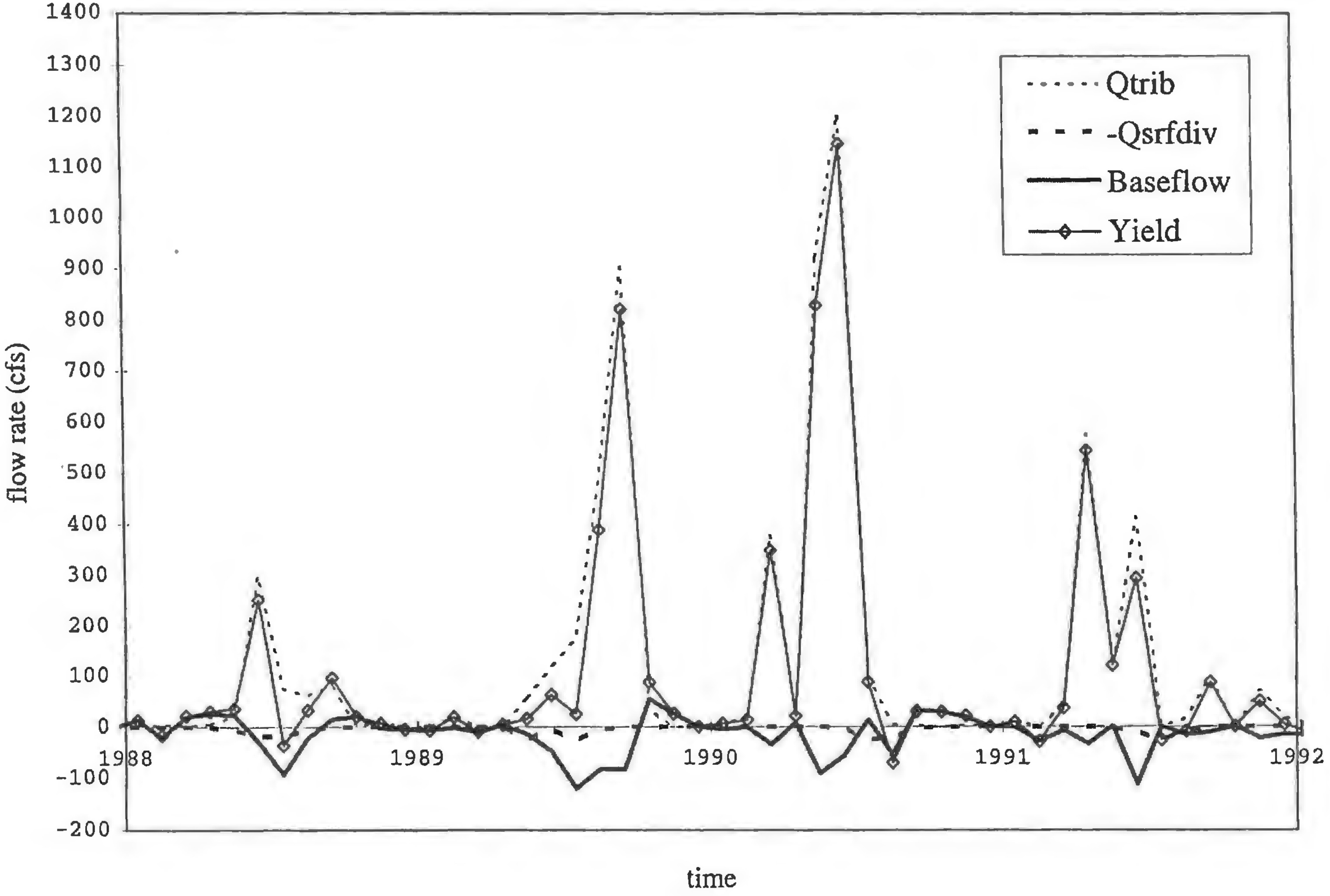


Figure 8.13. Monthly stream yield components for 1988-1991.

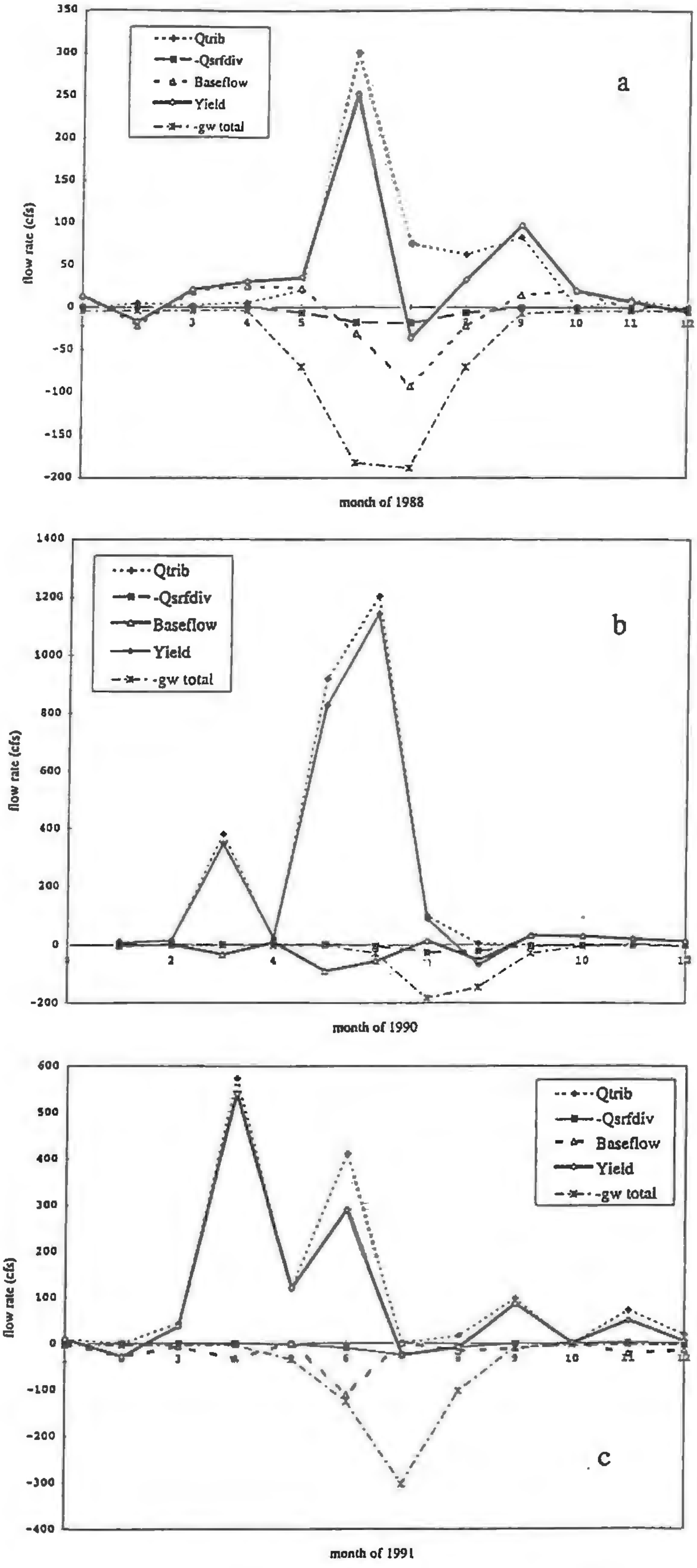


Fig. 8.14. Monthly stream yield components for (a) 1988, (b) 1990, and (c) 1991 for the Republican River between Concordia and Clay Center.

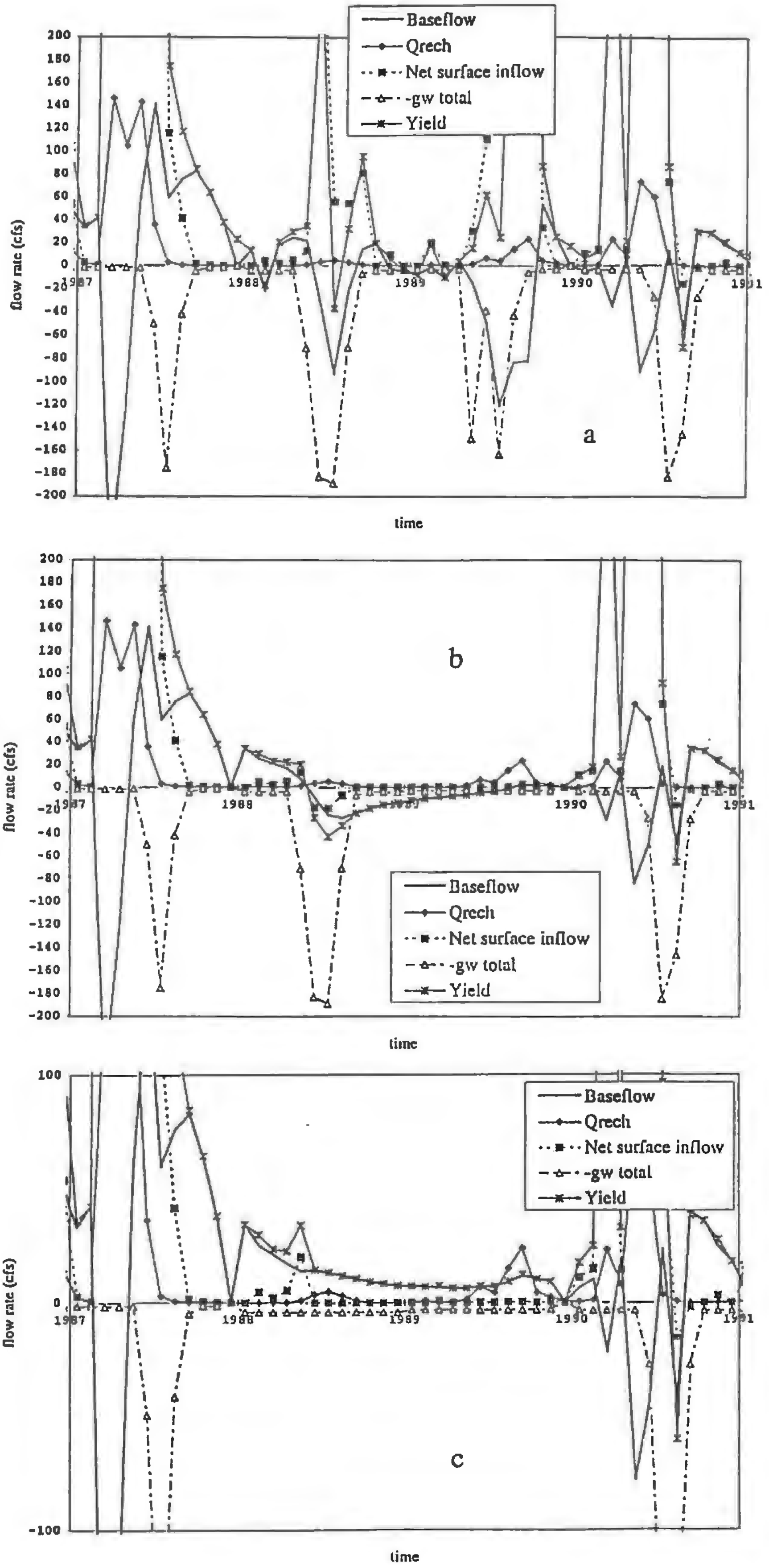


Fig. 8.15. Monthly hydrologic components for 1987-1990 for (a) the base case, (b) a hypothetical scenario where from May 1988 to December 1989 the incoming streamflows at Concordia were fixed at 170 cfs, and no tributary inflows occurred, and (c) same as (b) but in addition, pumping during 1988 was shut down.

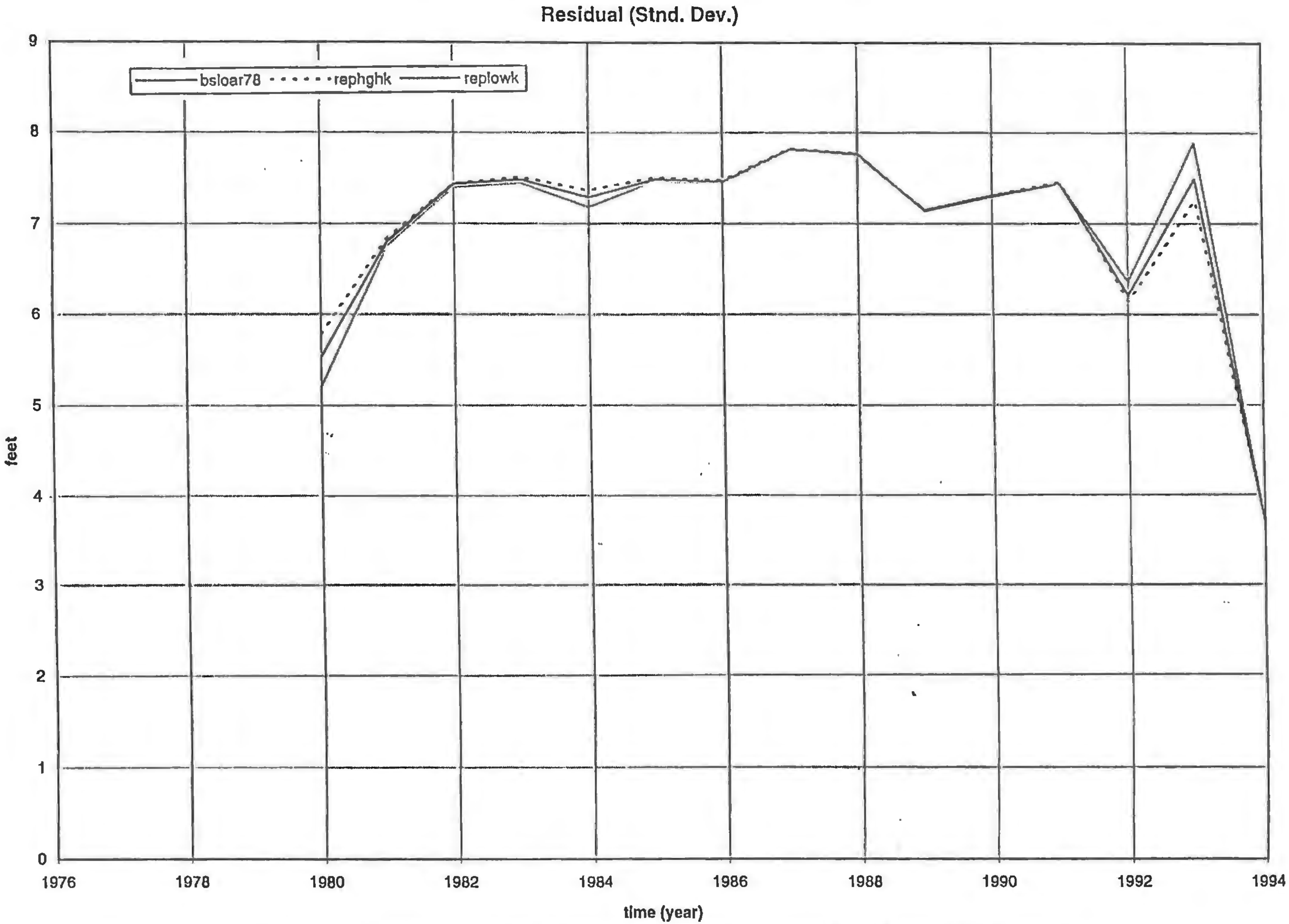


Figure 9.1. Annual series of modified root mean squared (RMS) error (or standard deviation) of water level residuals (in ft) for the 1977-1994 period for the baseline value of hydraulic conductivity (K=422 ft/day), a higher value (K=522 ft/day), and a lower value (K=322 ft/day).

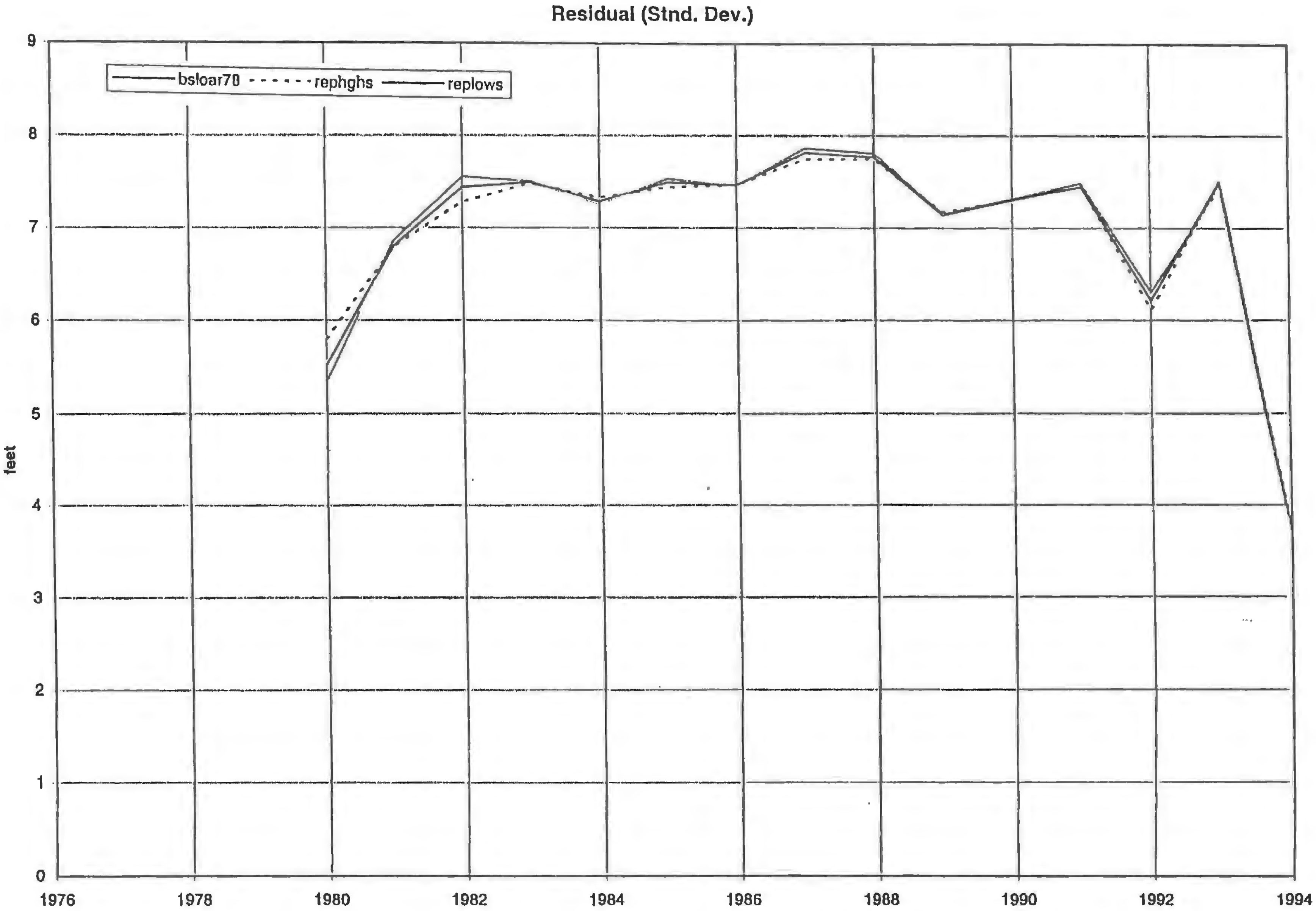


Figure 9.2. Annual series of modified root mean squared (RMS) error (or standard deviation) of water level residuals (in ft) for the 1977-1994 period for the baseline value of storativity (S=0.20), a higher value (S=0.30), and a lower value (S=0.15).

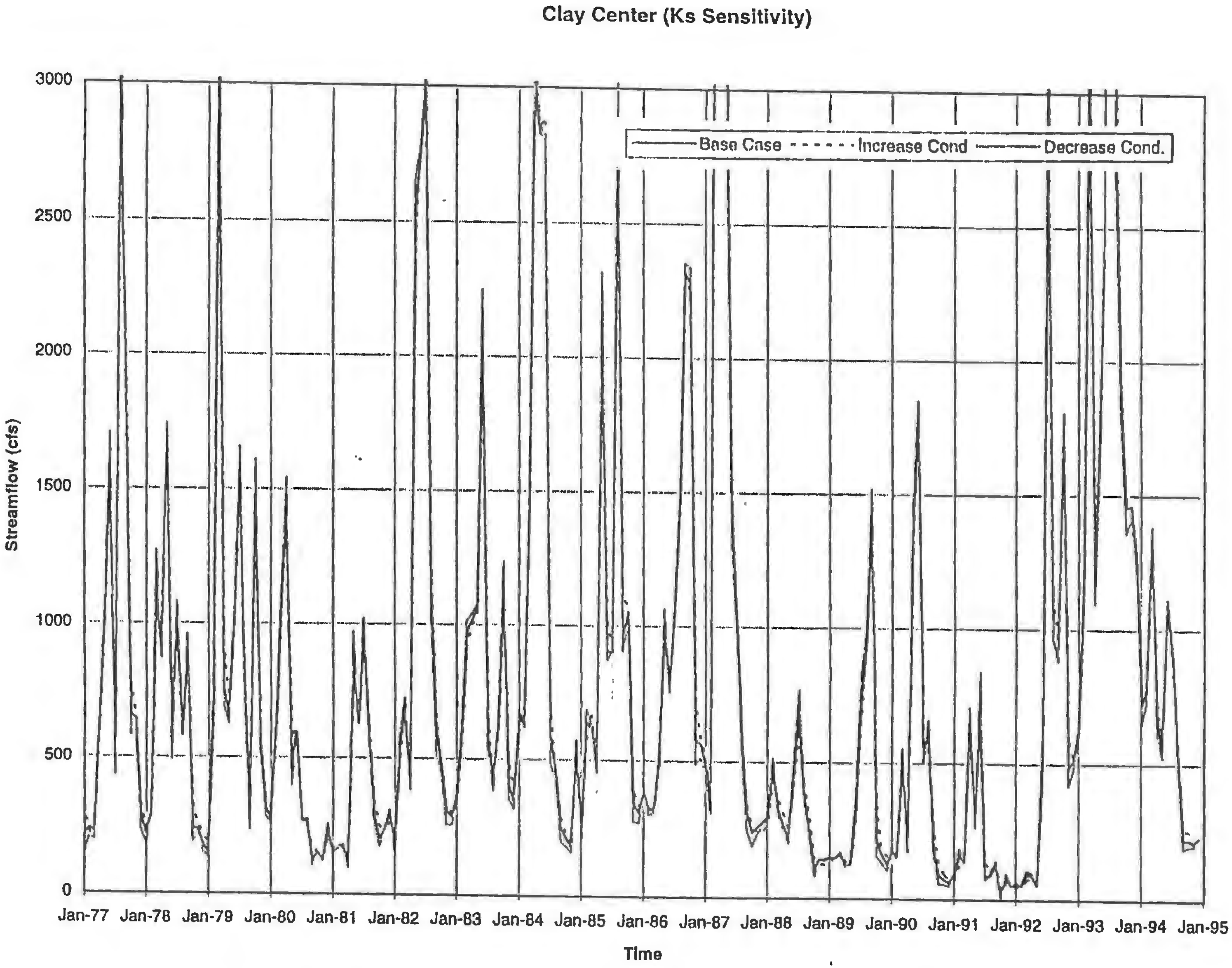


Figure 9.3. Riverbed hydraulic conductivity (k') sensitivity on streamflows at Clay Center. Baseline value k'=0.5 ft/day, higher k'=5 ft/day, and lower k'=0.05 ft/day.

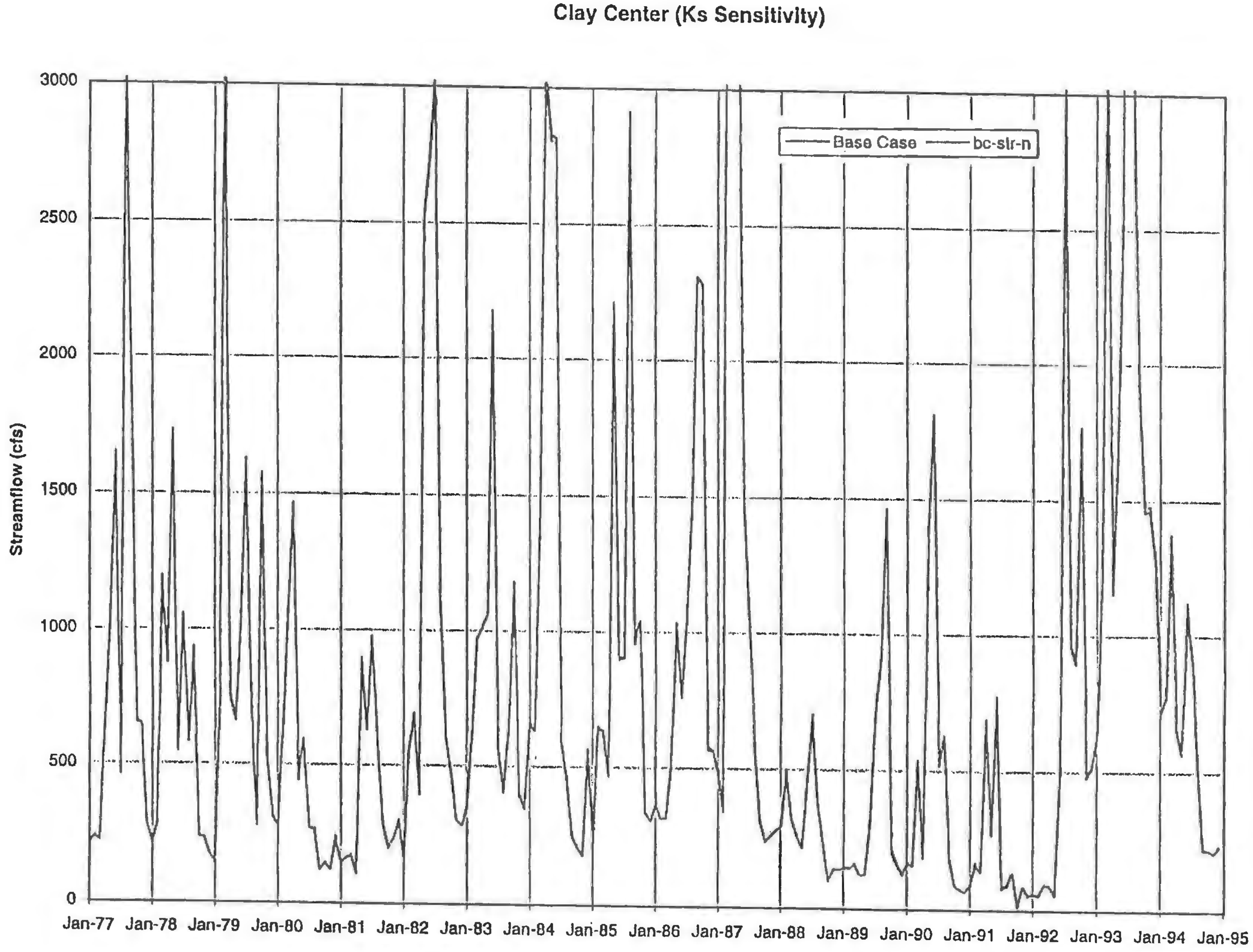


Figure 9.4. Republican River cross section sensitivity on streamflows at Clay Center.
Baseline cross section is the one measured at Clay Center and Concordia.
Alternate cross section is the rectangular one assumed in MODFLOW.

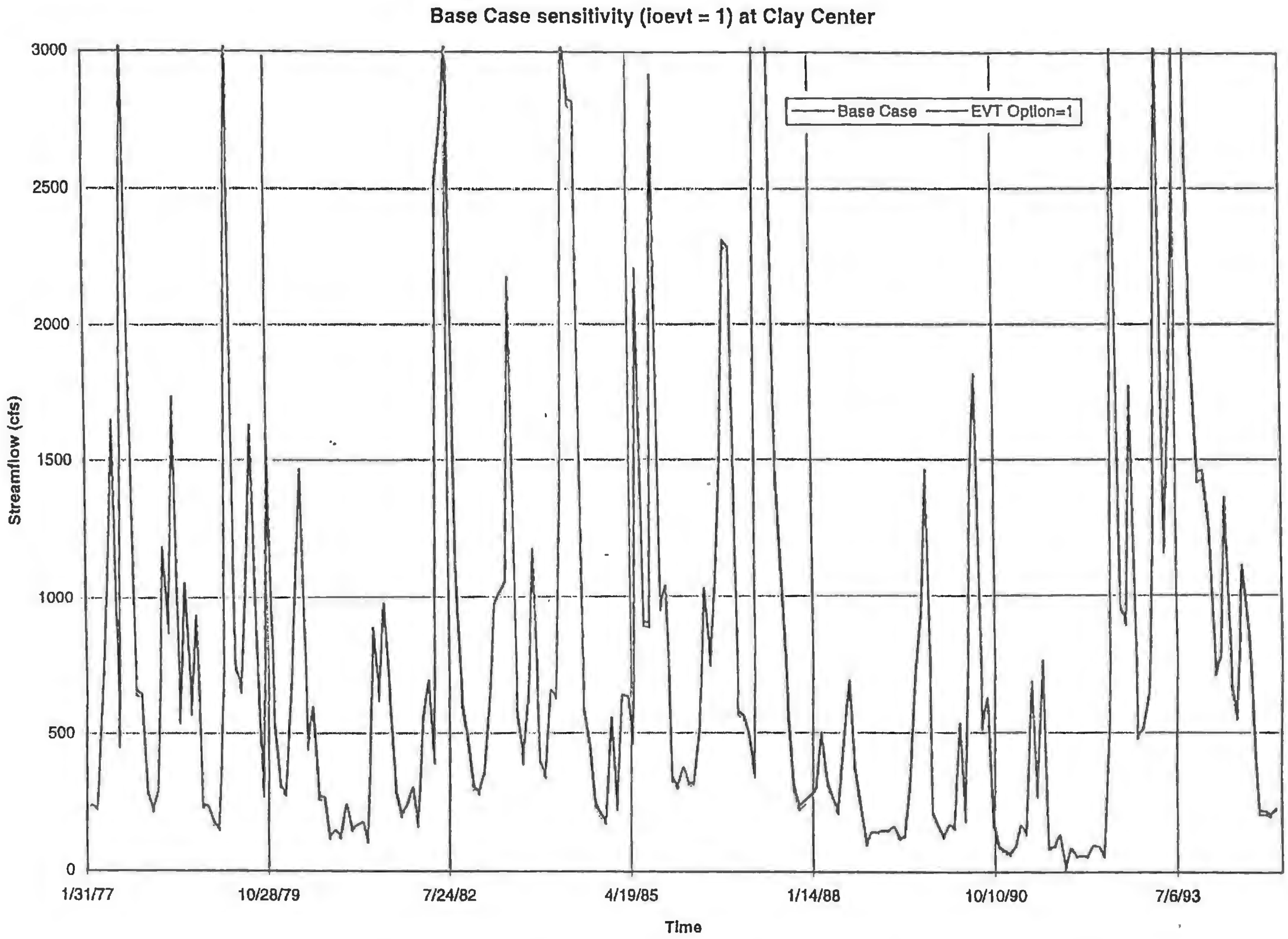


Figure 9.5. Streamflow sensitivity to ground-water evapotranspiration: Monthly time series. Base case assumes no ground-water evapotranspiration (darker line).

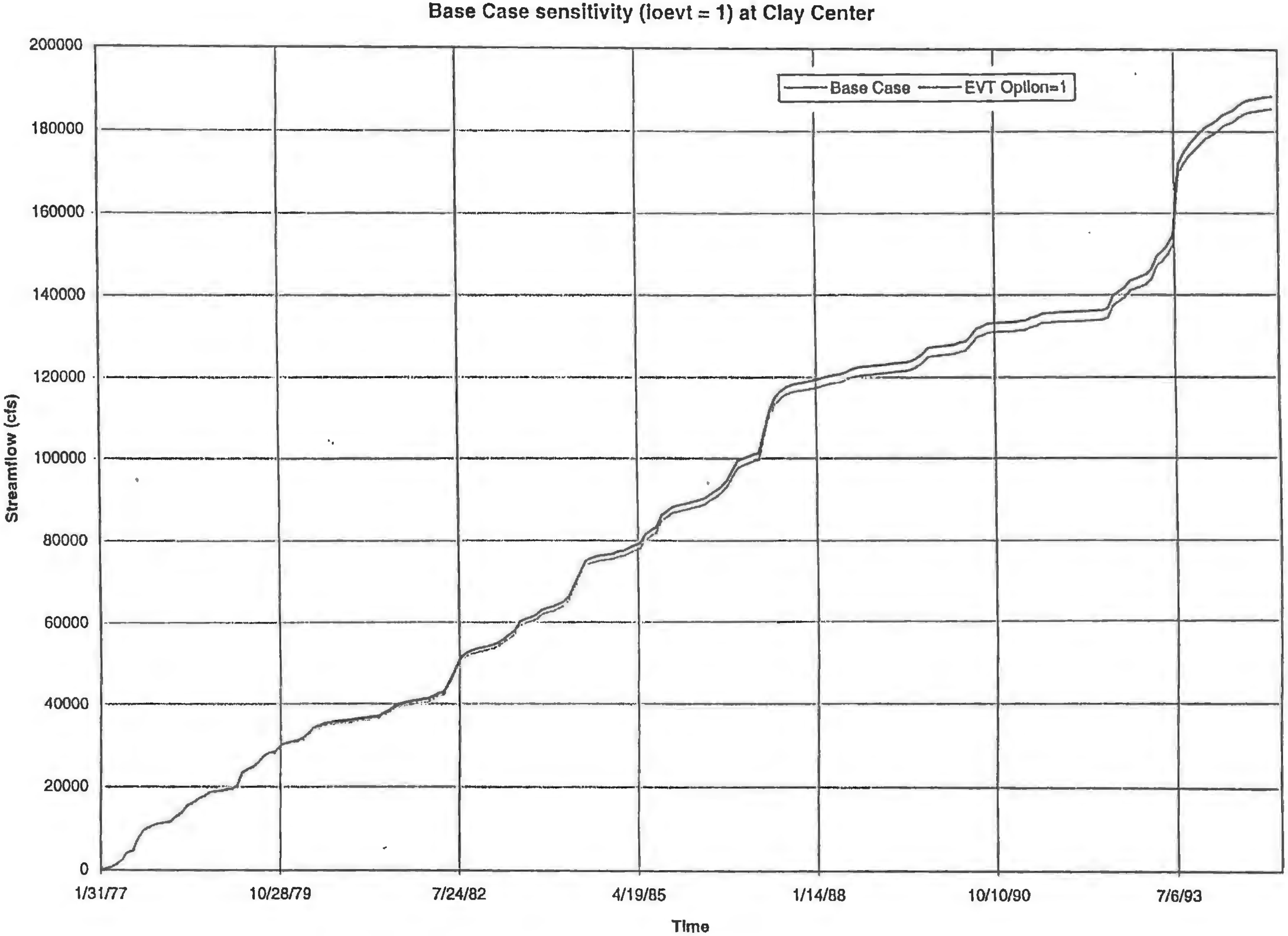


Figure 9.6. Streamflow sensitivity to ground-water evapotranspiration: Cumulative monthly time series. Base case assumes no ground-water evapotranspiration (darker line).

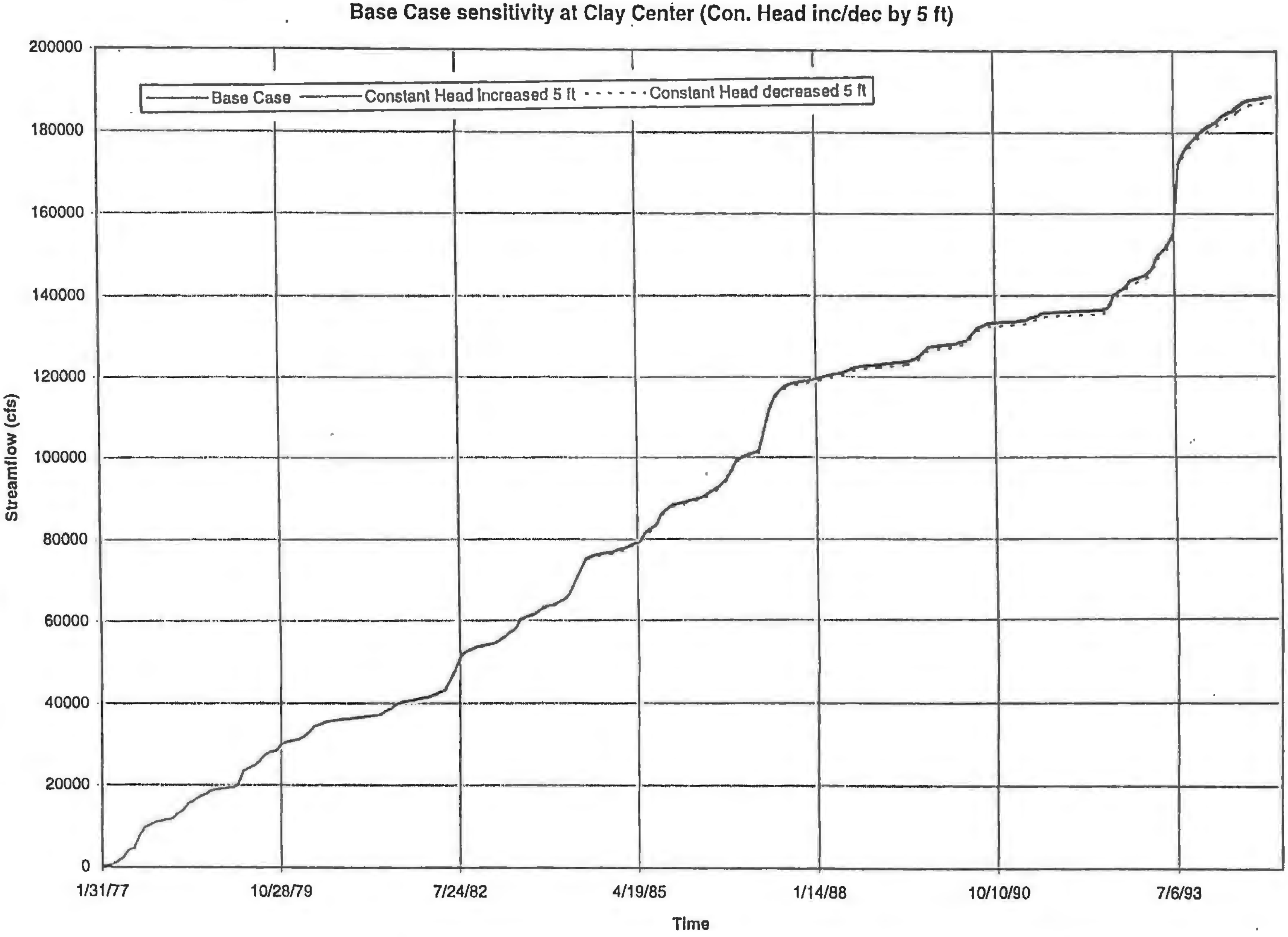


Figure 9.7. Western model boundary specified head sensitivity on streamflows at Clay Center. Base case western boundary was raised or lowered by 5 ft.

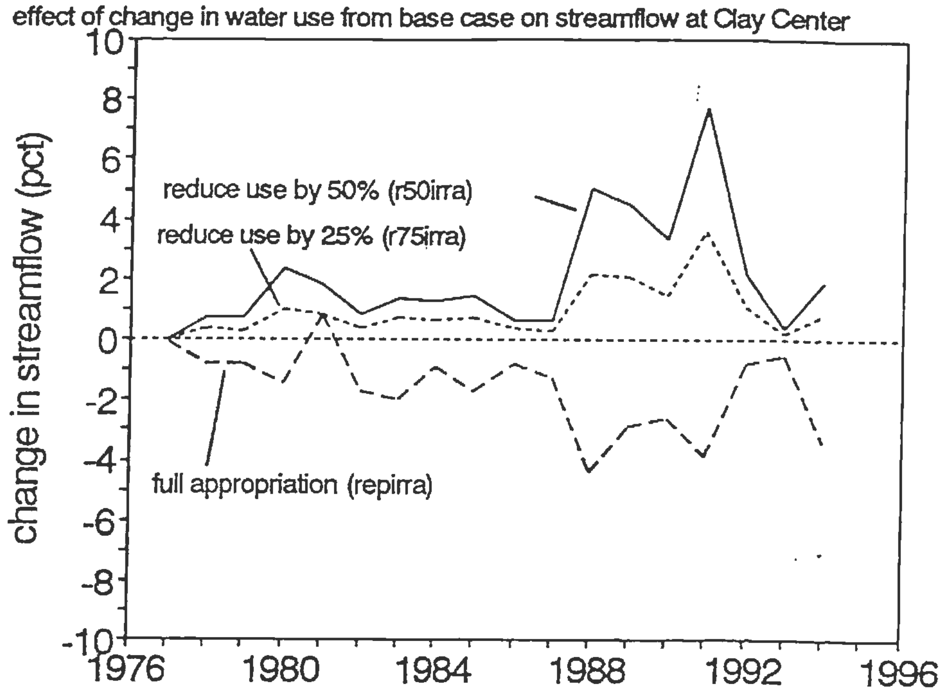


Figure 9.8. Sensitivity of streamflows at Clay Center to pumpage: Annual series. Long dash line represents change in streamflow when pumpage equals appropriated amounts. Solid line represents change in streamflow when pumpage equals 50% of appropriated amounts, and short dash line represents change in streamflow when pumpage equals 75% of appropriated amounts.

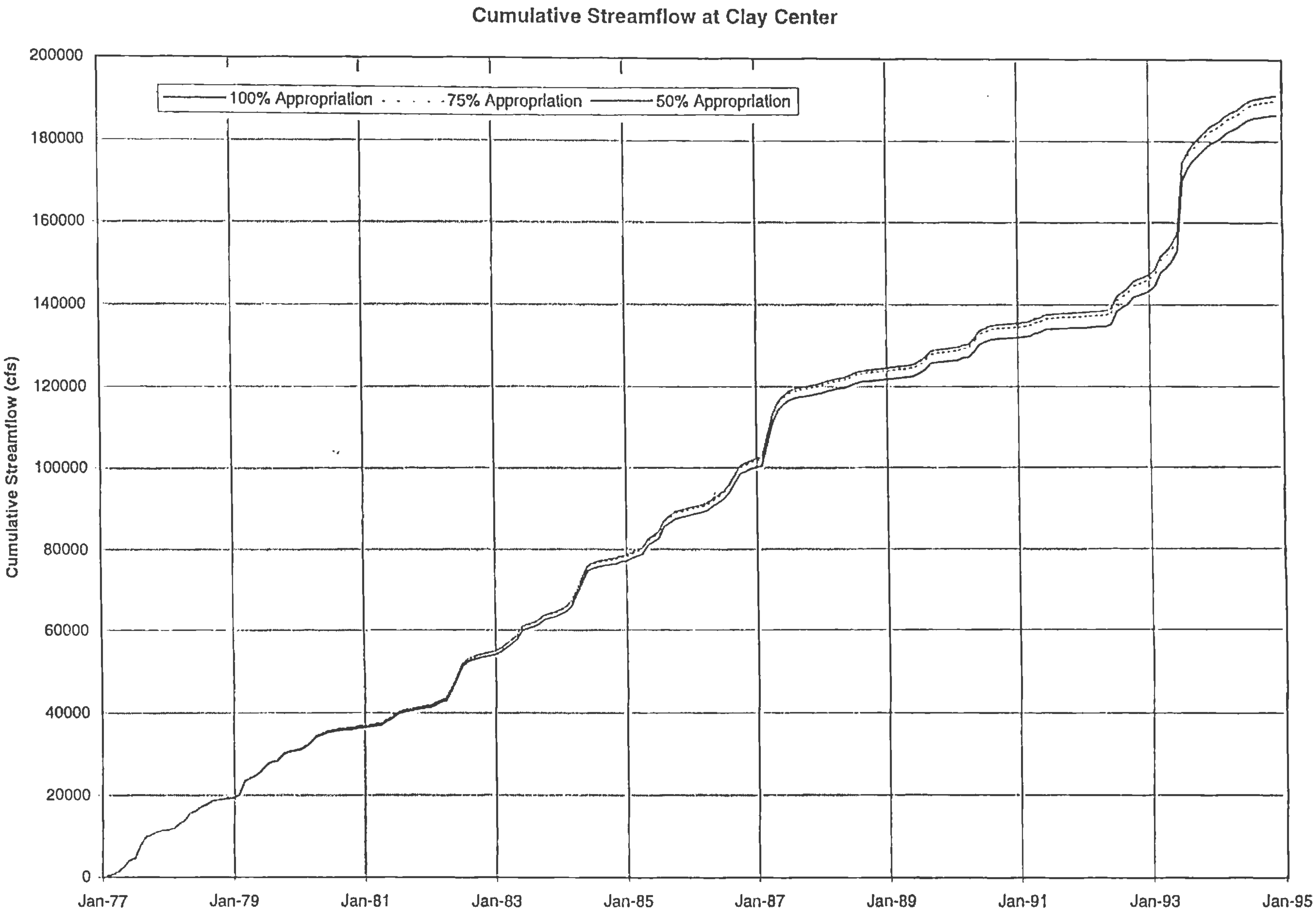


Figure 9.9. Sensitivity of streamflows at Clay Center to pumpage: Cumulative streamflows. Long dash line represents change in streamflow when pumpage equals appropriated amounts. Solid line represents change in streamflow when pumpage equals 50% of appropriated amounts, and short dash line represents change in streamflow when pumpage equals 75% of appropriated amounts.

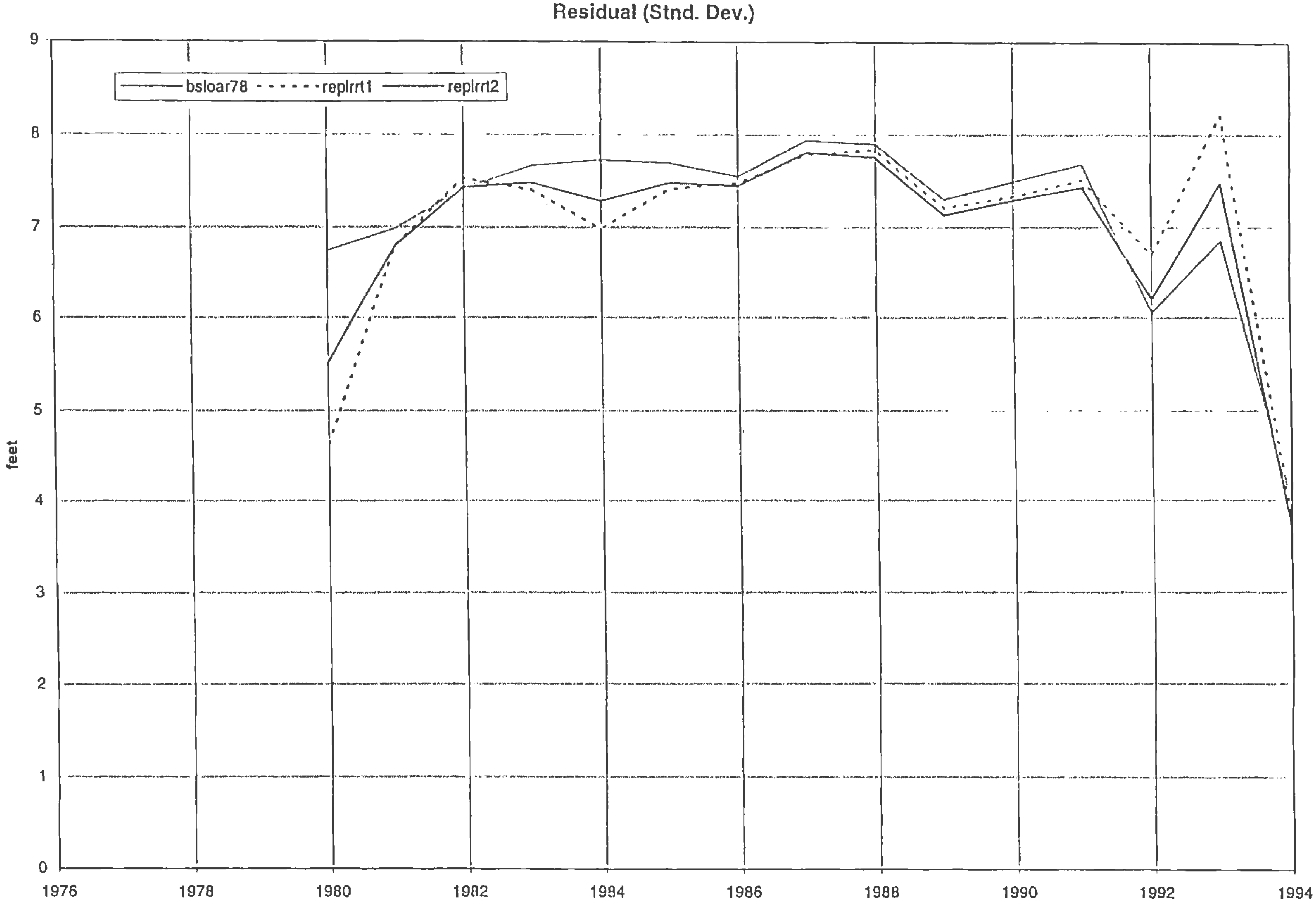


Figure 9.10. Annual series of modified root mean squared (RMS) error (or standard deviation) of water-level residuals (in ft) for the 1977-1994 period for the base case (solid line), and for increased irrigated area by 50% (dash line) or decreased irrigated area by 50% (gray line)

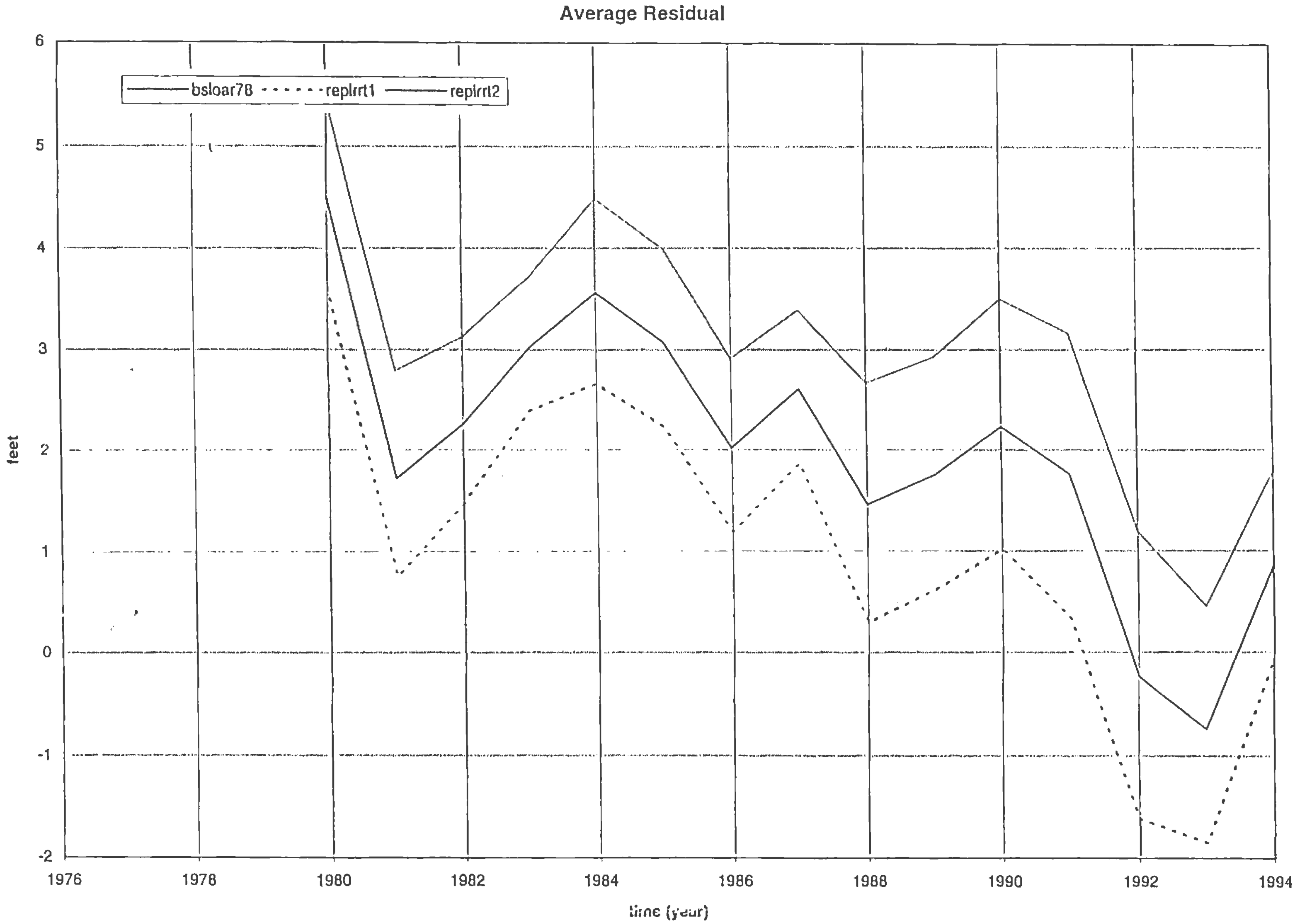


Figure 9.11. Annual series of average water-level residuals (in ft) for the 1977-1994 period for the base case (solid line), and for increased irrigated area by 50% (dash line) or decreased irrigated area by 50% (gray line).

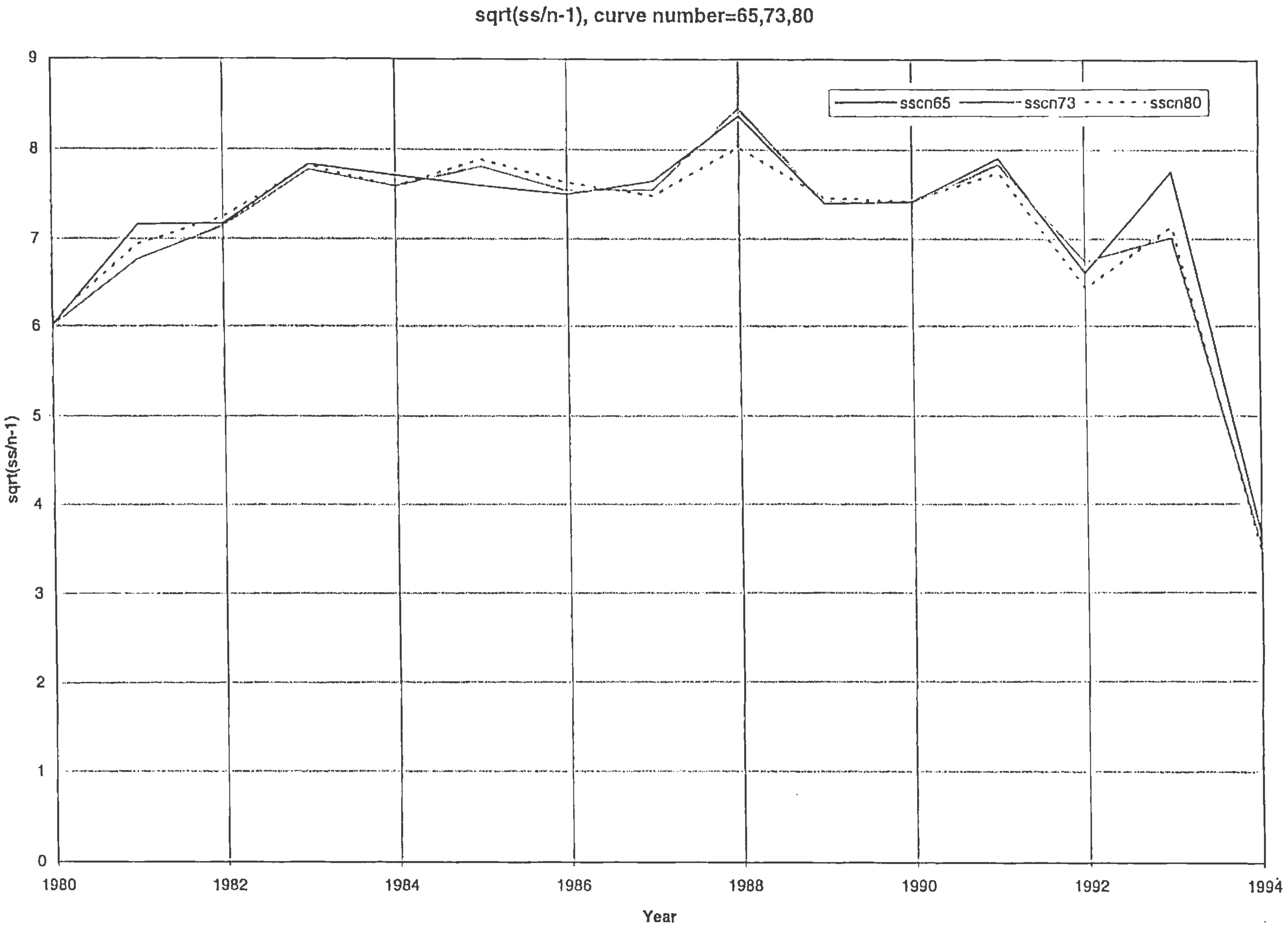


Figure 9.12. Annual series of modified root mean squared (RMS) error (or standard deviation) of water-level residuals (in ft) for the 1977-1994 period for curve numbers 65 (solid line), 73 (gray line) and 80 (dash line).

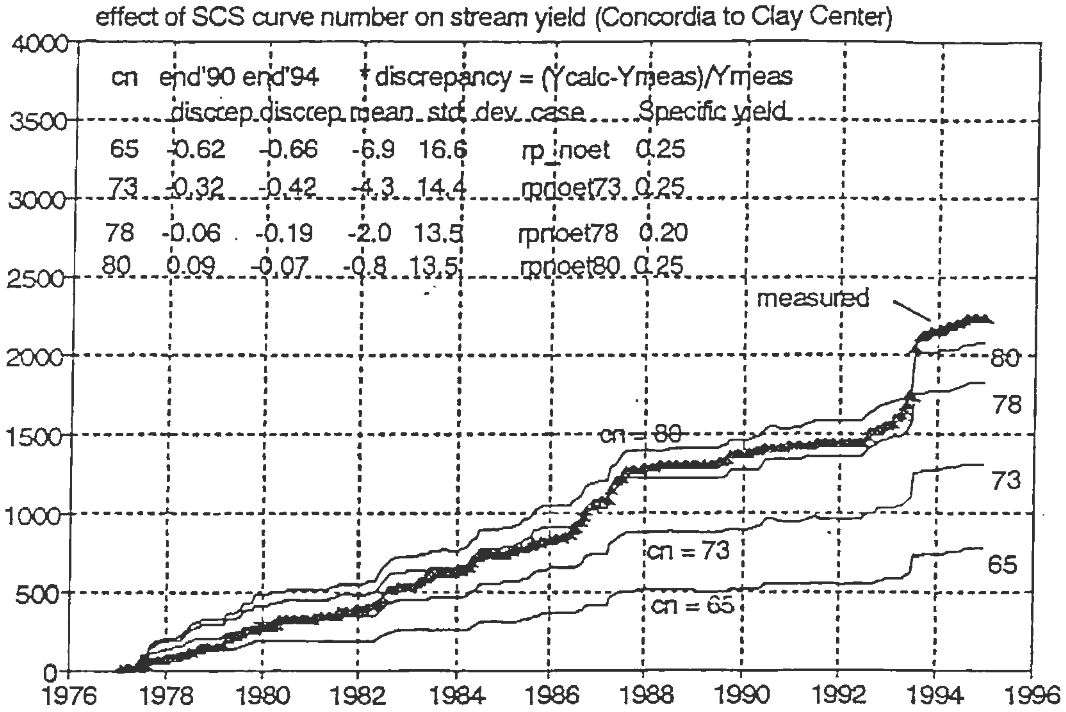


Figure 9.13. 1977-1994 cumulative stream-yield sensitivity to curve numbers 65, 73, 78, and 80. Measured stream yield shown in triangles.

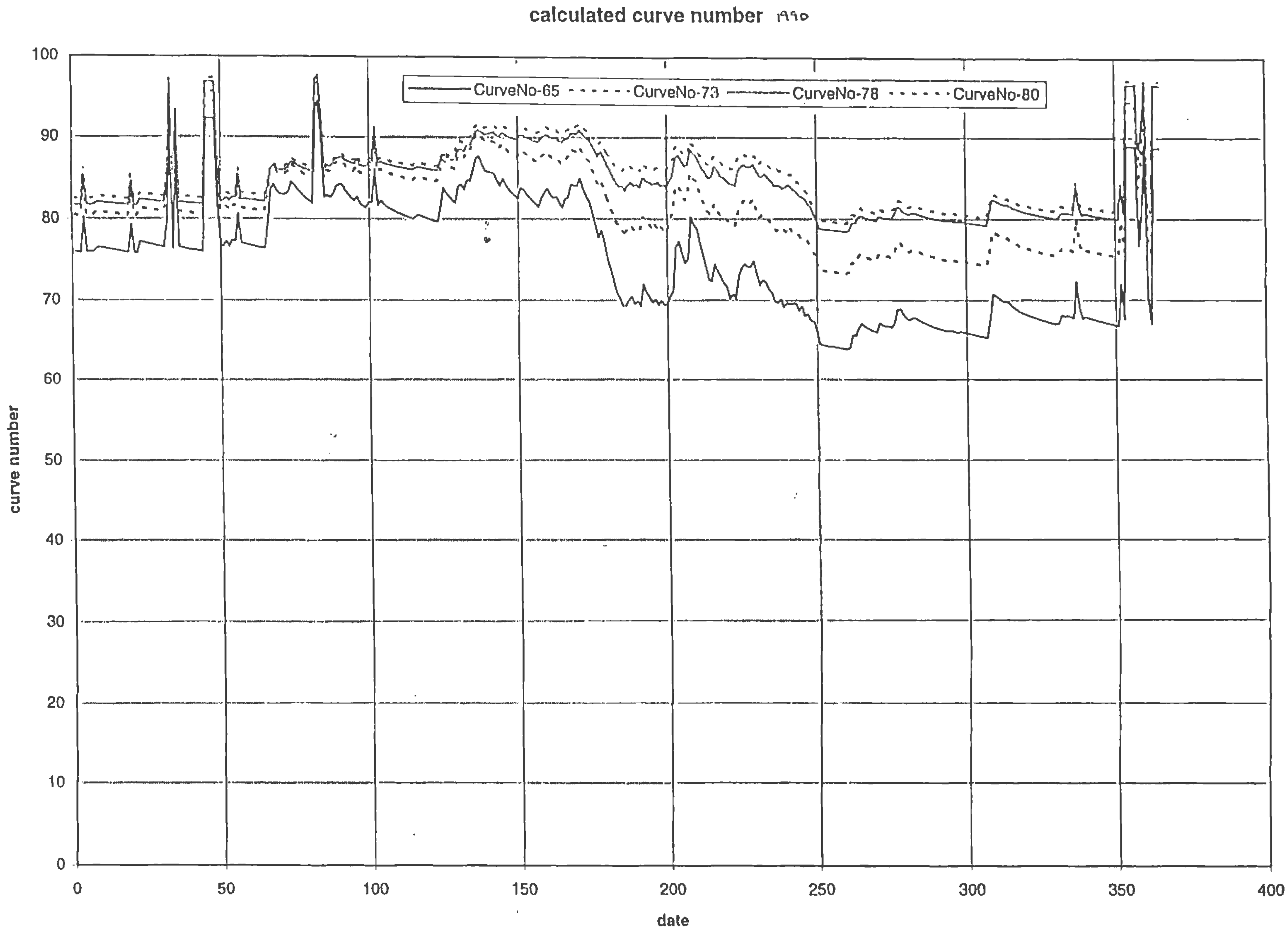


Figure 9.14. Temporal (daily) variation of curve numbers 65, 73, 78, and 80 for the Kipson soil during 1990.

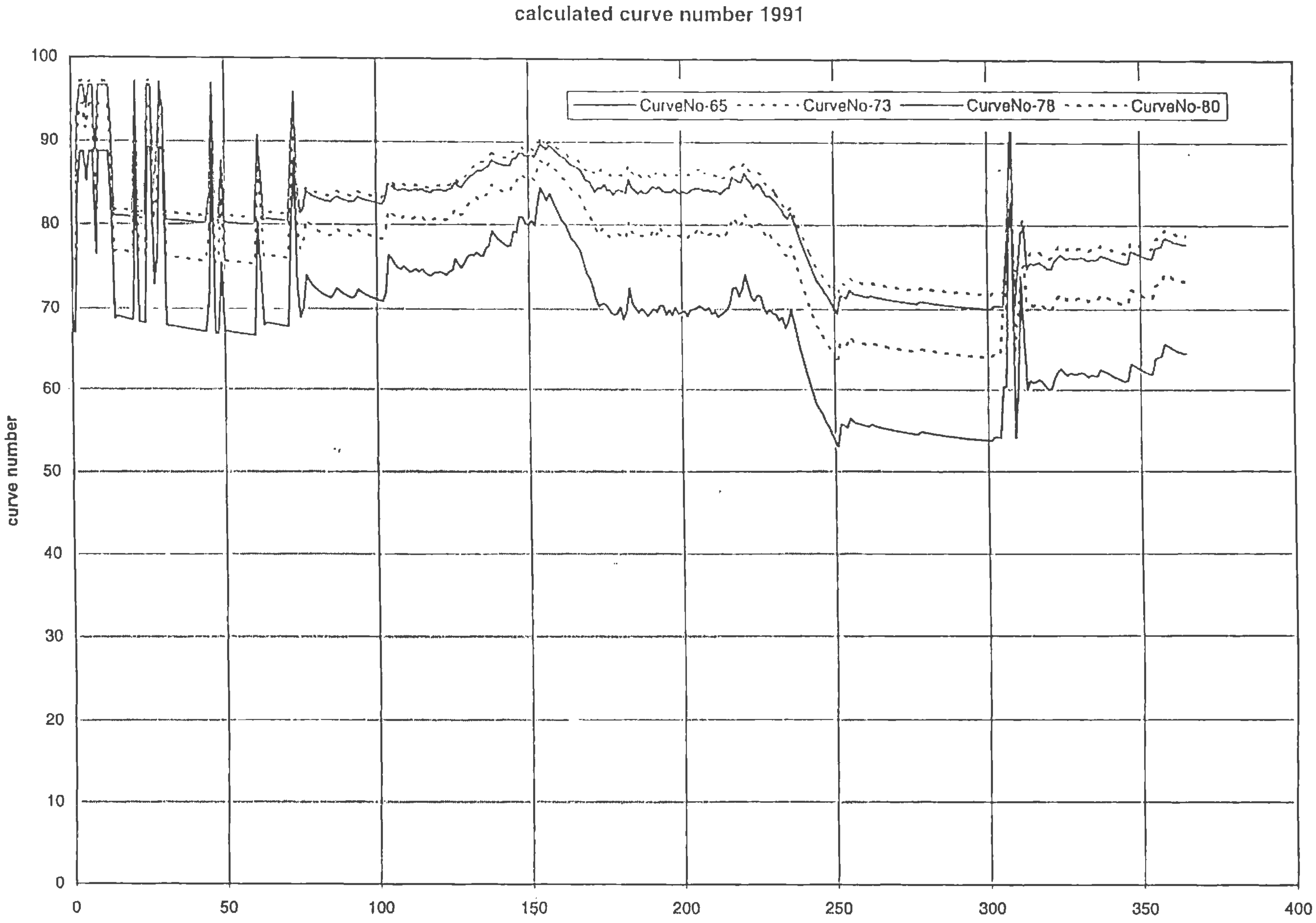


Figure 9.15. Temporal (daily) variation of curve numbers 65, 73, 78, and 80 for the Kipson soil during 1991.

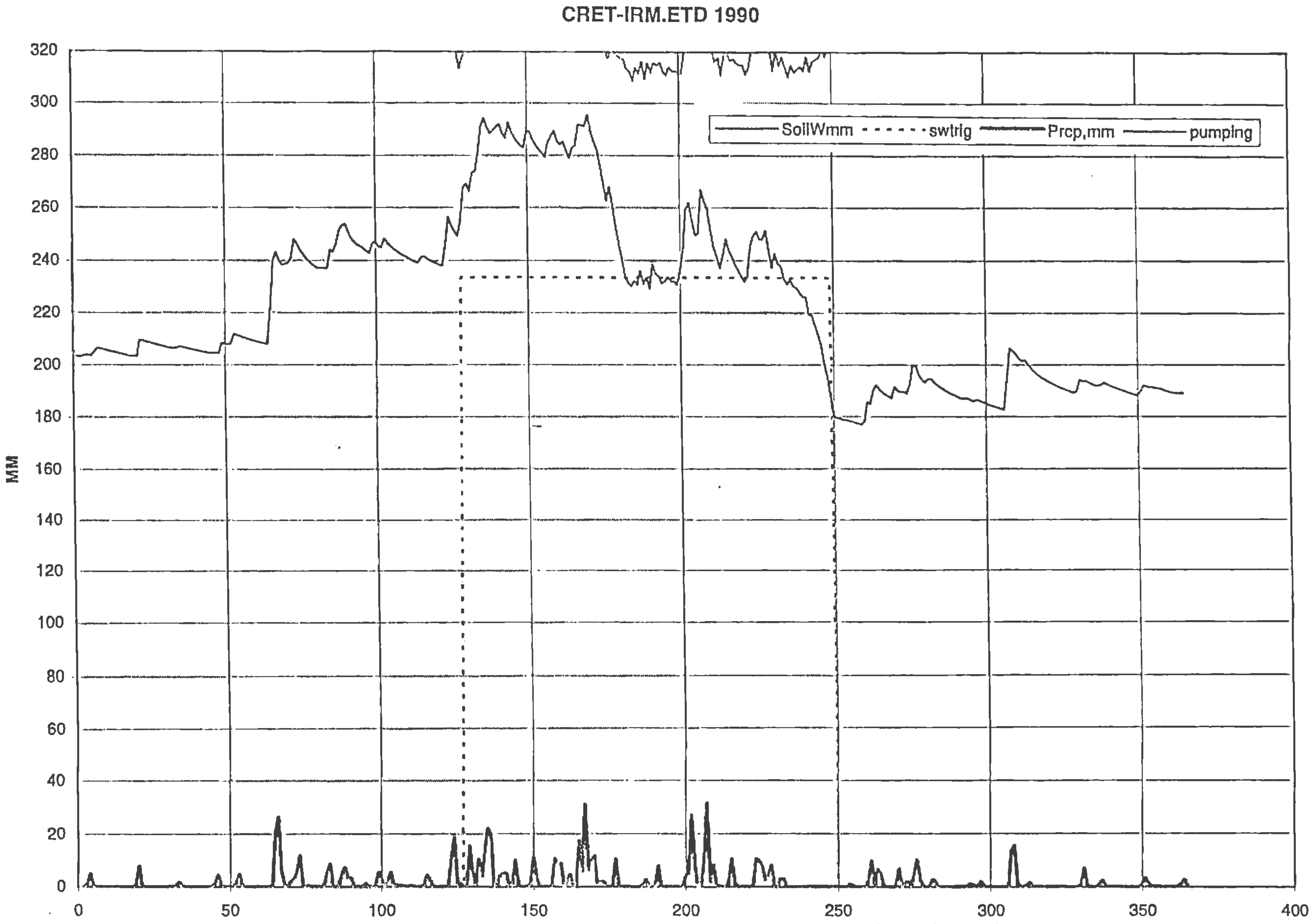


Figure 9.16. 1990 daily precipitation (mm; bottom) and soil-profile moisture (mm) variation for Crete soil with irrigated corn. The vertical dash lines represent the crop growing season, the horizontal dash line the soil profile water threshold to initiate irrigation during the crop growing season, and the top gray-line curve represents the assigned ground-water based irrigation (in mm measured from the top axis).

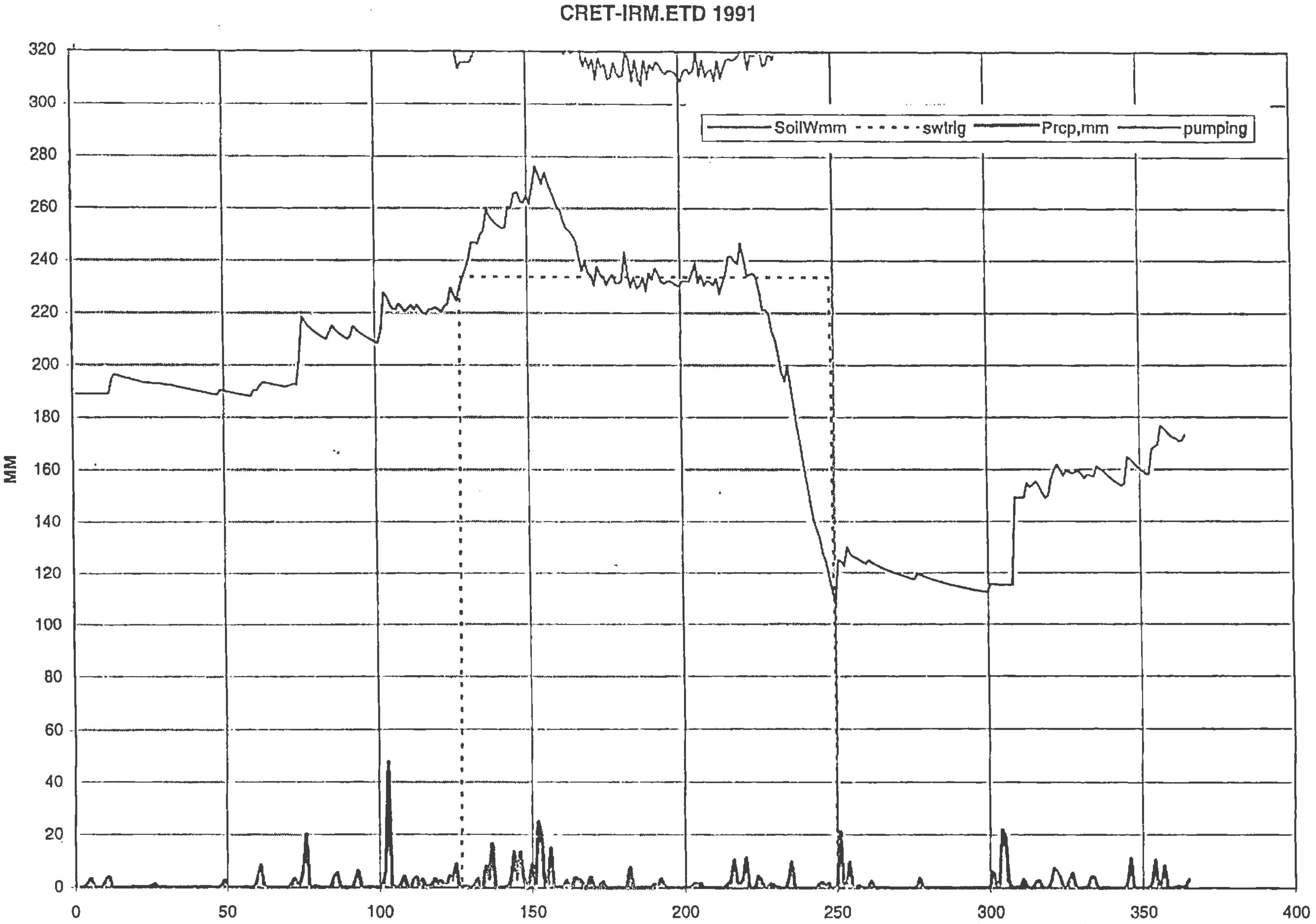


Figure 9.17. 1991 daily precipitation (mm; bottom) and soil-profile moisture (mm) variation for Crete soil with irrigated corn. The vertical dash lines represent the crop growing season, the horizontal dash line the soil profile water threshold to initiate irrigation during the crop growing season, and the top gray-line curve represents the assigned ground-water based irrigation (in mm measured from the top axis).

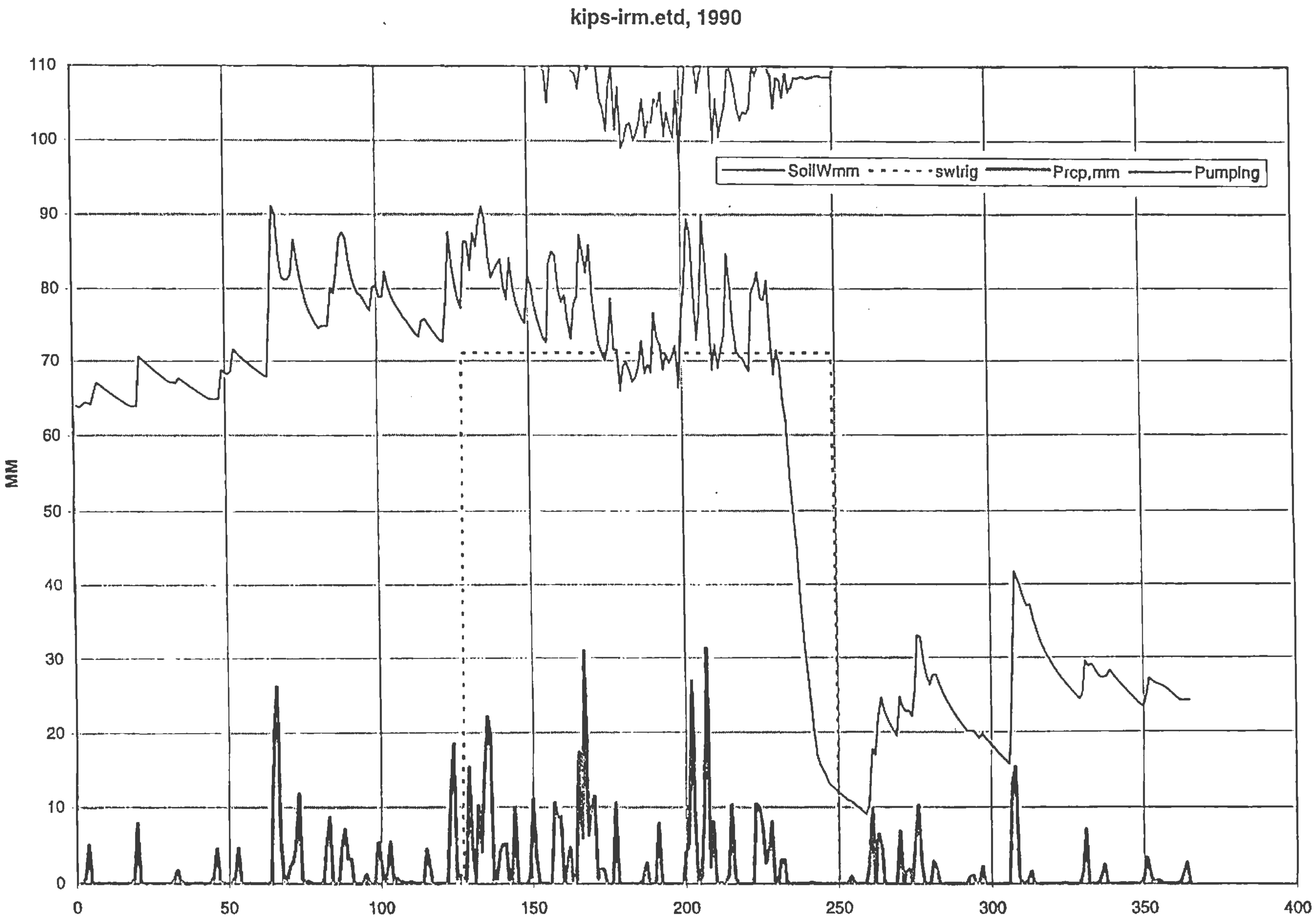


Figure 9.18. 1990 daily precipitation (mm; bottom) and soil-profile moisture (mm) variation for Kipson soil with irrigated corn. The vertical dash lines represent the crop growing season, the horizontal dash line the soil profile water threshold to initiate irrigation during the crop growing season, and the top gray-line curve represents the assigned ground-water based irrigation (in mm measured from the top axis).

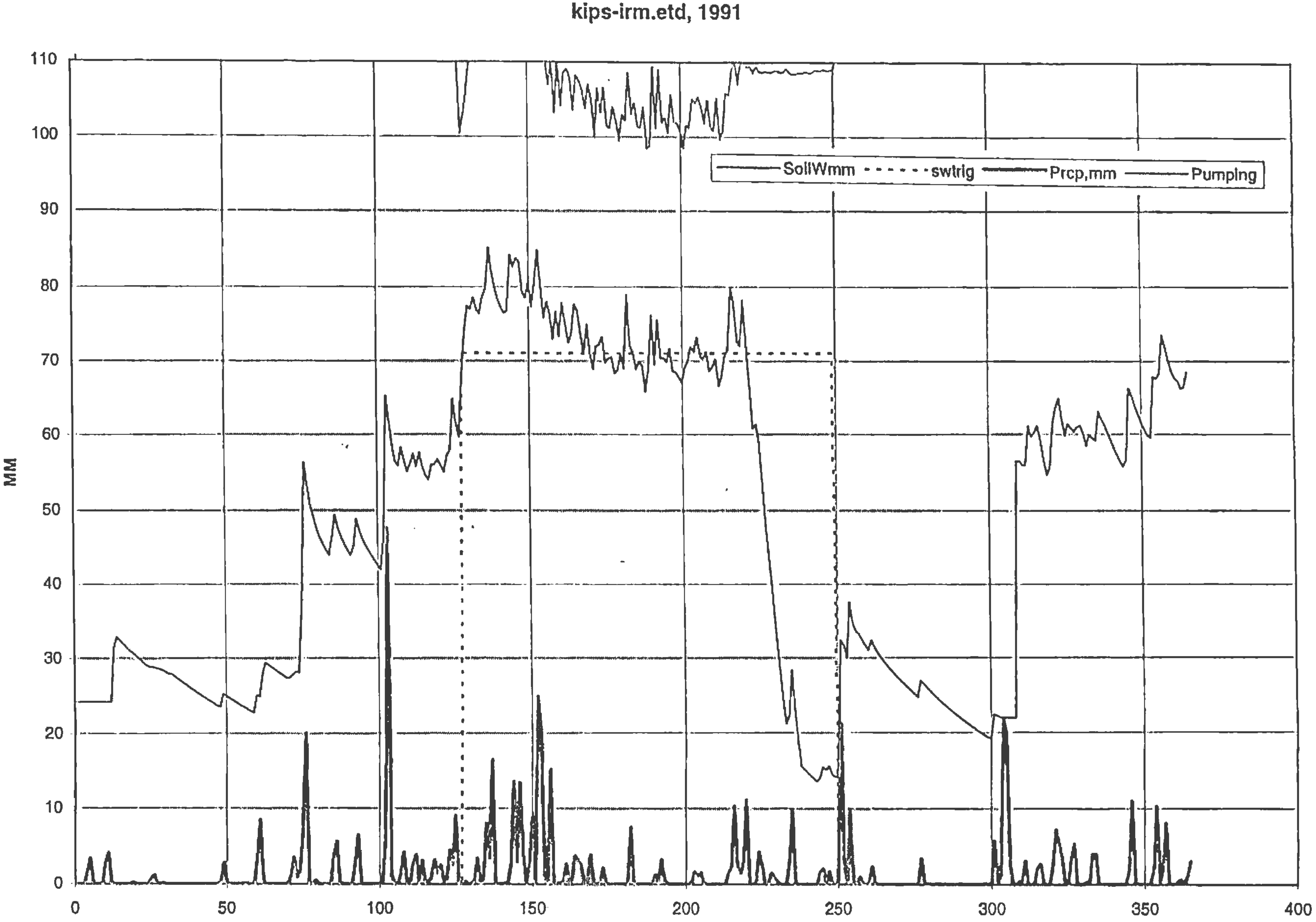


Figure 9.19. 1991 daily precipitation (mm; bottom) and soil-profile moisture (mm) variation for Kipson soil with irrigated corn. The vertical dash lines represent the crop growing season, the horizontal dash line the soil profile water threshold to initiate irrigation during the crop growing season, and the top gray-line curve represents the assigned ground-water based irrigation (in mm measured from the top axis).

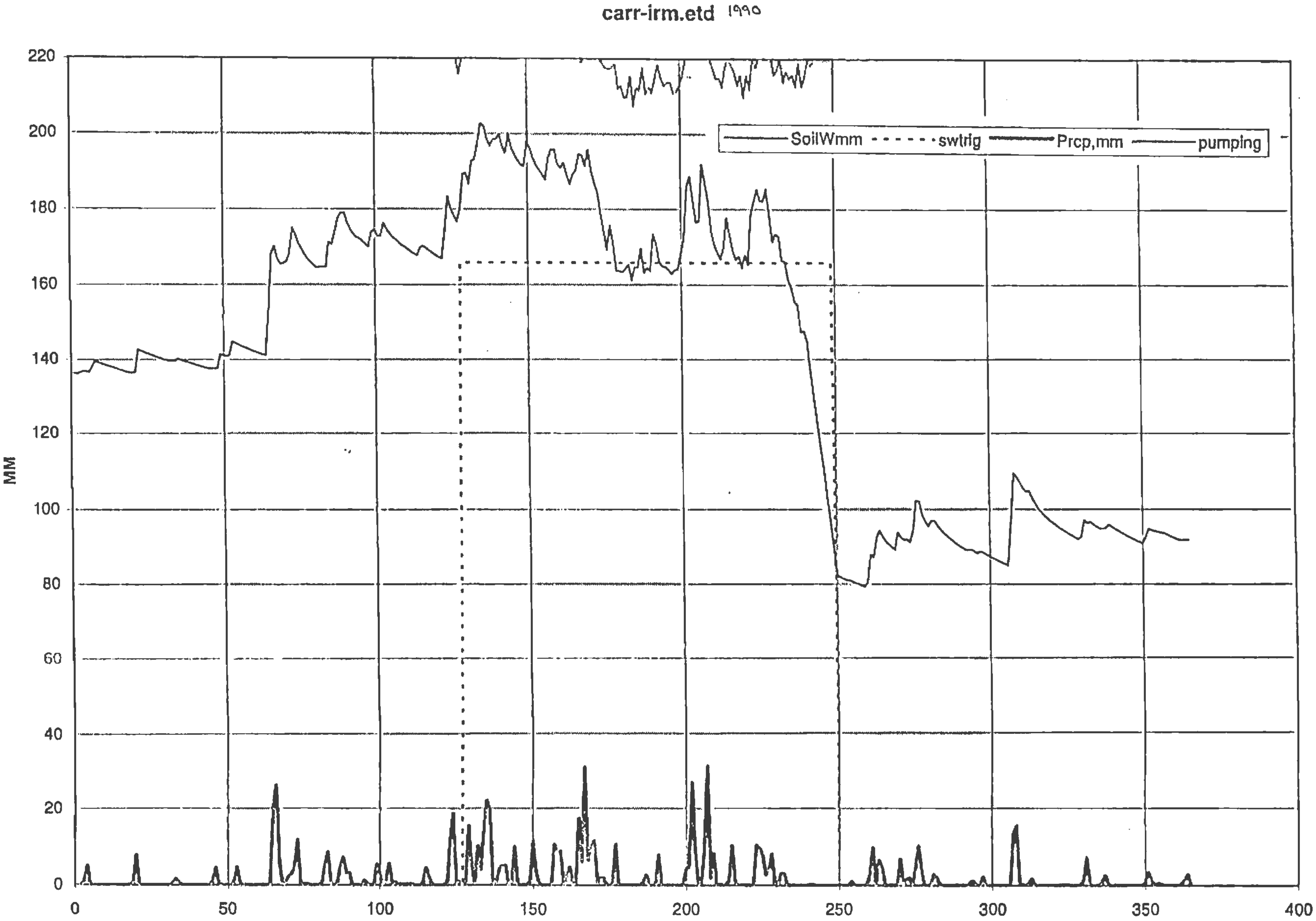


Figure 9.20. 1990 daily precipitation (mm; bottom) and soil-profile moisture (mm) variation for Carr soil with irrigated corn. The vertical dash lines represent the crop growing season, the horizontal dash line the soil profile water threshold to initiate irrigation during the crop growing season, and the top gray-line curve represents the assigned ground-water based irrigation (in mm measured from the top axis).

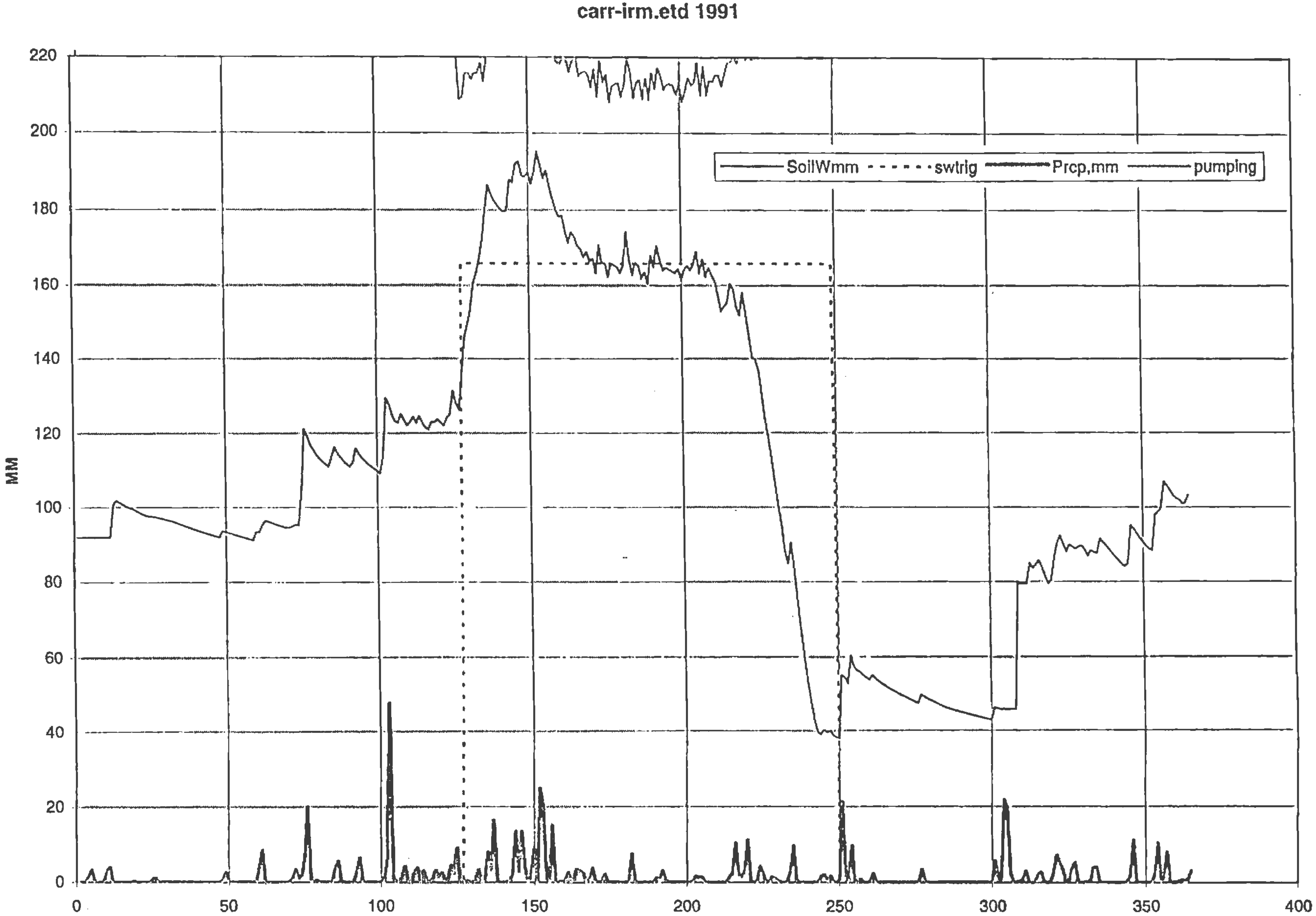


Figure 9.21. 1991 daily precipitation (mm; bottom) and soil-profile moisture (mm) variation for Carr soil with irrigated corn. The vertical dash lines represent the crop growing season, the horizontal dash line the soil profile water threshold to initiate irrigation during the crop growing season, and the top gray-line curve represents the assigned ground-water based irrigation (in mm measured from the top axis).

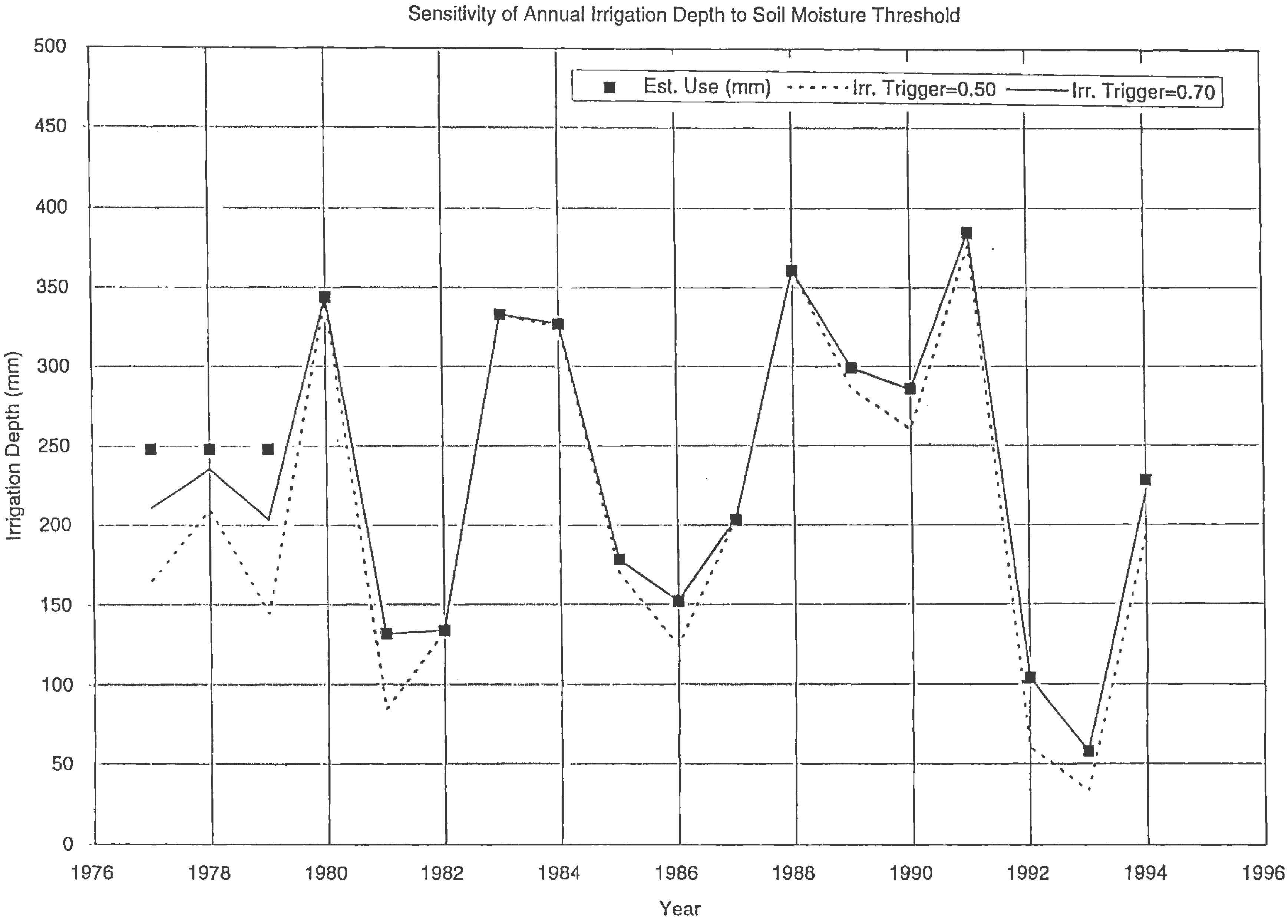


Figure 9.22. Reported (since 1980) versus simulated irrigation water use for two different soil moisture thresholds (irrigation triggers) used in SWAT for irrigation scheduling.

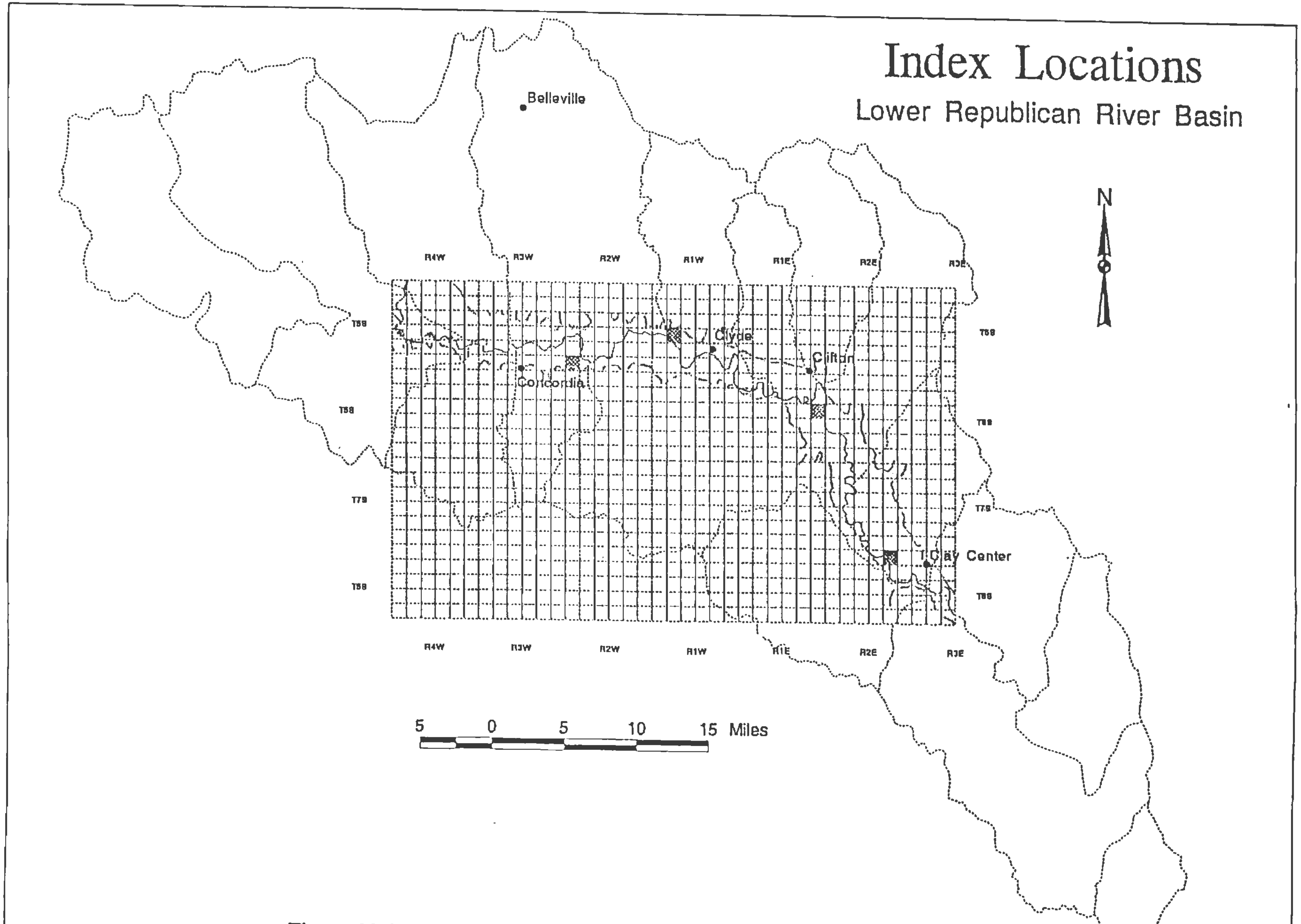
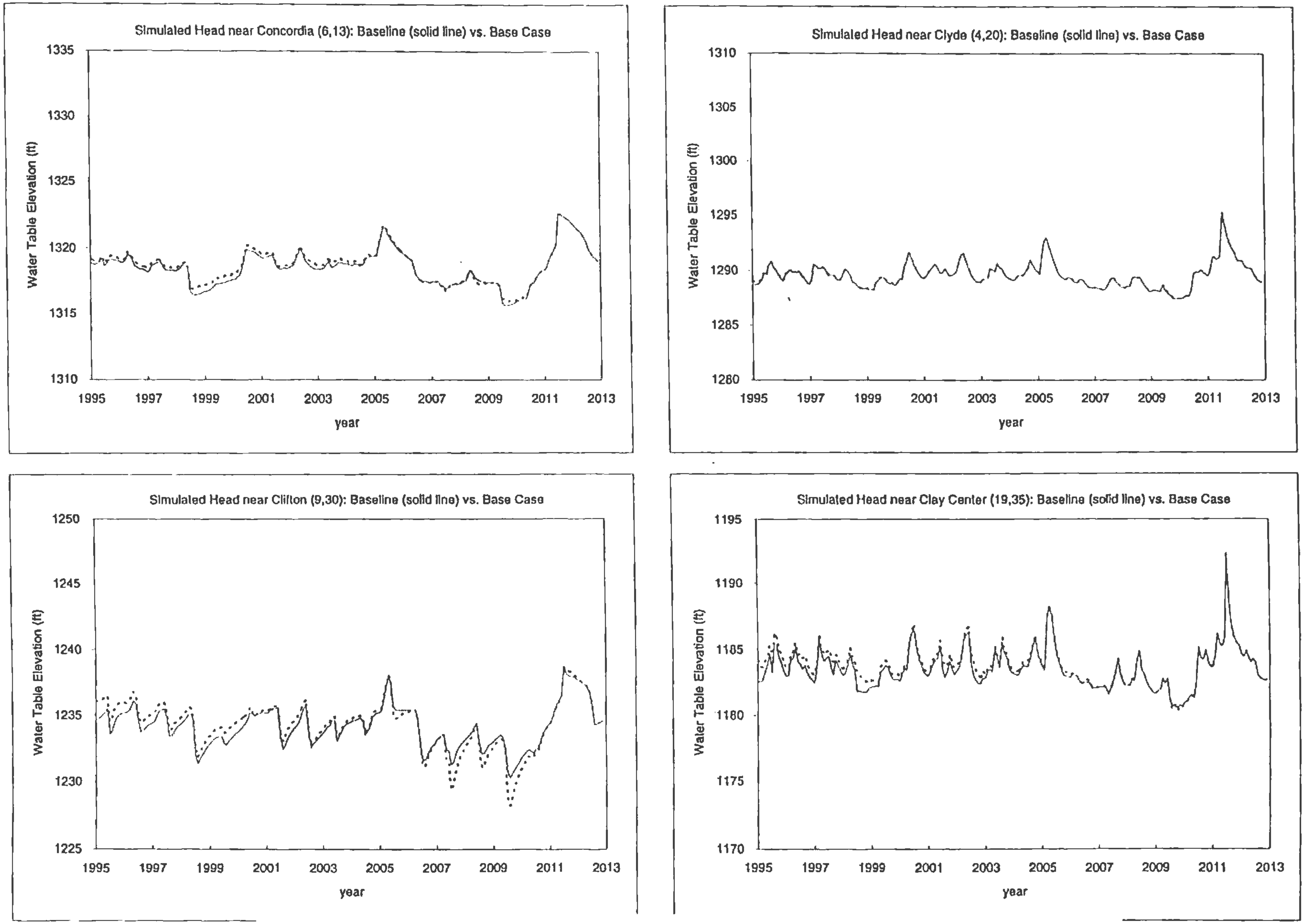


Figure 10.1. Index locations for monitoring ground-water level trends in the Lower Republican River valley.



Simulated Head near Concordia (6,13): Baseline (solid line) vs. Base Case

Simulated Head near Clyde (4,20): Baseline (solid line) vs. Base Case

Simulated Head near Clifton (9,30): Baseline (solid line) vs. Base Case

Simulated Head near Clay Center (19,35): Baseline (solid line) vs. Base Case

Figure 10.2. Simulated ground-water level hydrographs at the index locations (fig. 10.1) for the baseline scenario (1995-2012) and the base case (1977-1994). The base case data were shifted forward by 18 years for comparison.

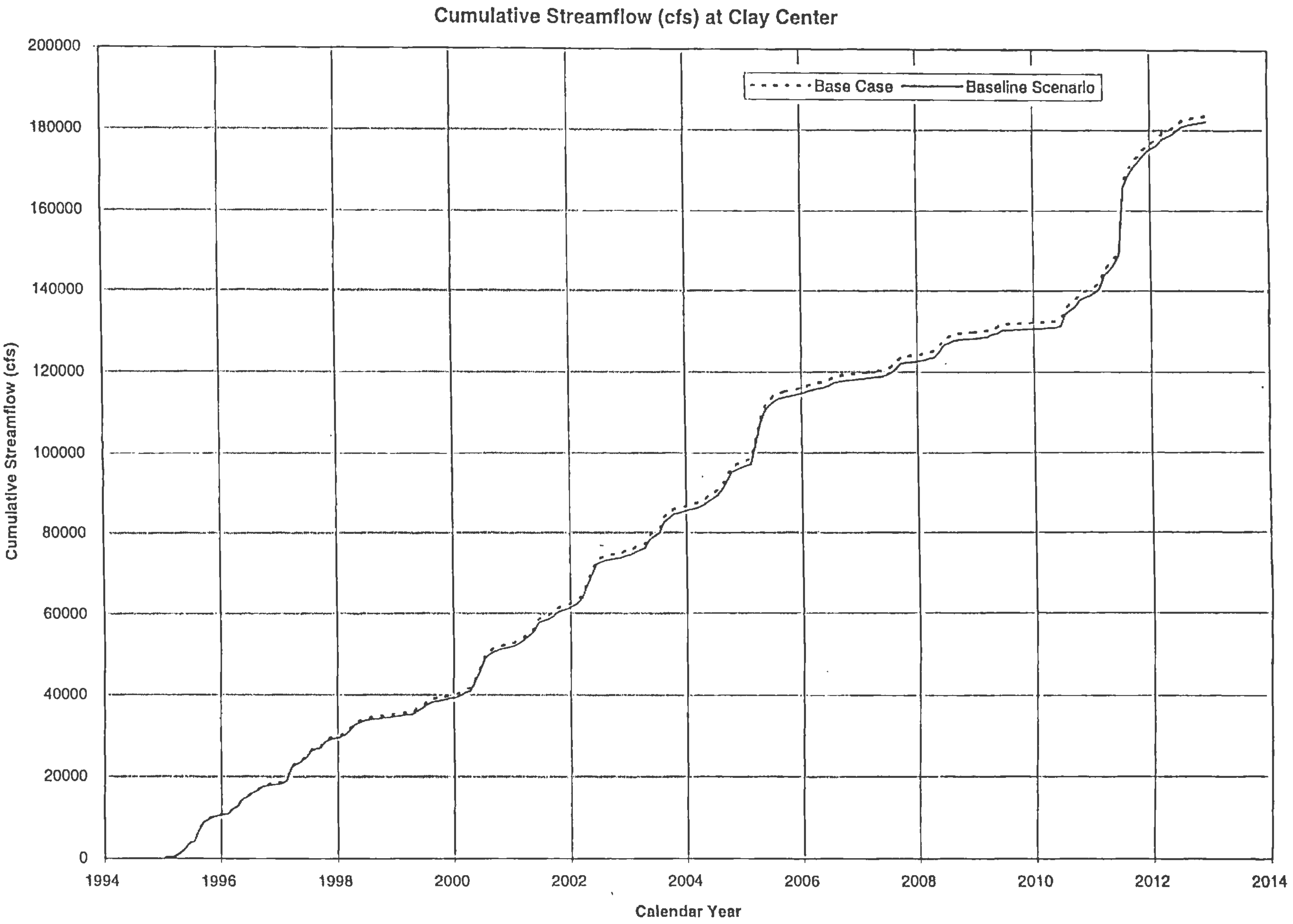


Figure 10.3. Simulated cumulative (1995-2012) streamflows at Clay Center for the baseline scenario. Simulated base case (1977-1994) cumulative streamflows at Clay Center, shifted forward by 18 years for comparison, are also shown.

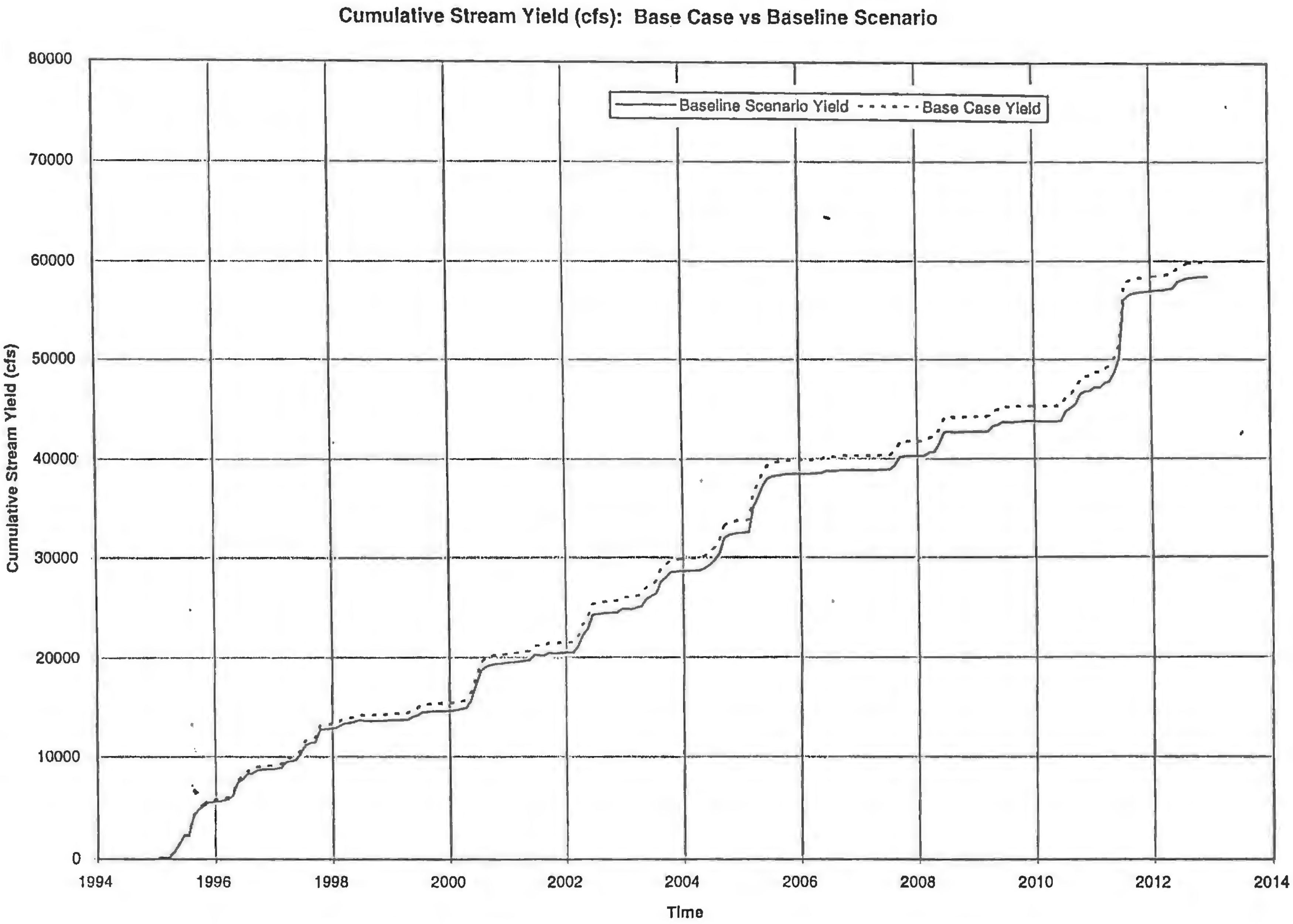


Figure 10.4. Simulated cumulative (1995-2012) stream yield from Concordia to Clay Center for the baseline scenario. Corresponding simulated base case (1977-1994) stream yield, shifted forward by 18 years for comparison, is also shown.

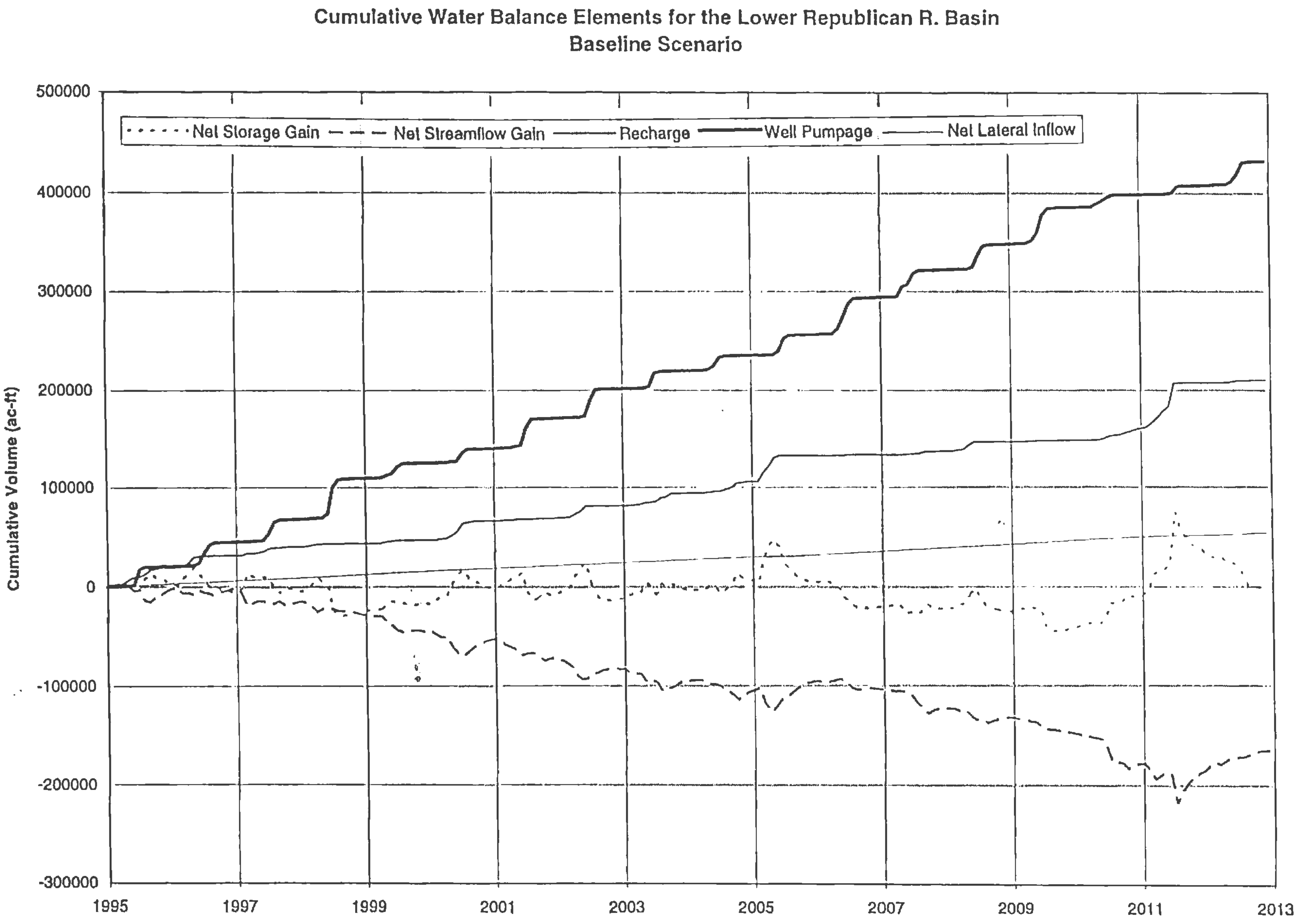


Figure 10.5. Cumulative monthly hydrologic budget components for the baseline scenario.

Figure 10.6. Comparison of hydrologic fluxes expressed as flow rates (cfs) for the Lower Republican River basin.

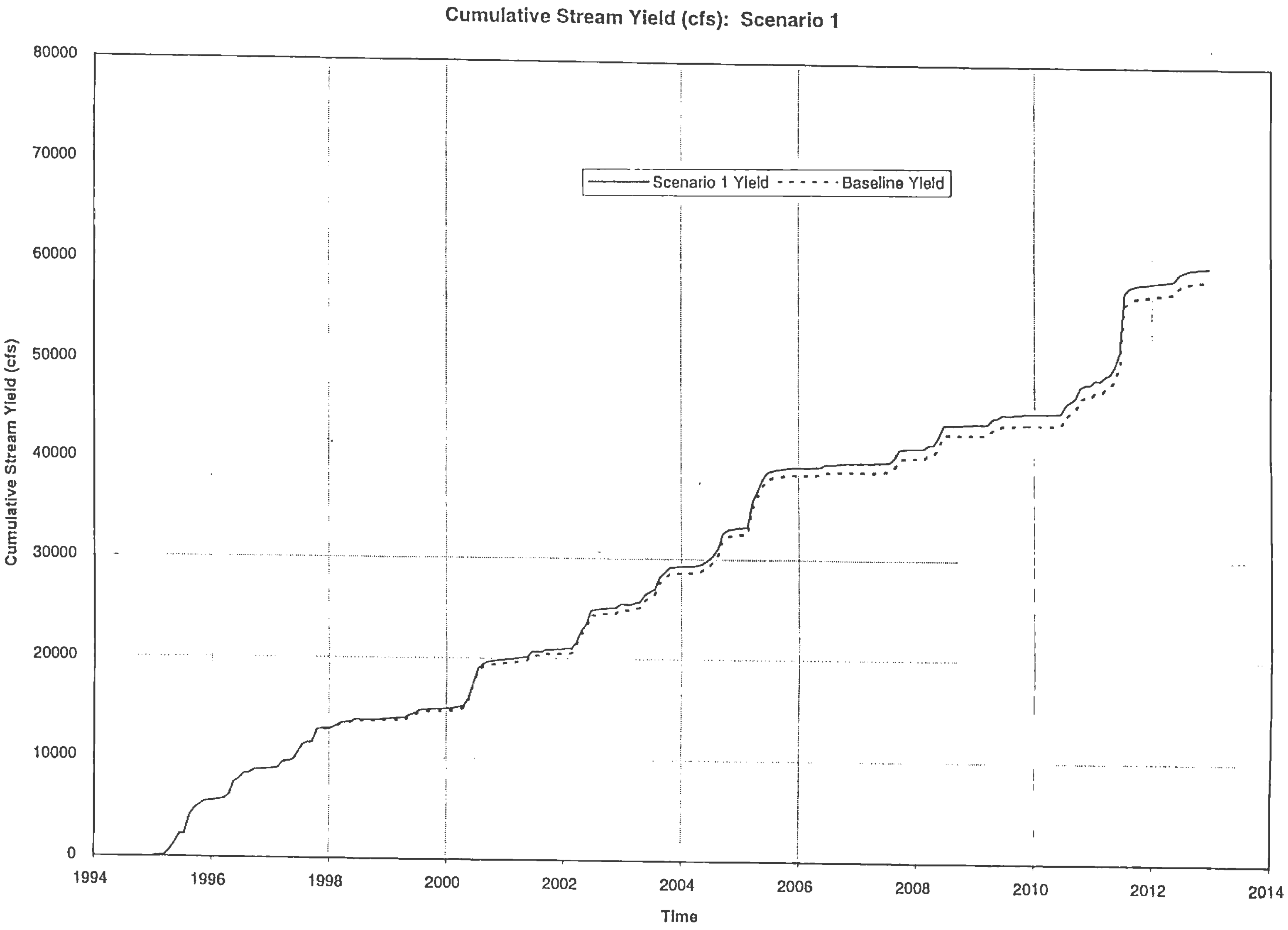


Figure 10.7. Simulated cumulative stream yield for scenario 1 compared to the baseline scenario.

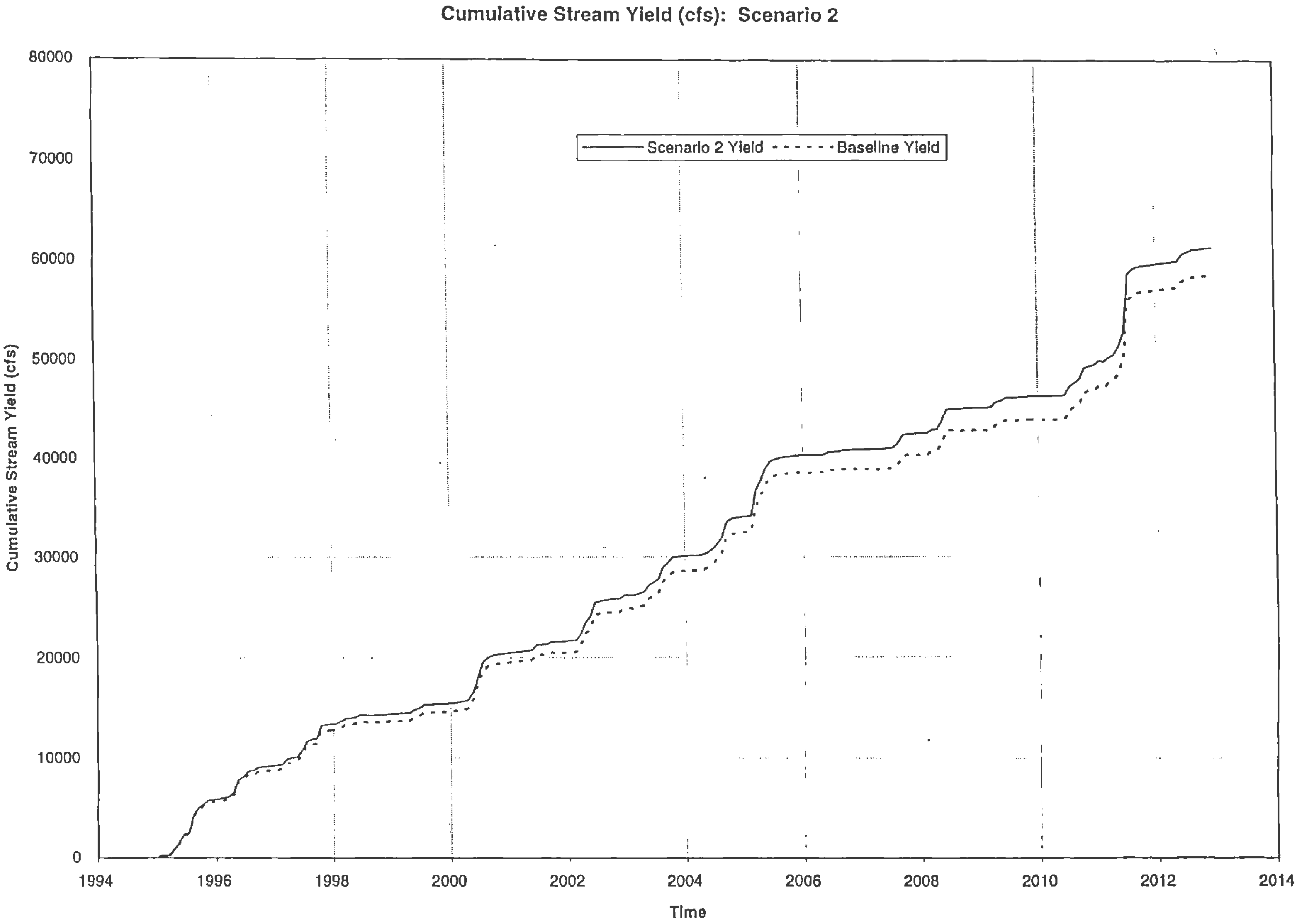


Figure 10.8. Simulated cumulative stream yield for scenario 2 compared to the baseline scenario.

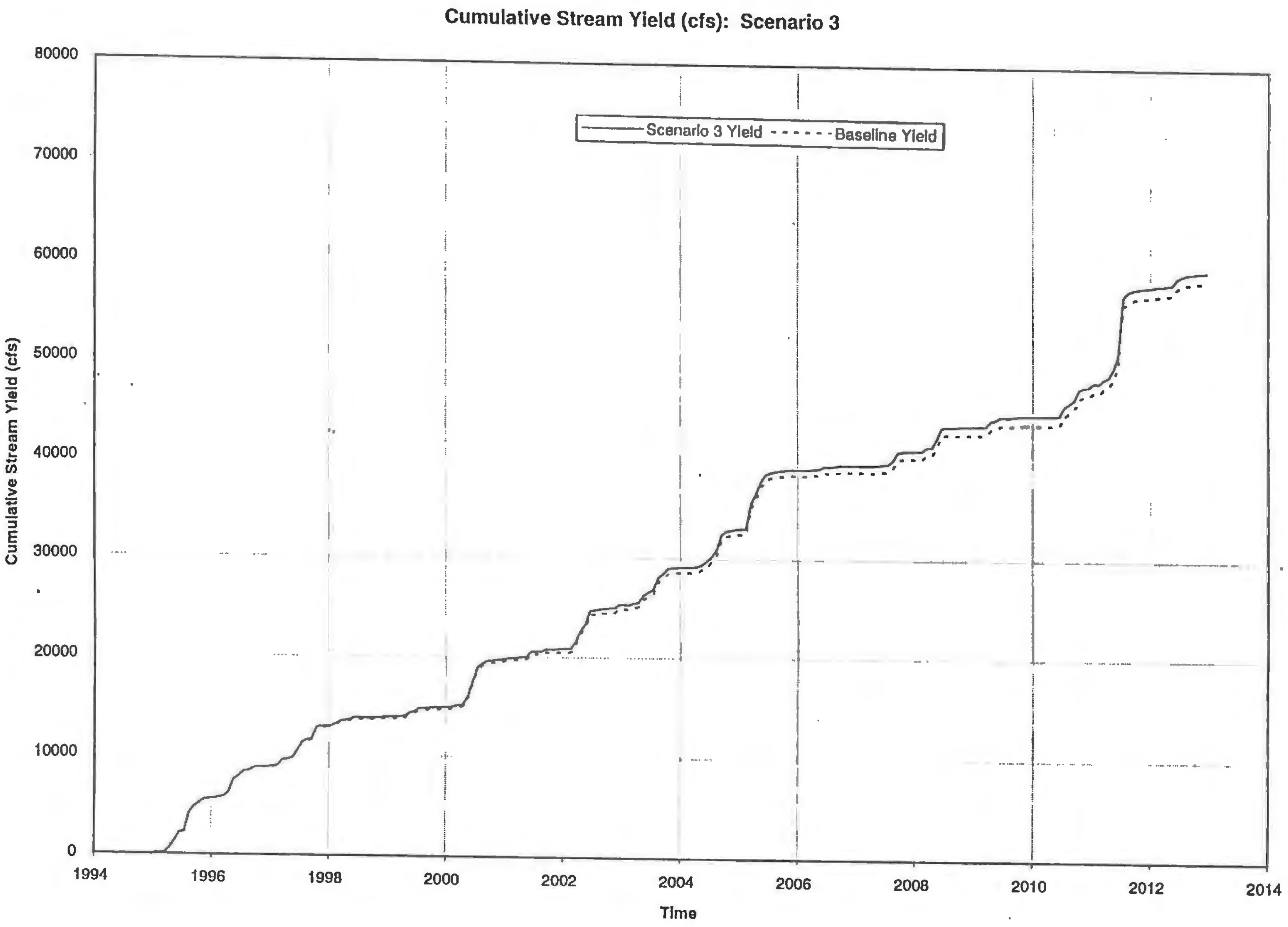


Figure 10.9. Simulated cumulative stream yield for scenario 3 compared to the baseline scenario.

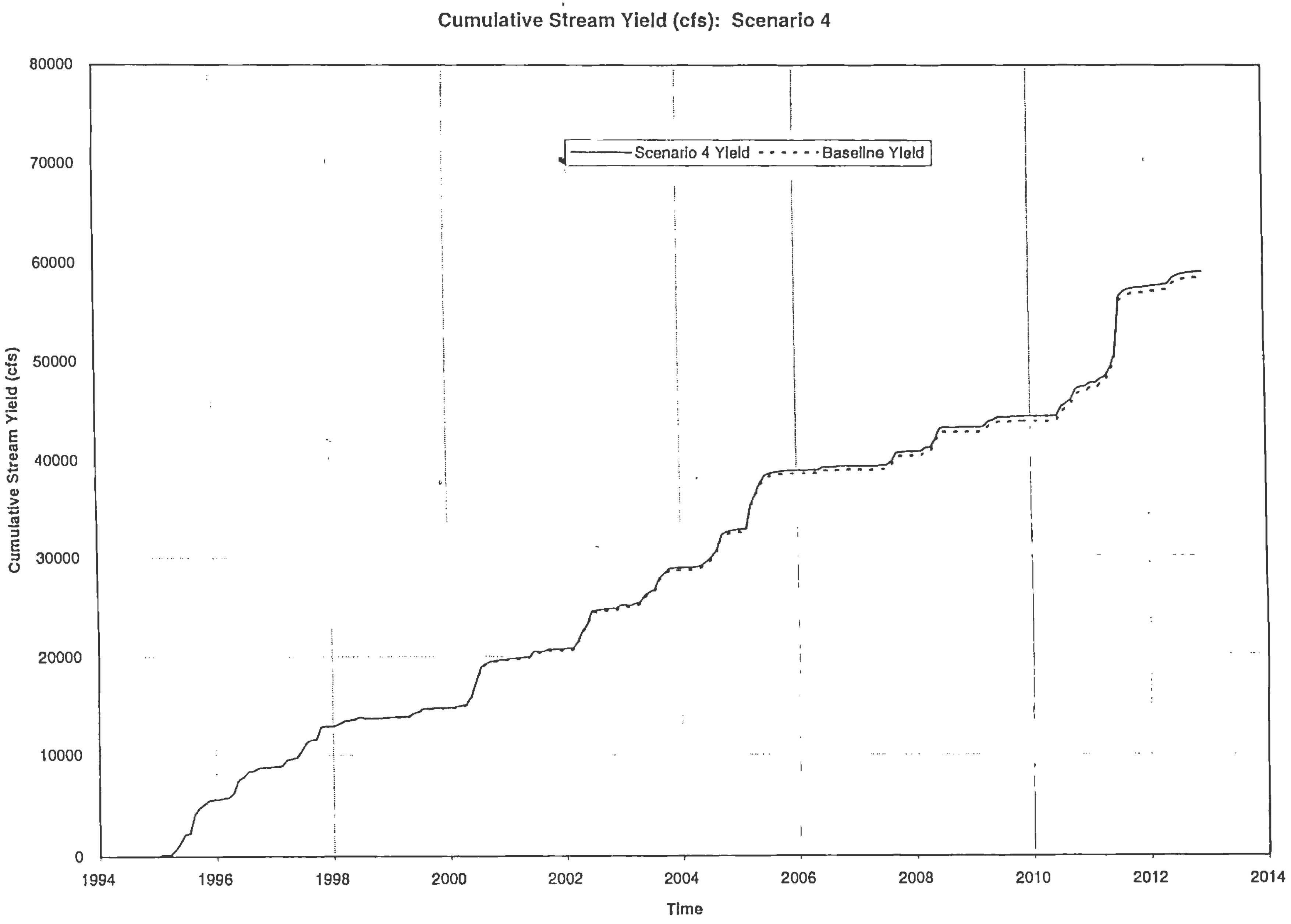


Figure 10.10. Simulated cumulative stream yield for scenario 4 compared to the baseline scenario.

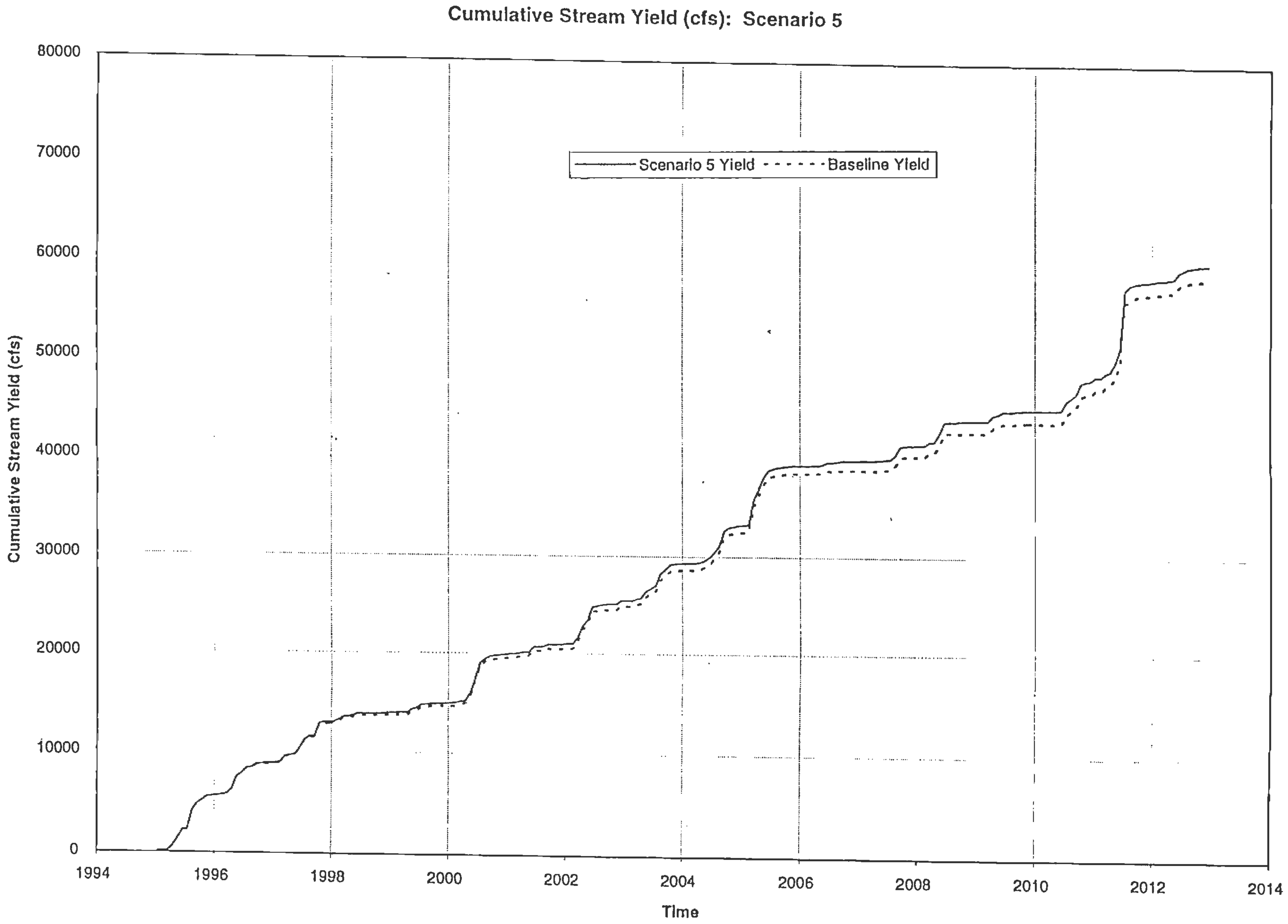


Figure 10.11 Simulated cumulative stream yield for scenario 5 compared to the baseline scenario.

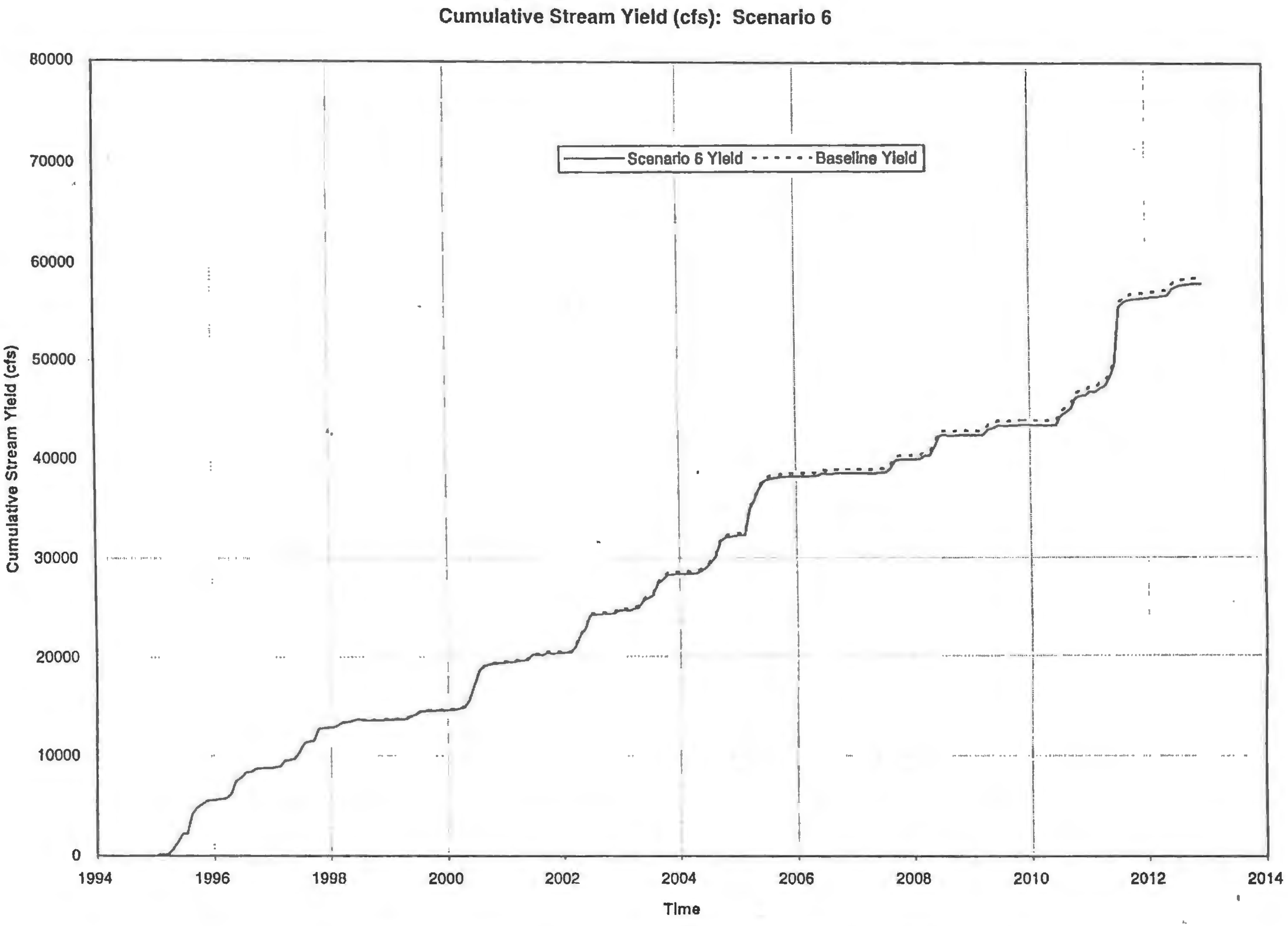


Figure 10.12. Simulated cumulative stream yield for scenario 6 compared to the baseline scenario.

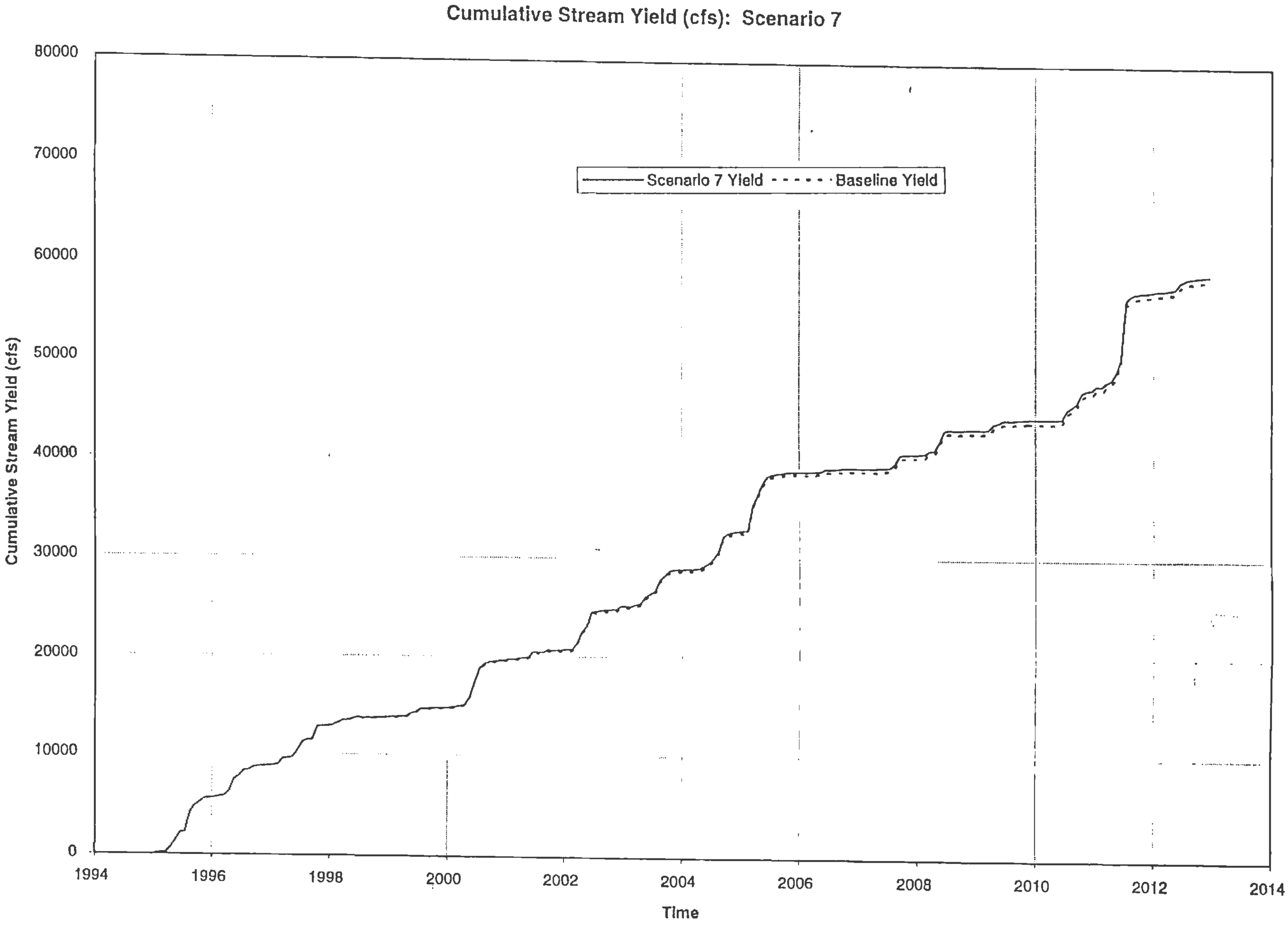


Figure 10.13. Simulated cumulative stream yield for scenario 7 compared to the baseline scenario.

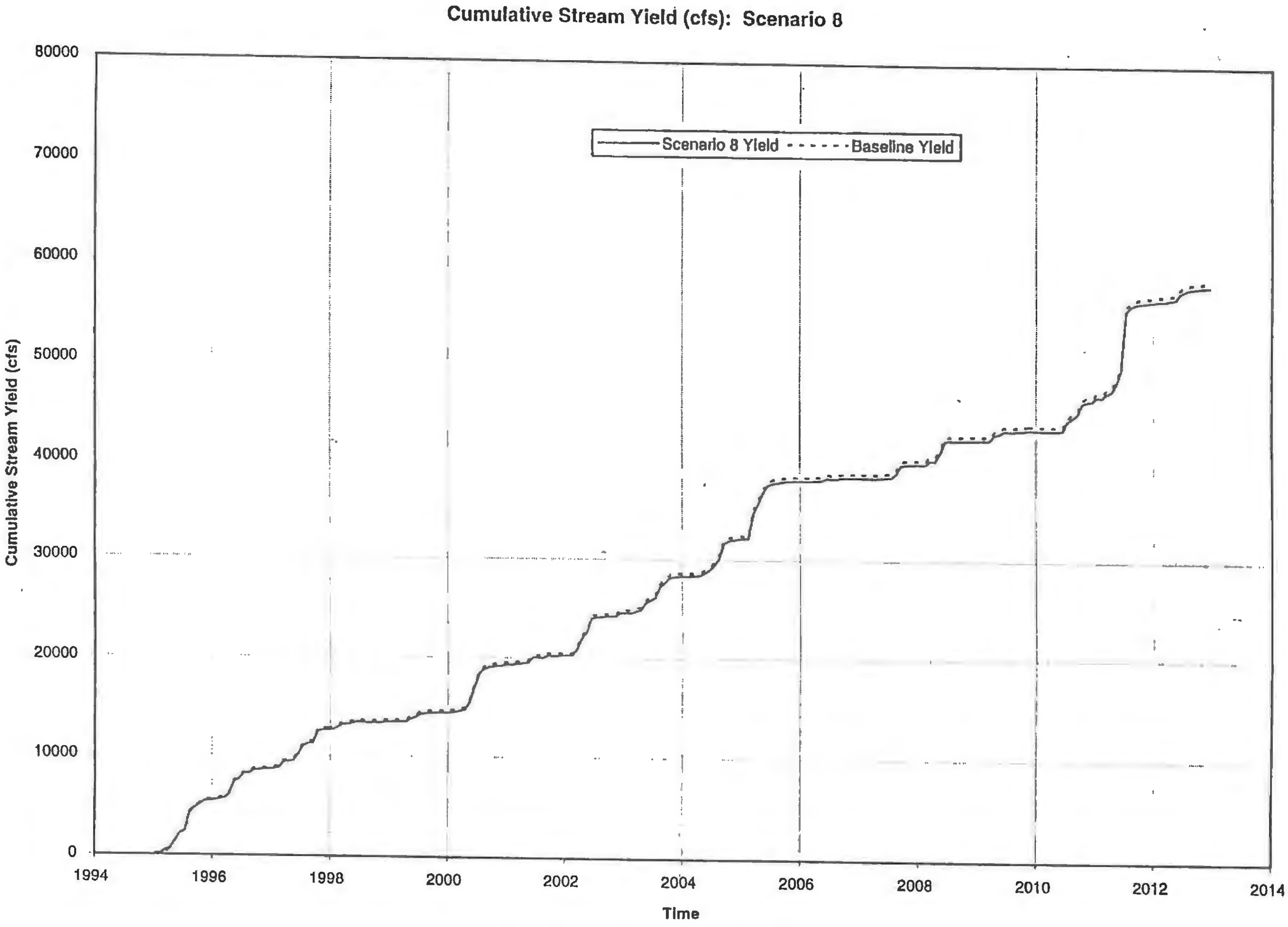


Figure 10.14. Simulated cumulative stream yield for scenario 8 compared to the baseline scenario.

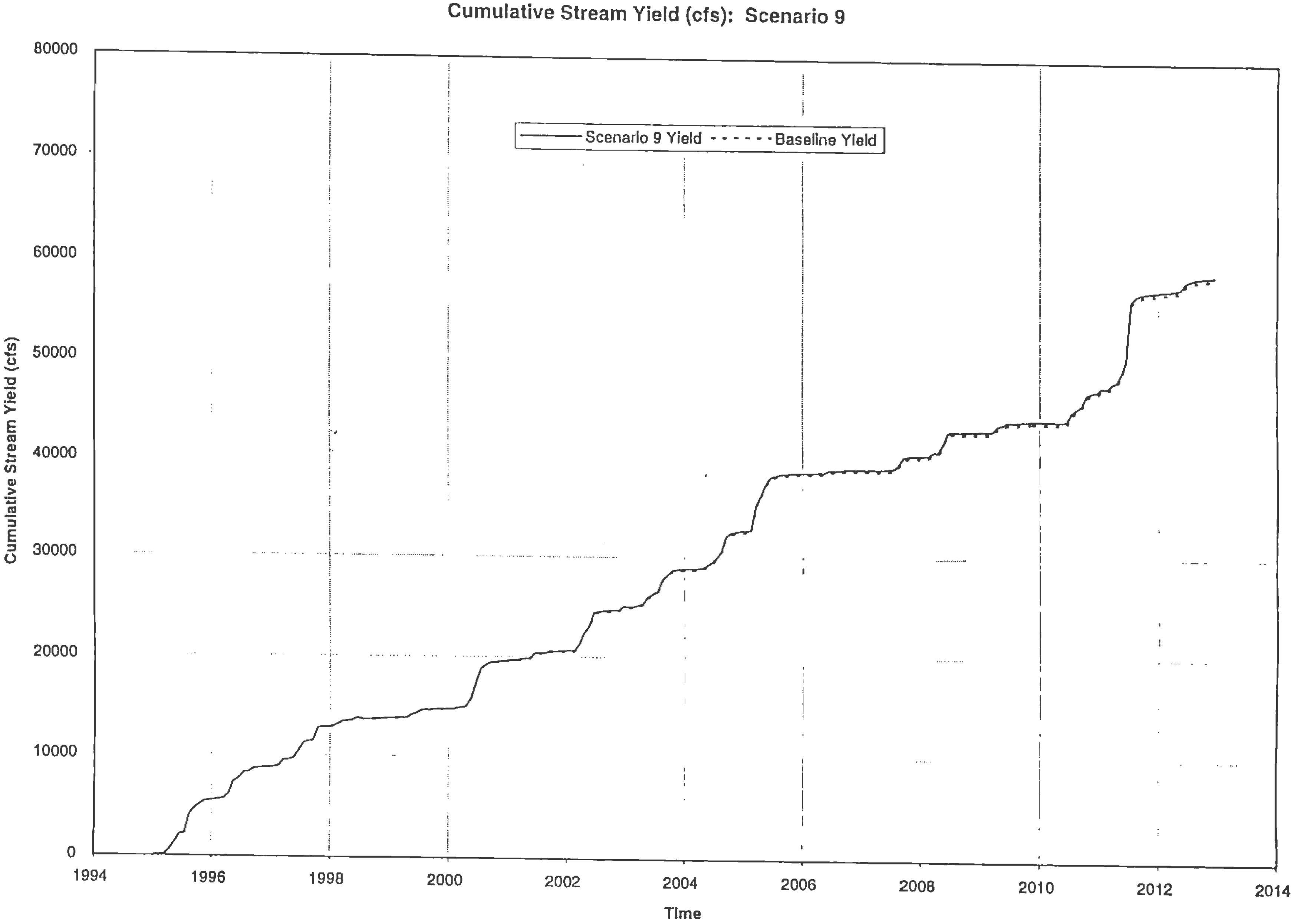


Figure 10.15. Simulated cumulative stream yield for scenario 9 compared to the baseline scenario.

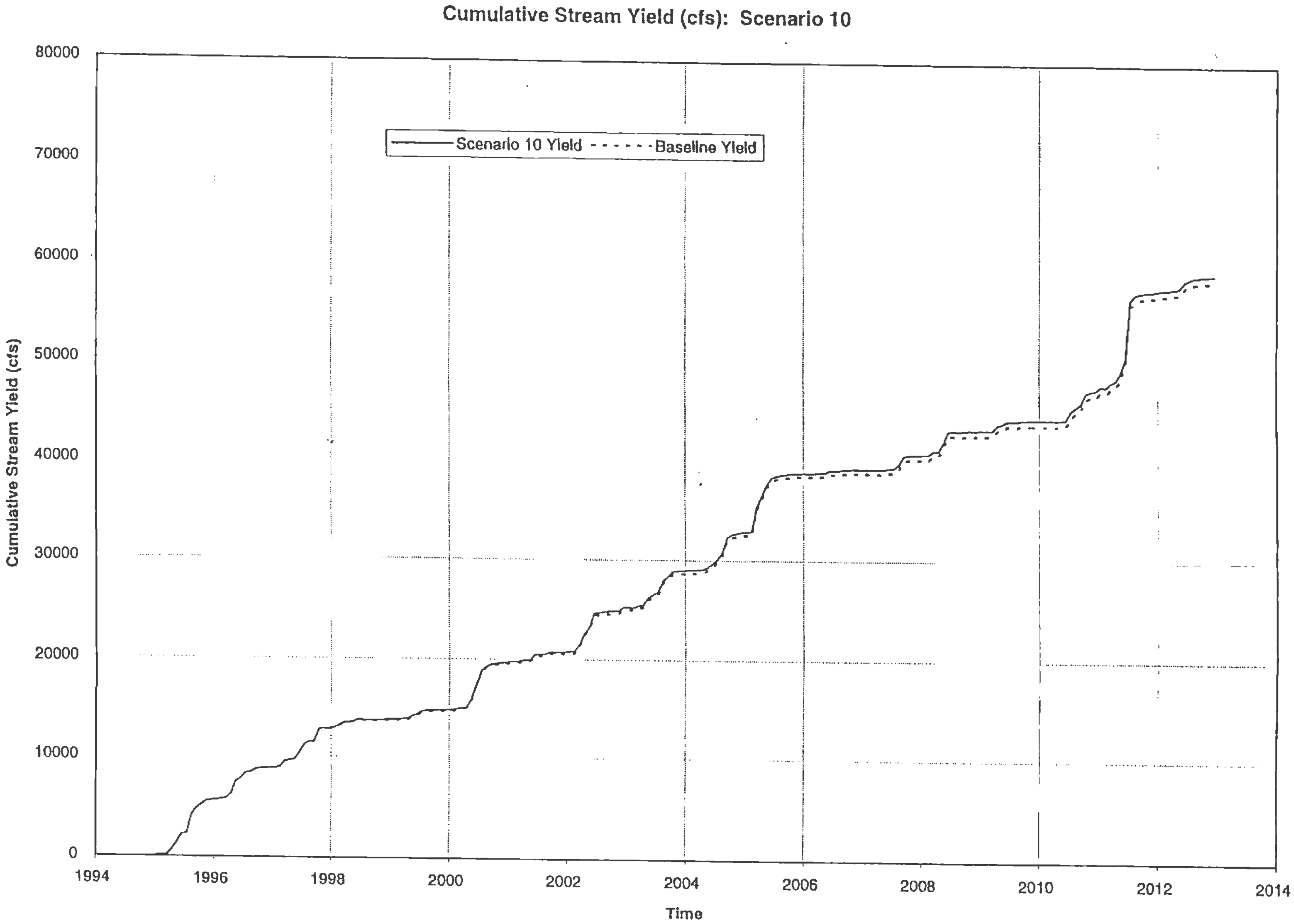


Figure 10.16. Simulated cumulative stream yield for scenario 10 compared to the baseline scenario.

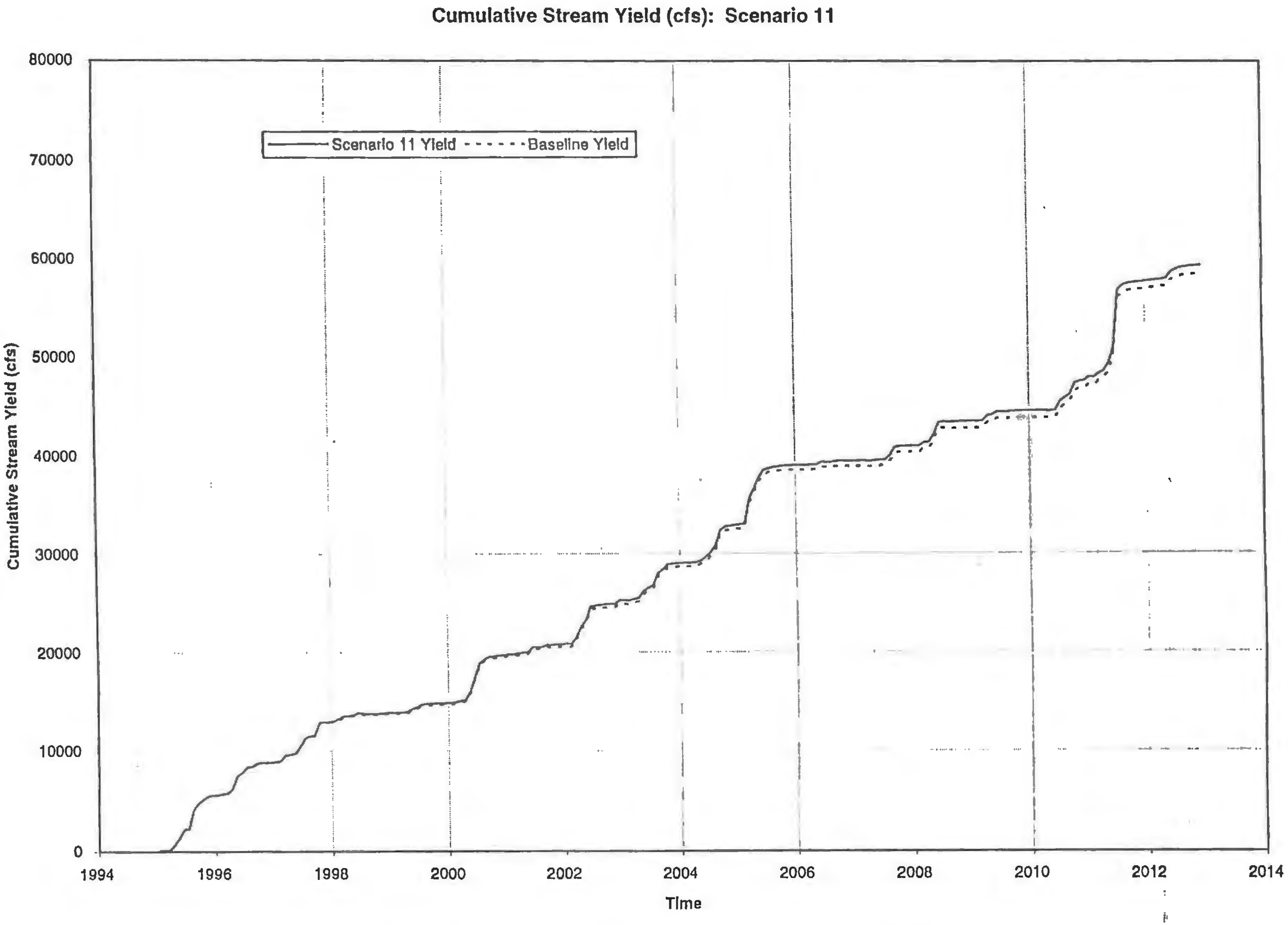


Figure 10.17. Simulated cumulative stream yield for scenario 11 compared to the baseline scenario.

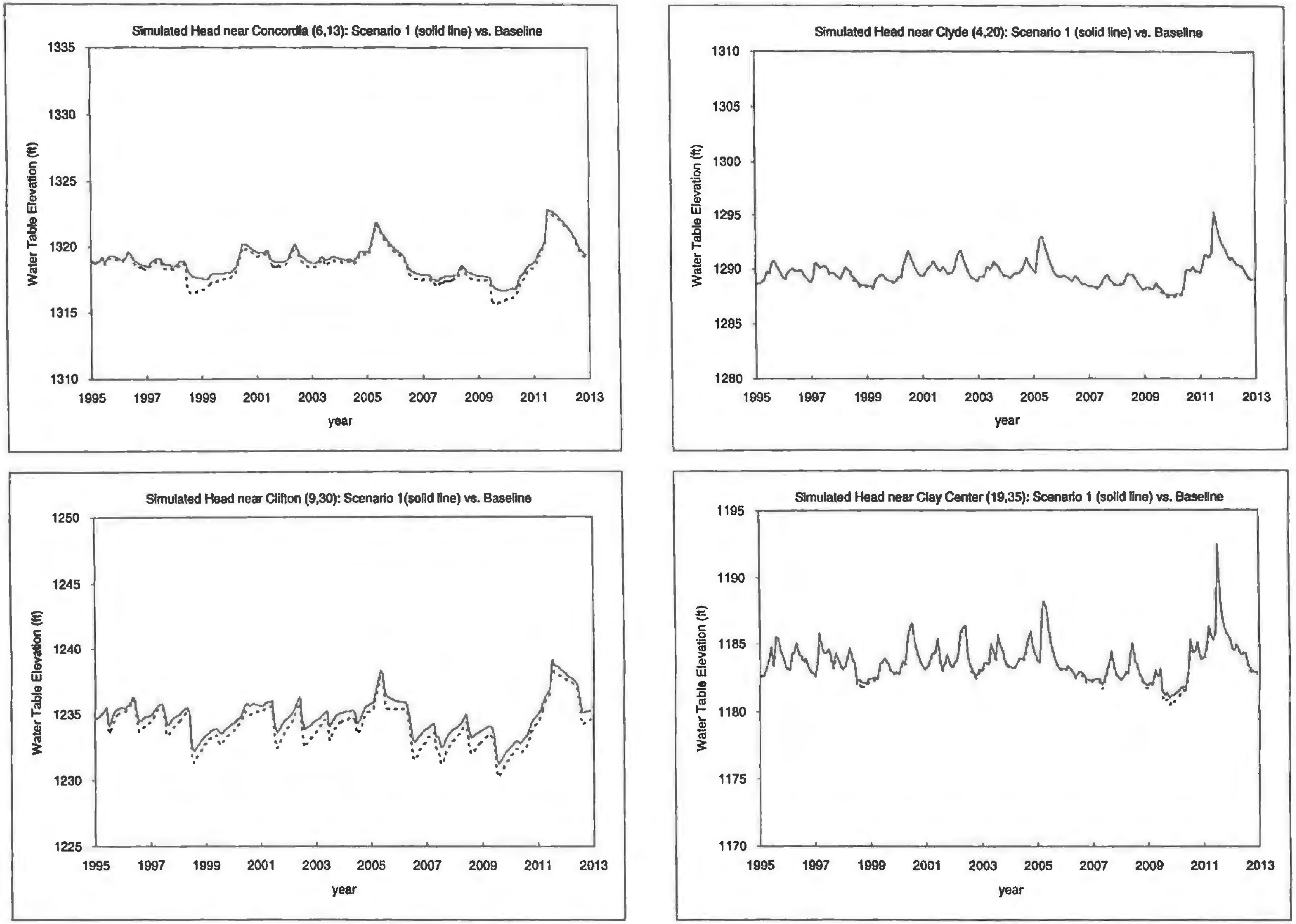


Figure 10.18. Simulated ground-water levels at the index locations (fig. 10.1) for scenario 1 compared to the baseline scenario.

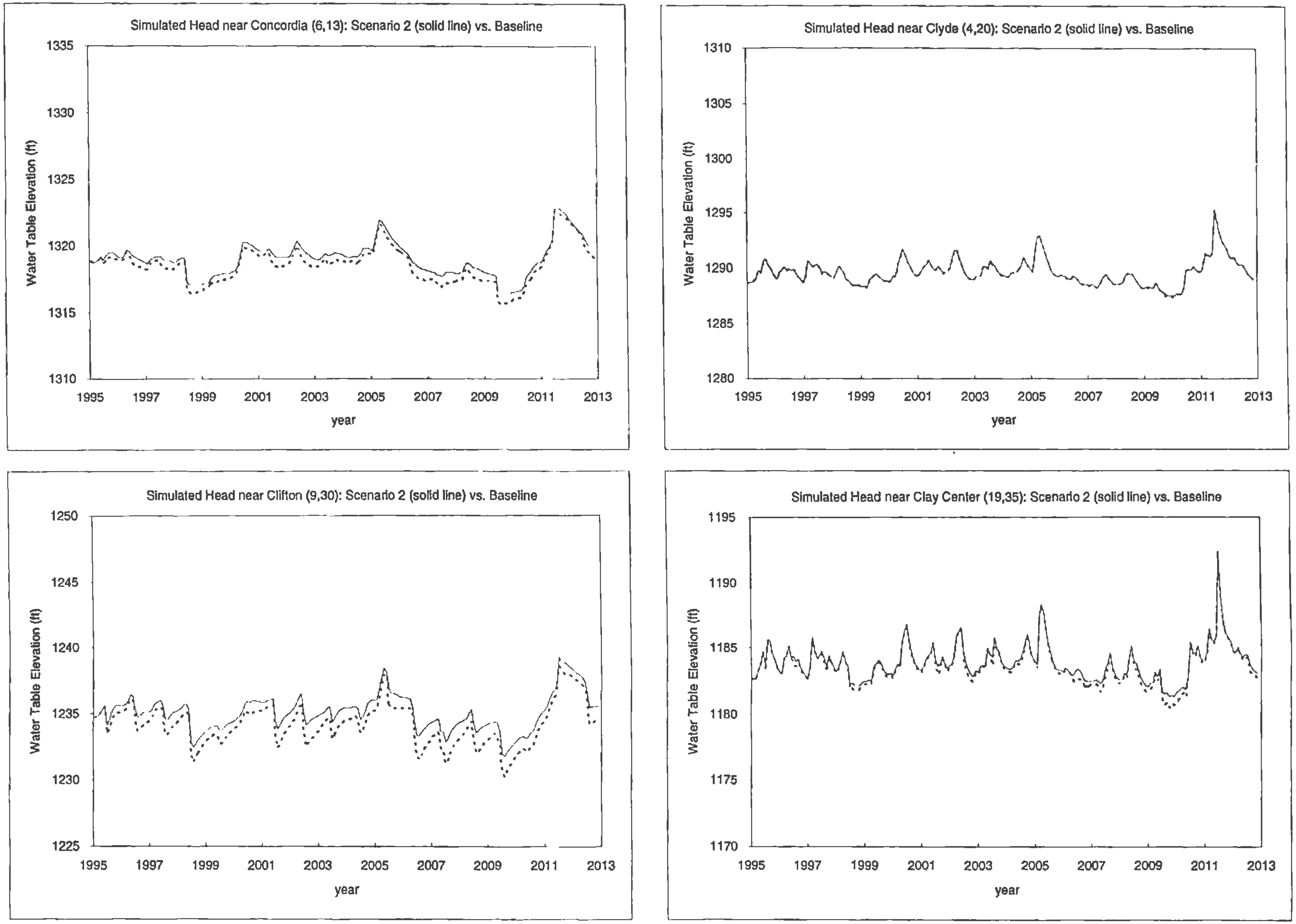


Figure 10.19. Simulated ground-water levels at the index locations (fig. 10.1) for scenario 2 compared to the baseline scenario.

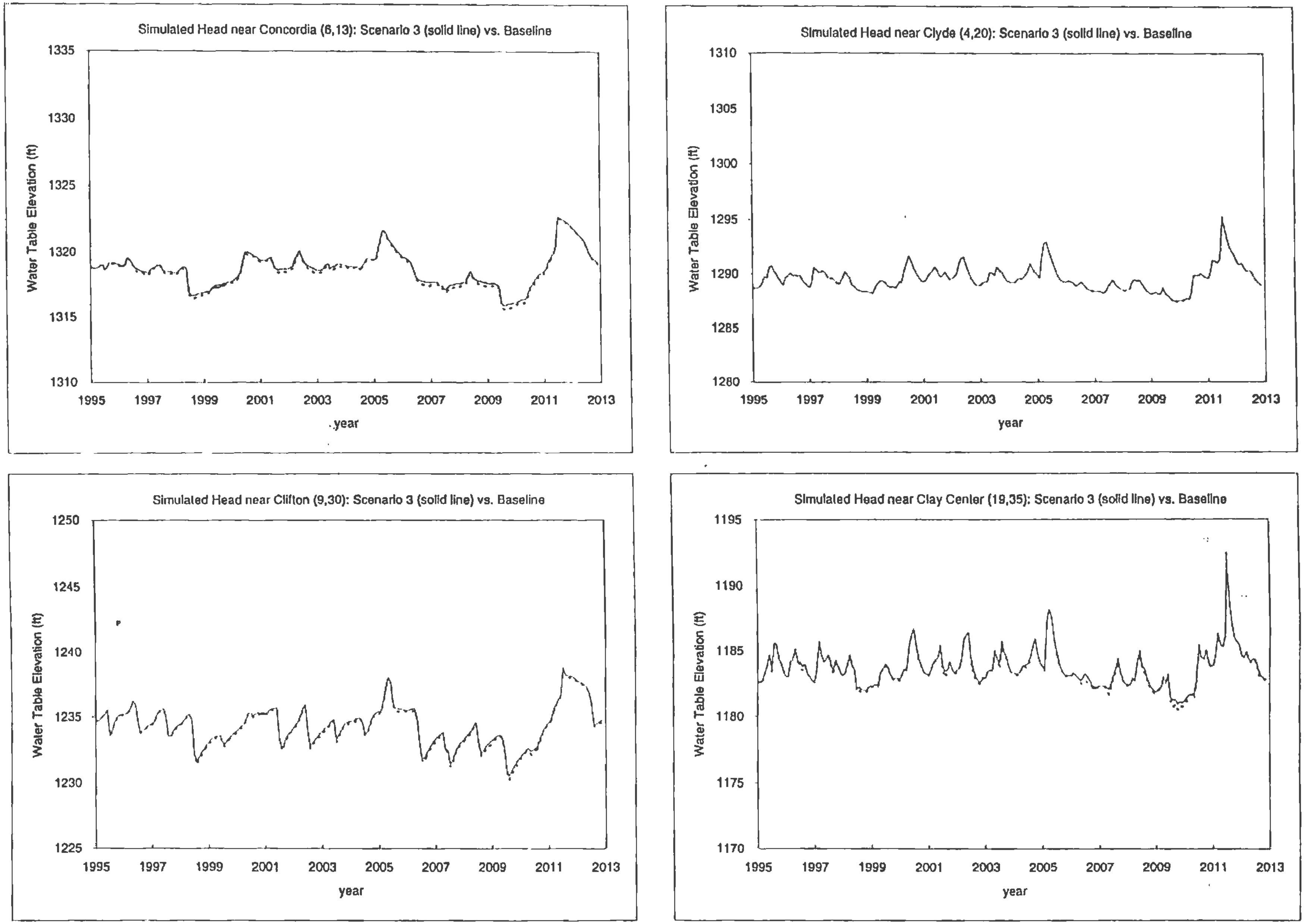


Figure 10.20. Simulated ground-water levels at the index locations (fig. 10.1) for scenario 3 compared to the baseline scenario.

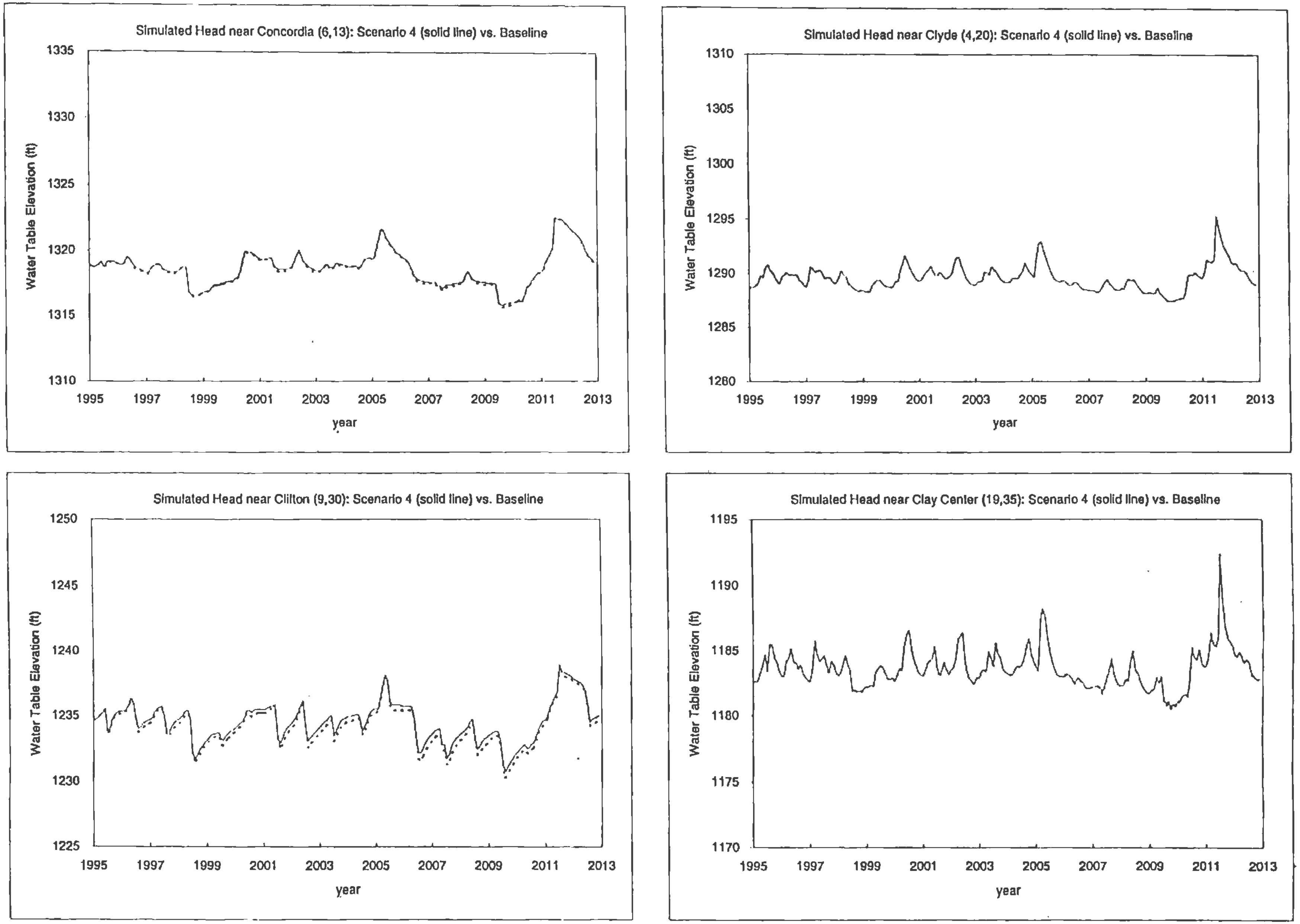


Figure 10.21. Simulated ground-water levels at the index locations (fig. 10.1) for scenario 4 compared to the baseline scenario.

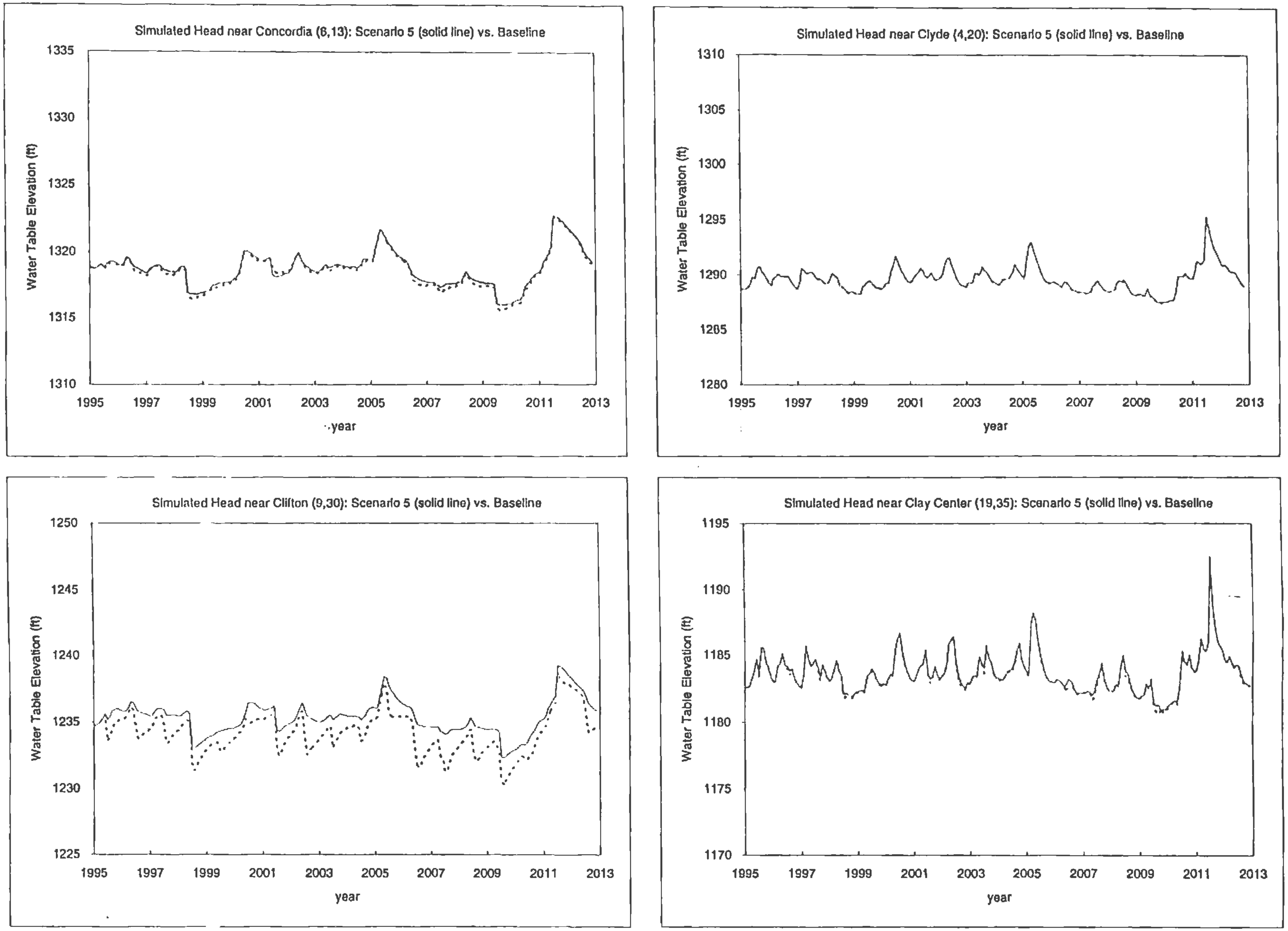


Figure 10.22. Simulated ground-water levels at the index locations (fig. 10.1) for scenario 5 compared to the baseline scenario.

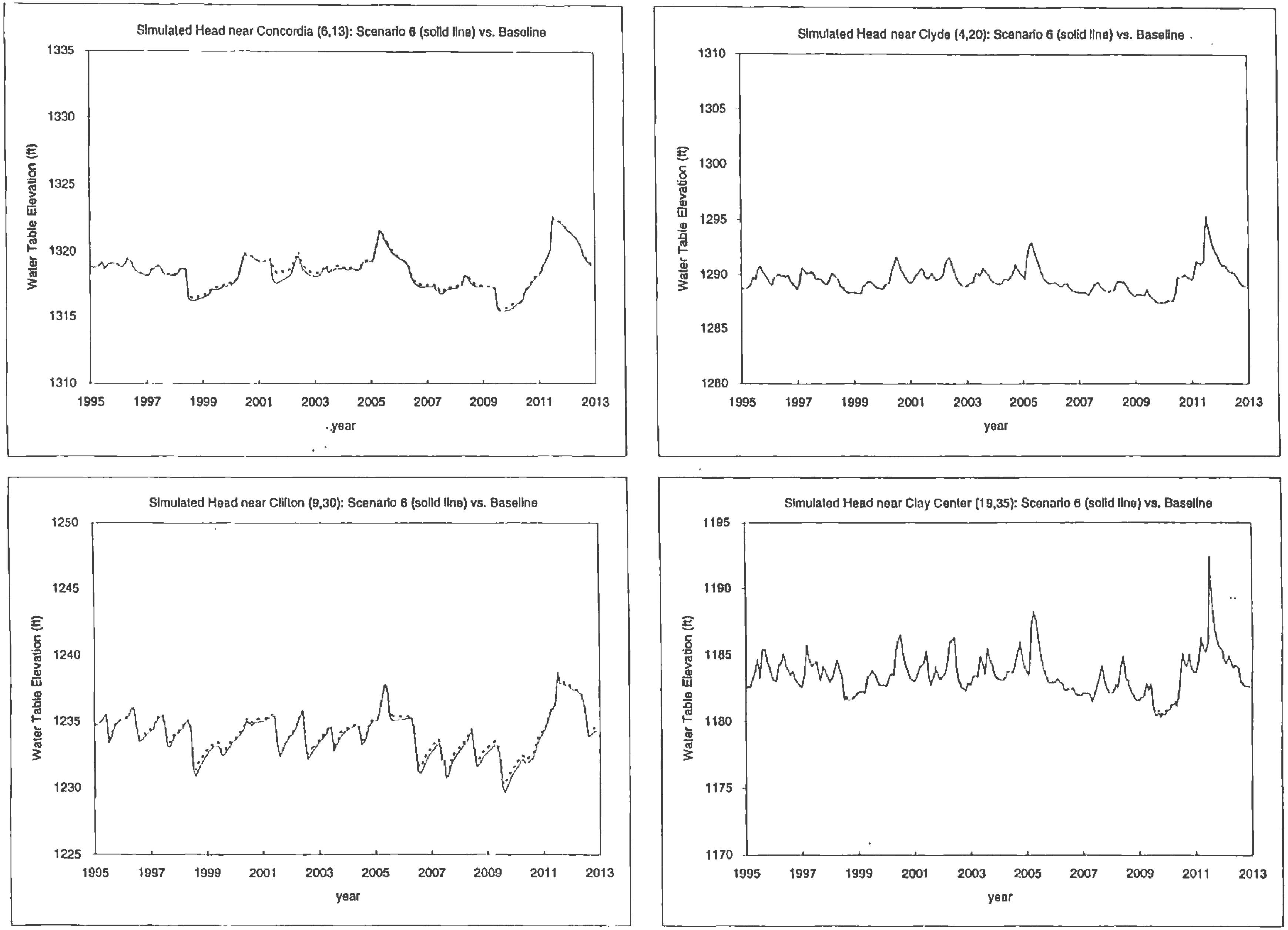


Figure 10.23. Simulated ground-water levels at the index locations (fig. 10.1) for scenario 6 compared to the baseline scenario.

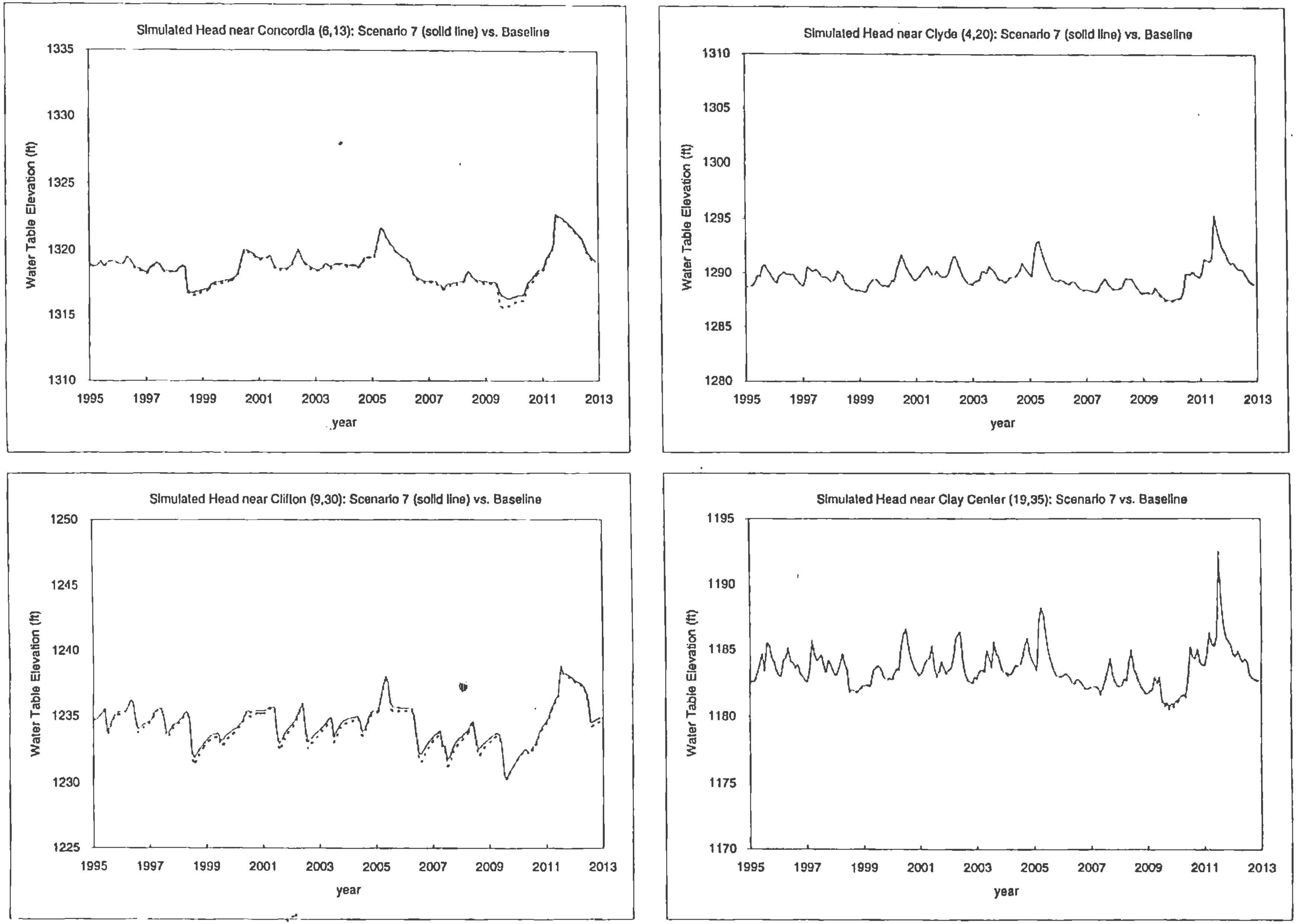
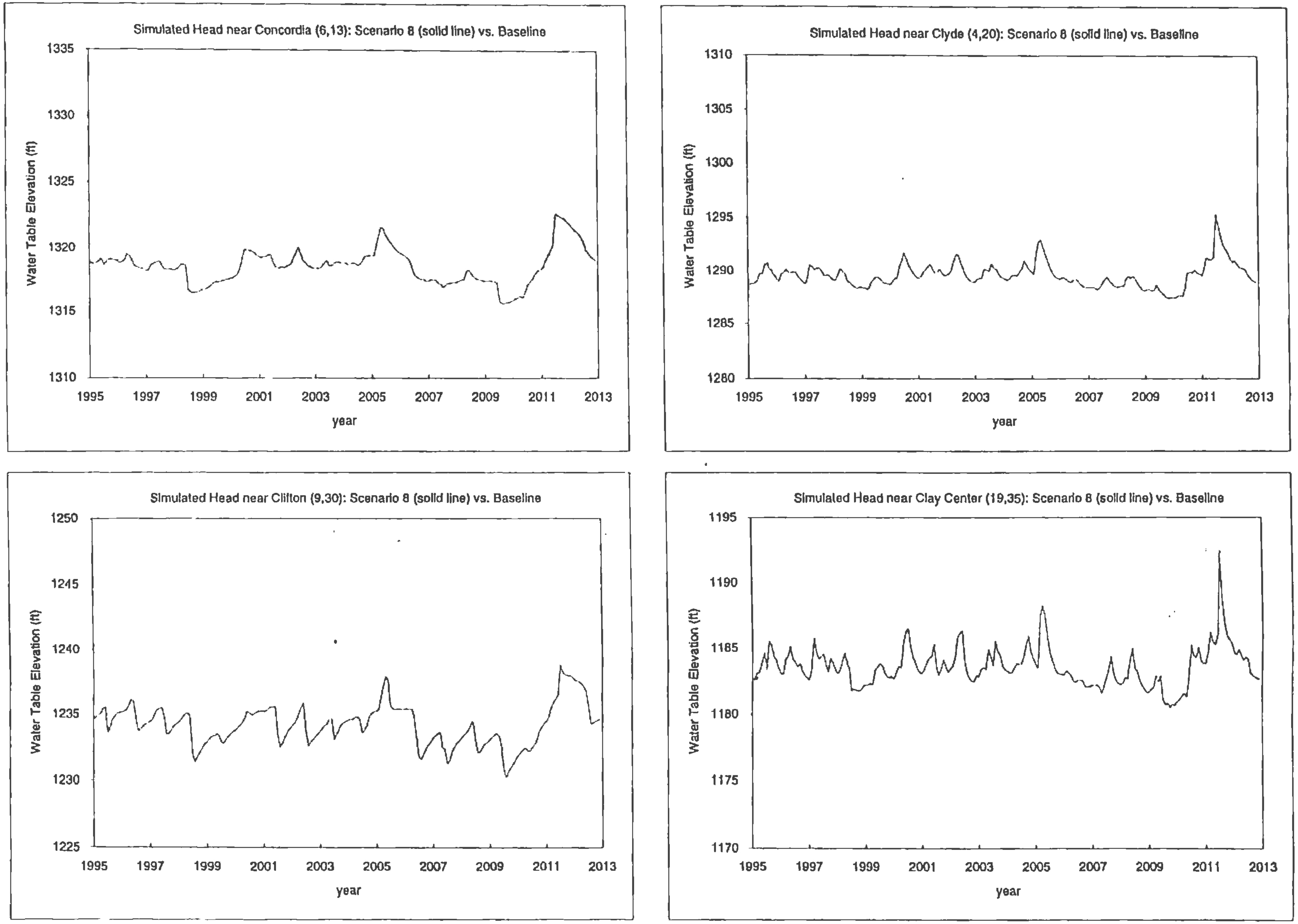


Figure 10.24. Simulated ground-water levels at the index locations (fig. 10.1) for scenario 7 compared to the baseline scenario.


Simulated Head near Concordia (6,13): Scenario 8 (solid line) vs. Baseline

Simulated Head near Clyde (4,20): Scenario 8 (solid line) vs. Baseline

Simulated Head near Clifton (9,30): Scenario 8 (solid line) vs. Baseline

Simulated Head near Clay Center (19,35): Scenario 8 (solid line) vs. Baseline

Figure 10.25. Simulated ground-water levels at the index locations (fig. 10.1) for scenario 8 compared to the baseline scenario.

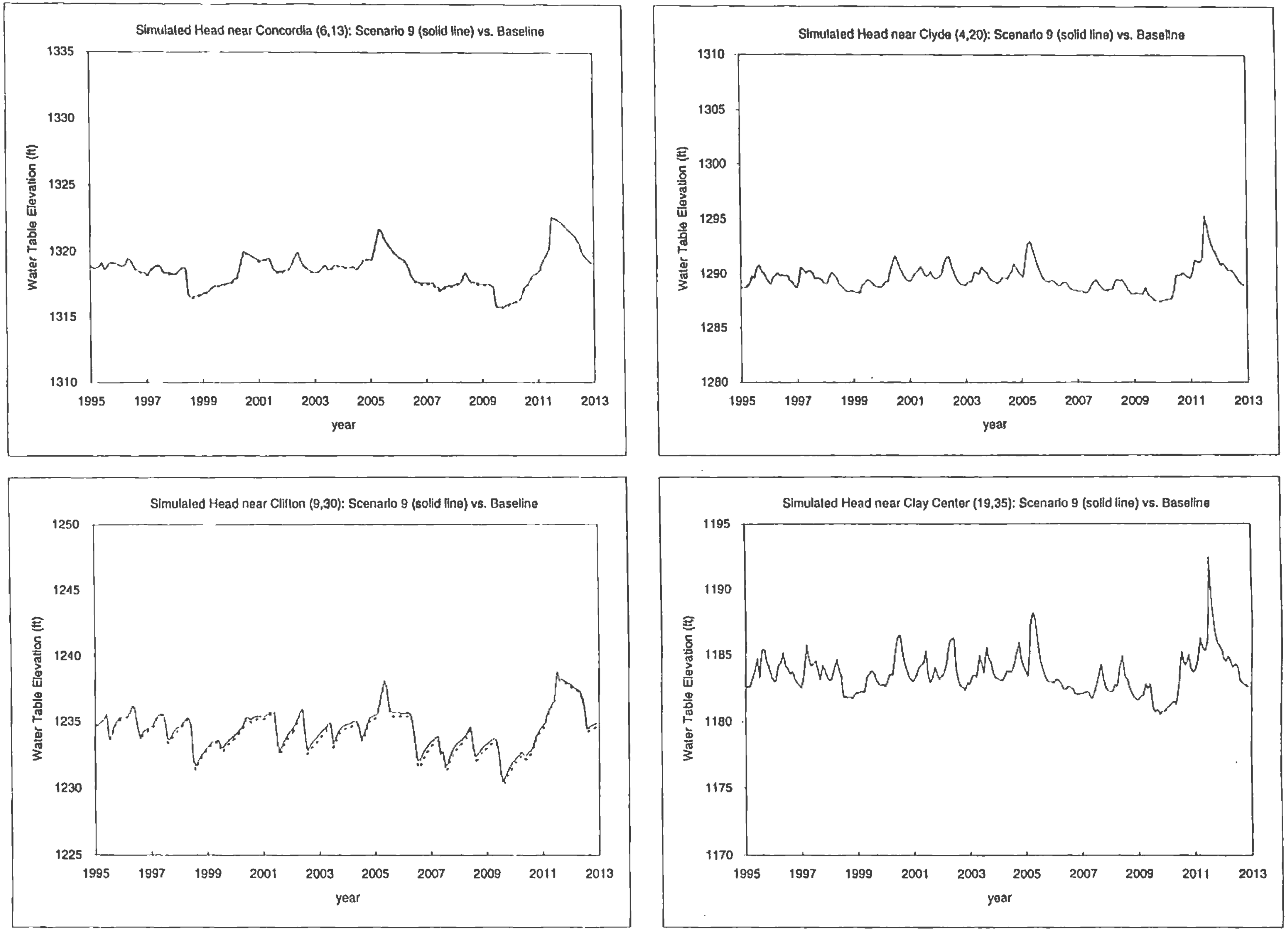


Figure 10.26. Simulated ground-water levels at the index locations (fig. 10.1) for scenario 9 compared to the baseline scenario.

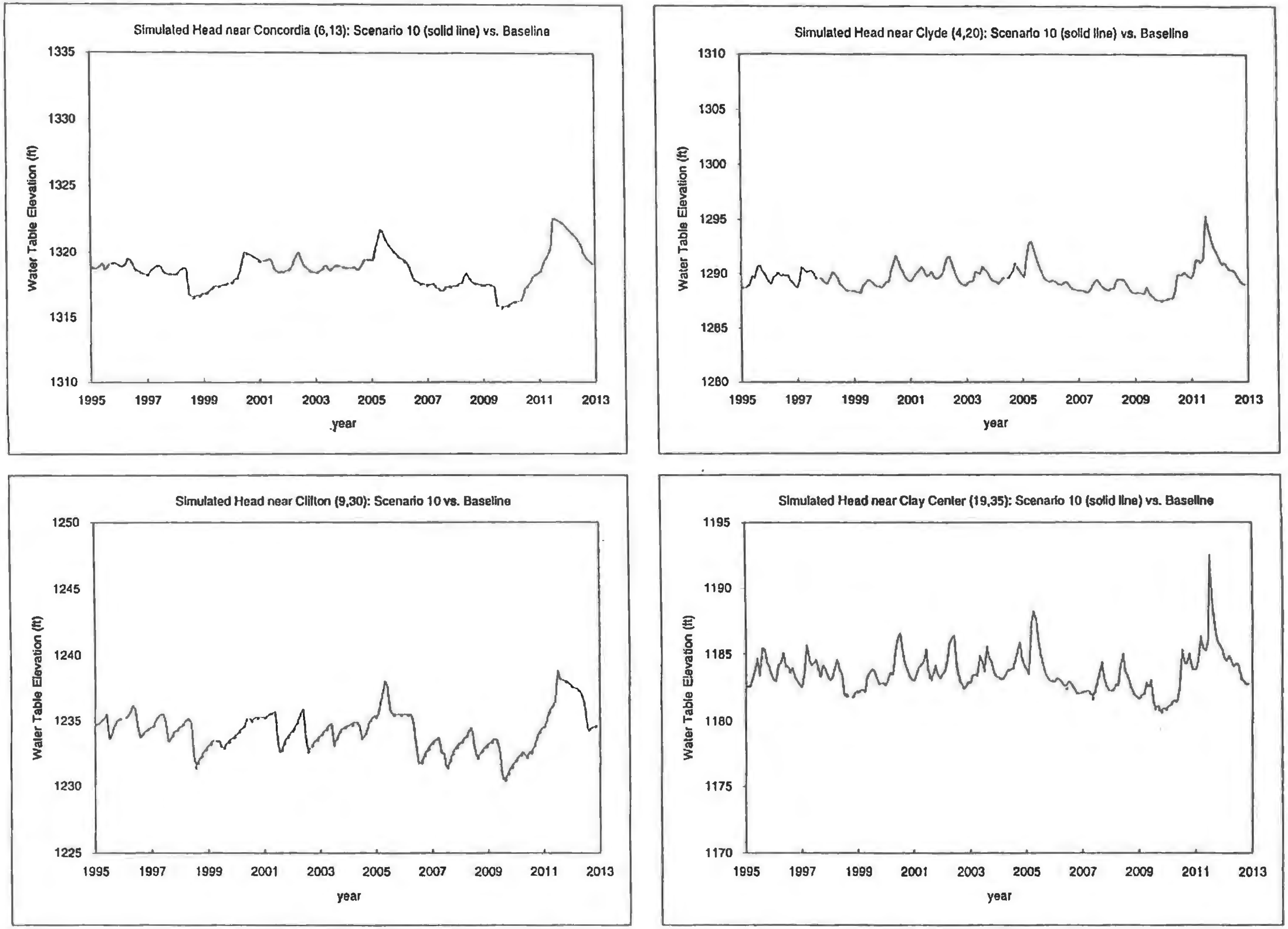


Figure 10.27. Simulated ground-water levels at the index locations (fig. 10.1) for scenario 10 compared to the baseline scenario.

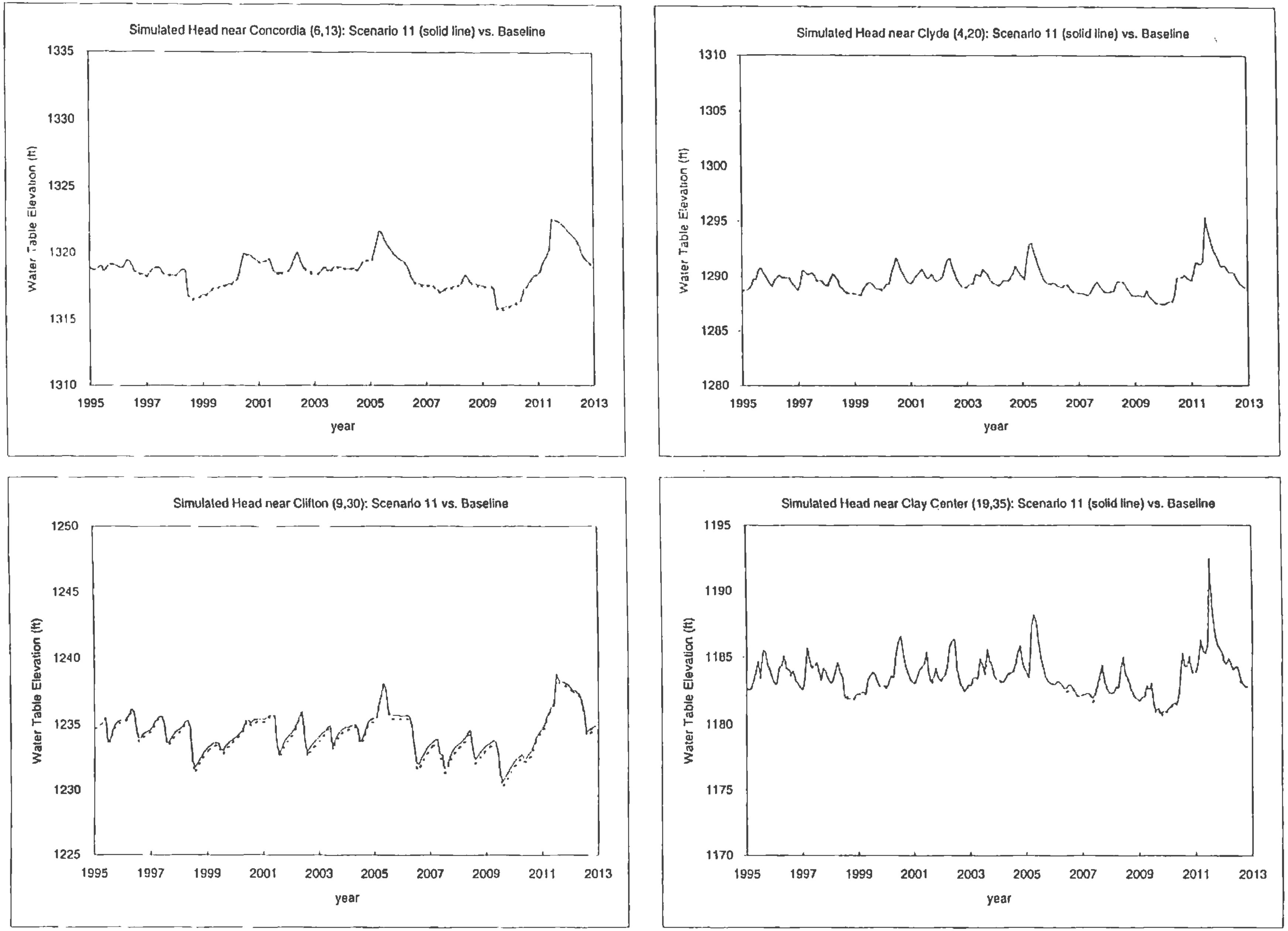


Figure 10.28. Simulated ground-water levels at the index locations (fig. 10.1) for scenario 11 compared to the baseline scenario.