Attachment C
to Technical Memorandum No.2

Hydrologic Study of Re-operating Phoenix Lake
for Flood Detention and Water Supply

Hydrologic Study of Re-operating Phoenix Lake for Flood Detention and Water Supply

Prepared for
Marin County Flood Control and Water Conservation District, Flood Zone 9

Prepared by
Stetson Engineers Inc.
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INTRODUCTION

Phoenix Lake is located on Ross Creek, a major tributary of Corte Madera Creek. The lake is owned, operated, and maintained by MMWD primarily for the purpose of water supply reserve for use during shortages, but also for wildlife habitat and public recreation and enjoyment. The watershed above Phoenix Lake encompasses about 1,400 acres. When filled to the spillway crest, the lake covers 25 acres and holds approximately 300 acre-ft of water based on the 2009 bathymetric survey (Figure 1).

The lake dam is penetrated by a gated, 30-inch diameter, low-level outlet pipe that has an intake invert elevation at 130 ft (NGVD29[1]) and a discharge capacity of approximately 115 cfs when the lake is full[2]. This low-level outlet is normally kept closed and has been used infrequently since it was built. The spillway is situated on the right side of the dam (looking upstream). In 1985 the spillway was modified by lowering the crest by six feet, from elevation 180 ft down to elevation 174 ft. This modification effectively lowered the normal lake water level and reduced the lake storage capacity by about 120 acre-ft, from 420 acre-ft to its present day capacity of 300 acre-ft.

Phoenix Lake currently functions as a de facto detention basin. During heavy storms, the lake water level rises above the spillway crest. The resulting "surcharge" storage attenuates stormflow and reduces the peak flow in the creek downstream. In theory, the attenuation effect could be enhanced through changes in lake operations. Modifications to the intake of low-level outlet pipe would be needed to facilitate changed operations. Preliminary analysis by Stetson indicates that drawing the lake level down ahead of a forecasted storm to el.140 ft, in concert with installing a 6-foot high inflatable/deflatable rubber dam across the spillway, would provide sufficient storage space in the lake to detain floodwaters and effectively reduce 100-year peak flows along Ross Creek and Corte Madera Creek, including key breakout points in Ross.

Further study of the compatibility of operating Phoenix Lake for both flood detention and water supply is needed in light of the lake's role in providing reserve supply during shortages, as well as wildlife functions and recreational opportunities to the community. Manipulation of lake levels for flood detention would be limited to the wet season, which

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[1] All elevations used herein are referenced to the NGVD29 datum.
[2] Based on a head vs. discharge curve for the pipe developed by Stetson Engineers using HEC-HMS.

should allow enough time for the lake to refill by late spring. The purpose of this hydrologic study was to analyze and verify whether natural inflows to the lake during the spring refilling period are indeed sufficient to refill the lake for a given starting date for refilling (e.g., March 15^{th} or April 1^{st}). This study considered the likelihood that regulatory agencies would require instream flow releases during the spring refilling period to maintain instream flow conditions necessary to sustain/enhance downstream aquatic habitat, which otherwise would have occurred as spillway overflow under historical lake operations.

ANALYSIS

The following steps were taken to conduct the hydrologic study:

1) Select representative hydrologic period of analysis
2) Analyze historical daily spillway overflows during spring to determine the anticipated required instream flow releases
3) Analyze historical daily inflows to Phoenix Lake during spring
4) Conduct reservoir re-operations analysis for spring using new operating rules

1) Select Representative Hydrologic Period of Analysis

The representative hydrologic period of analysis was selected after analyzing the historical flow records in spring at the Ross streamflow gage. USGS has monthly flow records at the Ross gage available from 1953 to 1993 (41 years). Figure 2a shows the average flow for each year for the period from March 1 to May 31 and Figure 2b shows the average flow from April 1 to May 31. Both graphs show that the period of 1984 to 1993 was dry in spring. The spring of 1988 was the second driest over the 41 year period[3]. To be conservative, the period from 1984 to 2010 was initially selected for the hydrologic study. This period includes the dry springs of 1984 to 1993 and records for latest years.

After reviewing the historical daily water level records of Phoenix Lake provided by MMWD for the initially selected period, seven years (1984, 1985, 1989, 1990, 1991, 1992, and 1996) were found to have incomplete data and, therefore, were removed from the selected period of analysis. The final selected period of analysis was from 1986 to 2010, excluding 1989-1992 and 1996. This final selected analysis period (20 years) still includes dry springs of 1987, 1988, and 1993 (shown in Figures 2a and 2b) and other dry springs post-1993.

[3] The spring of 1977 was the driest and the spring of 1988 was the second driest over the 41 year period. The average daily flows at Ross gage during the period of March 1 to May 31 in 1977 and 1988 were 2.22 cfs and 2.43 cfs, respectively (Figure 2a). The average daily flows at Ross gage during the period of April 1 to May 31 in 1977 and 1988 were 1.22 cfs and 2.52 cfs, respectively (Figure 2b).

2) Analyze Historical Daily Spillway Overflows during Spring to Determine the Anticipated Required Instream Flow Releases

The historical daily spillway overflows were estimated using the recorded daily water level records of Phoenix Lake and the spillway head vs. discharge curve provided by MMWD (refer to Figure 3 for the spillway head vs. discharge curve). The estimated historical daily spillway overflows during spring of all years are shown in Figure 4a and detailed in Figures 4b to 4e. The spikes shown in Figures 4b to 4e represent spillway overflows caused by storms. When there were no storms, spillway overflows were generally less than 3 cfs, and there were a lot of times during spring that there were no spillway overflows.

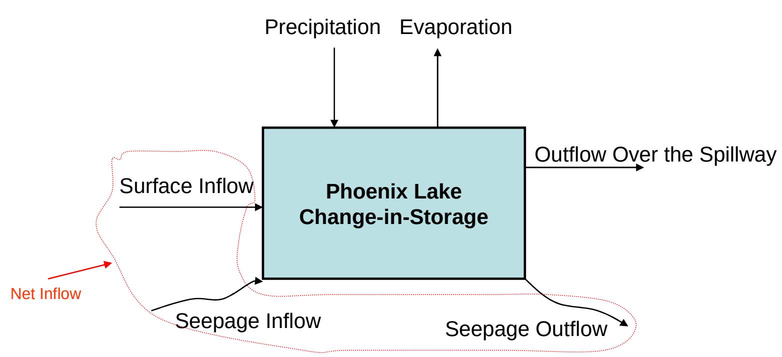
3) Analyze Historical Daily Inflows to Phoenix Lake during Spring

The study requires accurate estimates of historical daily inflows to the lake during spring. There are two basic methods available:

- Method 1: Use the recorded flows at Ross streamflow gage to prorate to Phoenix Lake by applying the drainage area ratio.
- Method 2: Use a water budget analysis approach of Phoenix Lake to back-calculate historical daily inflows.

Theoretically, if historical recorded lake levels are available and the spillway rating curve is reasonably accurate at low flows, Method 2 should be more accurate than Method 1. This is because flow during the spring in the Ross Valley is mostly base flow and prorating base flow from Ross gage to Phoenix Lake by applying the drainage area ratio may not be accurate.

Since recorded historical daily lake levels at Phoenix Lake are available, Method 2 was used to estimate the historical daily inflows to the lake in spring. The water budget components (see the chart below) include surface inflows to the lake, precipitation, evaporation, outflows over the spillway, seepage inflows and seepage outflows, and the resulting change-in-storage estimated from the recorded lake levels. The term “net inflow” in the chart below represents the sum of surface inflow and seepages.



Water Budget under “As-Operated” Conditions

The water budget analysis was conducted on a daily basis. Daily precipitation at Phoenix Lake was provided by MMWD. Daily outflow over the spillway was estimated using the recorded lake levels and the spillway rating curve. Daily evaporation was first estimated using the averaged long-term average monthly pan evaporation at San Francisco Airport and Oakland Airport converted to lake evaporation by multiplying a pan-to-lake evaporation coefficient of 0.75 (see Table 1), and then uniformly distributed to each day. The long-term average monthly evaporation data at San Francisco Airport and Oakland Airport were obtained from the California Climate Data Archive. The data show that long-term average monthly evaporation at San Francisco Airport is close to that at Oakland Airport, suggesting that long-term average monthly evaporation in Marin County would be similar too. It is worth noting that evaporation is a very minor component in the water budget analysis and would have negligible effect on the daily inflow estimates.

Table 1 Long-Term Monthly Pan Evaporation at San Francisco and Oakland Airports and Estimated Lake Evaporation

Month	Long-Term Monthly Pan Evaporation at San Francisco Airport (inch)	Long-Term Monthly Pan Evaporation at Oakland Airport (inch)	Averaged Monthly Pan Evaporation for the Two Stations (inch)	Averaged Monthly Lake Evaporation (inch)
Jan	1.7	1.8	1.8	1.3
Feb	2.4	2.3	2.4	1.8
Mar	3.8	3.8	3.8	2.9
Apr	5.3	4.8	5.1	3.8
May	6.4	5.7	6.1	4.5
Jun	7.1	6.4	6.8	5.1
Jul	6.7	6.4	6.6	4.9
Aug	6.6	6.0	6.3	4.7
Sep	5.9	5.4	5.7	4.2
Oct	4.4	4.0	4.2	3.2
Nov	2.4	2.4	2.4	1.8
Dec	1.7	1.8	1.8	1.3
Annual	54.5	50.7	52.6	39.5

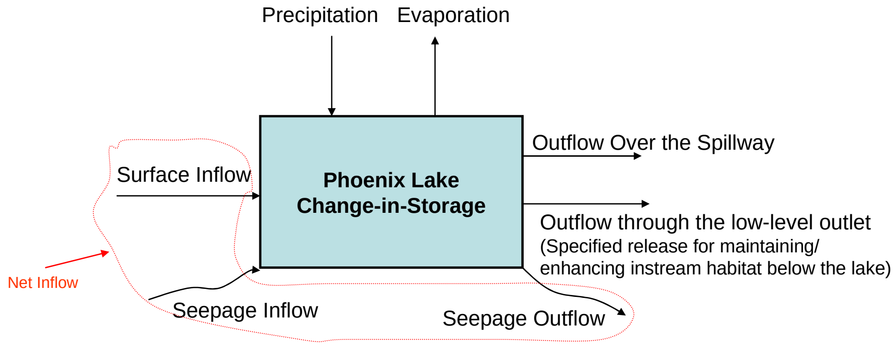
Note: Lake Evaporation = Pan Evaporation × 0.75.

Once the daily change-in-storage, precipitation, evaporation, and outflow over the spillway are estimated, the net inflow to Phoenix Lake can be back-calculated using a water budget analysis approach. The back-calculated net inflows to Phoenix Lake are shown in Figure 5a and detailed in Figures 5b to 5e. The net inflows are the sum of surface inflows, seepage inflows, and seepage outflows. Figures 5a to 5e show that there were days that the net inflows were negative, indicating seepage outflows were higher than inflows in those days.

4) Conduct Reservoir Re-Operations Analysis for Spring Using New Operating Rules

A reservoir operations analysis was conducted to re-operate the reservoir for spring using new operating rules (e.g., fall and winter drawdown for flood control, minimum instream flow releases). The purpose of the analysis was to evaluate refilling of the lake during the spring after fall drawdown for winter flood detention according to the "rule curve" (see Figure 6) which was developed to meet the needs of both flood detention and reserve water supply. Operating according to the rule curve would draw down the lake far enough (to elevation 160 ft) to enable complete drawdown to the final target level, elevation 140 feet, within 24-hours of a forecasted large storm event[4]. The existing 30-inch low-level outlet has sufficient capacity to enable drawdown even during times when heavy base inflows can precede impending storms (see Figure 9).

Compared to the water budget method described in Step 3, the reservoir operations analysis included an additional outflow component; that is, instream flow release through the low-level outlet for maintaining/enhancing instream habitat below the lake (see the chart below). The amount of instream flow release through the low-level outlet in spring under re-operated conditions was assumed to be similar, on average, to the historical spillway overflows, which were analyzed in Step 2 [5].



Water Budget under Re-Operated Conditions

[4] The "rule curve" (see Figure 6) does not set a defined time for the initial drawdown to el. 160 ft. Drawdown of Phoenix Lake will follow a two-step procedure. The first step is initial drawdown of the lake and the second step is final drawdown of the lake and opening of the low-level outlet. The first step can occur at any time during the rainy season. Watershed moisture conditions will be continually monitored by tracking soil moisture content, groundwater levels, discharges from seeps and springs, and base flows in creeks. When this monitoring indicates watershed moisture approaching saturation, then the lake will be gradually drawn down to elevation 160 ft, 14 ft below the spillway crest, and maintained at that level. (It is possible that the initial drawdown will not happen during very dry years when the water supply reserve of Phoenix Lake is needed most). The second step will be triggered by a forecast of potential flooding issued by the National Weather Service, in which case the low level outlet will be opened and the lake will be further drawn down 20 ft, to elevation 140 ft, and maintained at that level. The low-level outlet will remain open thereafter, continuing on its own to pass inflows into the lake. The lake will fill during the storm as inflow into the lake exceeds outflow through the low-level outlet.

[5] An instream flow release requirement imposed by regulatory agencies is anticipated, but the amount of the release can not be determined at this time. Agencies would likely base their requirement on consultation with Flood Zone 9 and MMWD and on an instream flow study performed by a fishery scientist and hydrologist. For purposes of this analysis, instream releases of 1 to 2 cfs, or inflow, whichever is less, were used.

Given the available net inflows estimated in Step 3, the outcome of whether the lake can be refilled by late spring depends on (1) the starting date for refilling, (2) the initial lake level at the starting date for refilling, and (3) the instream flow release through the low-level outlet. Table 2 is a summary of the selected simulated scenarios. The simulation results of lake levels for the starting date of April 1st are shown in Figures 7a to 7d. Results for the starting date of March 15th are shown in Figures 8a to 8d. In the analysis, when the lake level first reaches the spillway crest (i.e., 174 ft), no further instream flow release through the low-level outlet was made because the spillway overflows, thereafter, would maintain instream habitat below the lake.

Table 2 Summary of Simulated Scenarios

Scenario	Initial Lake Level (ft in NGVD29)	Starting Date for Refilling	Instream Flow Release Through the Low-Level Outlet (cfs)
1	160 ft	April 1st	2 cfs
2	160 ft	April 1st	1 cfs
3	160 ft	April 1st	2 cfs or inflow, whichever is less
4	160 ft	April 1st	1 cfs or inflow, whichever is less
5	160 ft	March 15th	2 cfs
6	160 ft	March 15th	1 cfs
7	160 ft	March 15th	2 cfs or inflow, whichever is less
8	160 ft	March 15th	1 cfs or inflow, whichever is less

FINDINGS

1) Operating Phoenix Lake at a lower level during the winter would add reliability to the flood control function of the lake. But operating at a lower level is not essential if (a) watershed saturation is continually and closely monitored and (b) large storms are reliably forecasted sufficiently in advance to enable drawdown of the lake before the storms begin.

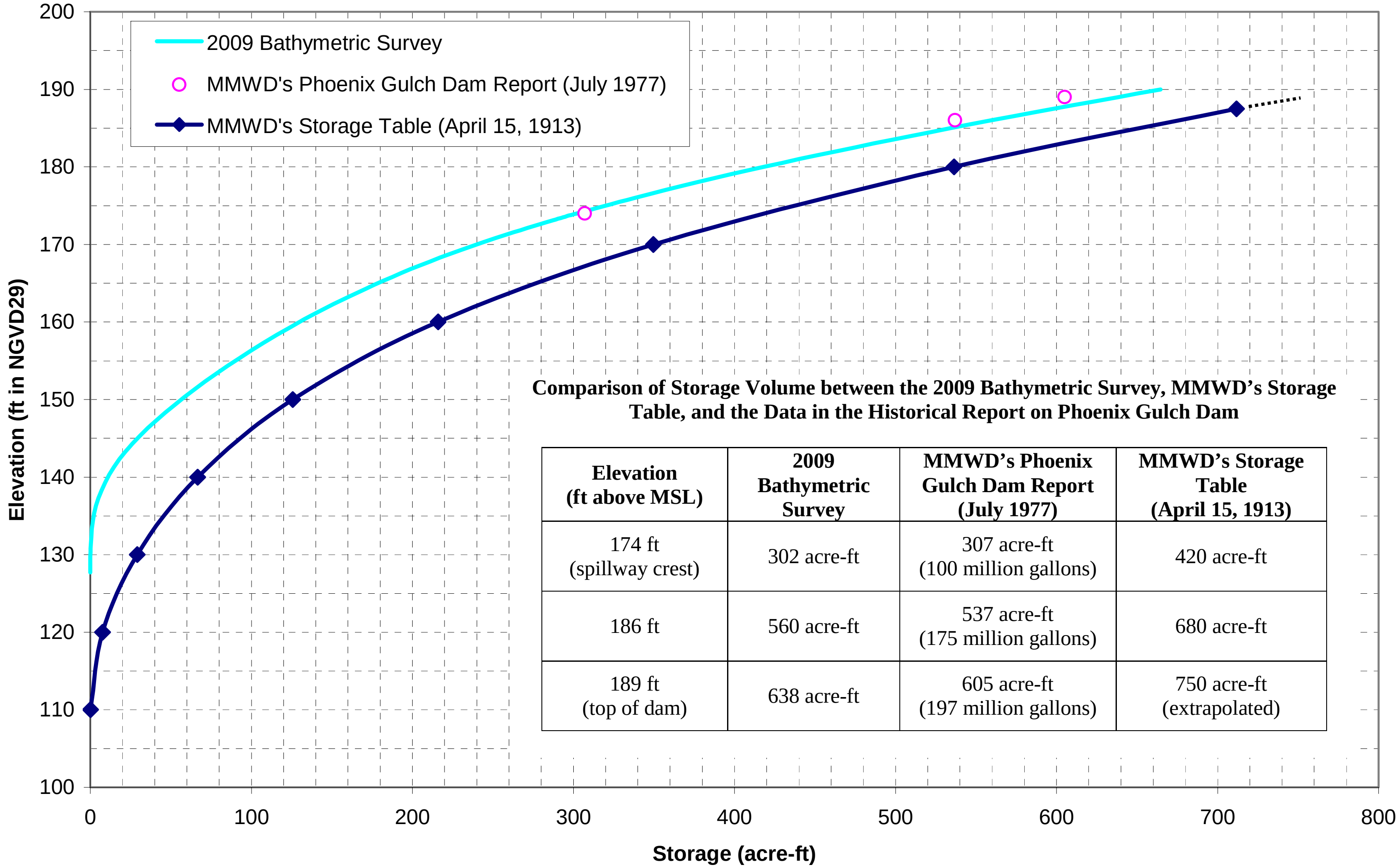
2) Operating Phoenix Lake full during the winter, at el. 174 ft, would still enable complete drawdown to the final target level for winter flood operations, elevation 140 ft, within 48-hours of a forecasted large storm event (see Figure 9).

3) Operating Phoenix Lake partially drawn down during the winter, at el. 160 ft, would enable complete drawdown to the final target level for winter flood operations, elevation 140 ft, within 24-hours of a forecasted large storm event (see Figure 9).

4) In most years, inflow into Phoenix Lake during the spring would be sufficient to refill the lake from the winter flood operations drawdown level, el. 160 ft, to the spillway crest, el. 174 ft. However, in very dry years, complete refill may not occur.

5) The starting date of refill (e.g., March 15th or April 1st), and the amount of the required instream flow release (e.g., 1 cfs, 2 cfs, or inflow) significantly affects refilling of the lake.

Figure 1 Phoenix Lake Elevation - Storage Curve



Comparison of Storage Volume between the 2009 Bathymetric Survey, MMWD's Storage Table, and the Data in the Historical Report on Phoenix Gulch Dam

Elevation (ft above MSL)	2009 Bathymetric Survey	MMWD's Phoenix Gulch Dam Report (July 1977)	MMWD's Storage Table (April 15, 1913)
174 ft (spillway crest)	302 acre-ft	307 acre-ft (100 million gallons)	420 acre-ft
186 ft	560 acre-ft	537 acre-ft (175 million gallons)	680 acre-ft
189 ft (top of dam)	638 acre-ft	605 acre-ft (197 million gallons)	750 acre-ft (extrapolated)

Figure 2a Average Daily Flow at Ross Gage from March 1 to May 31

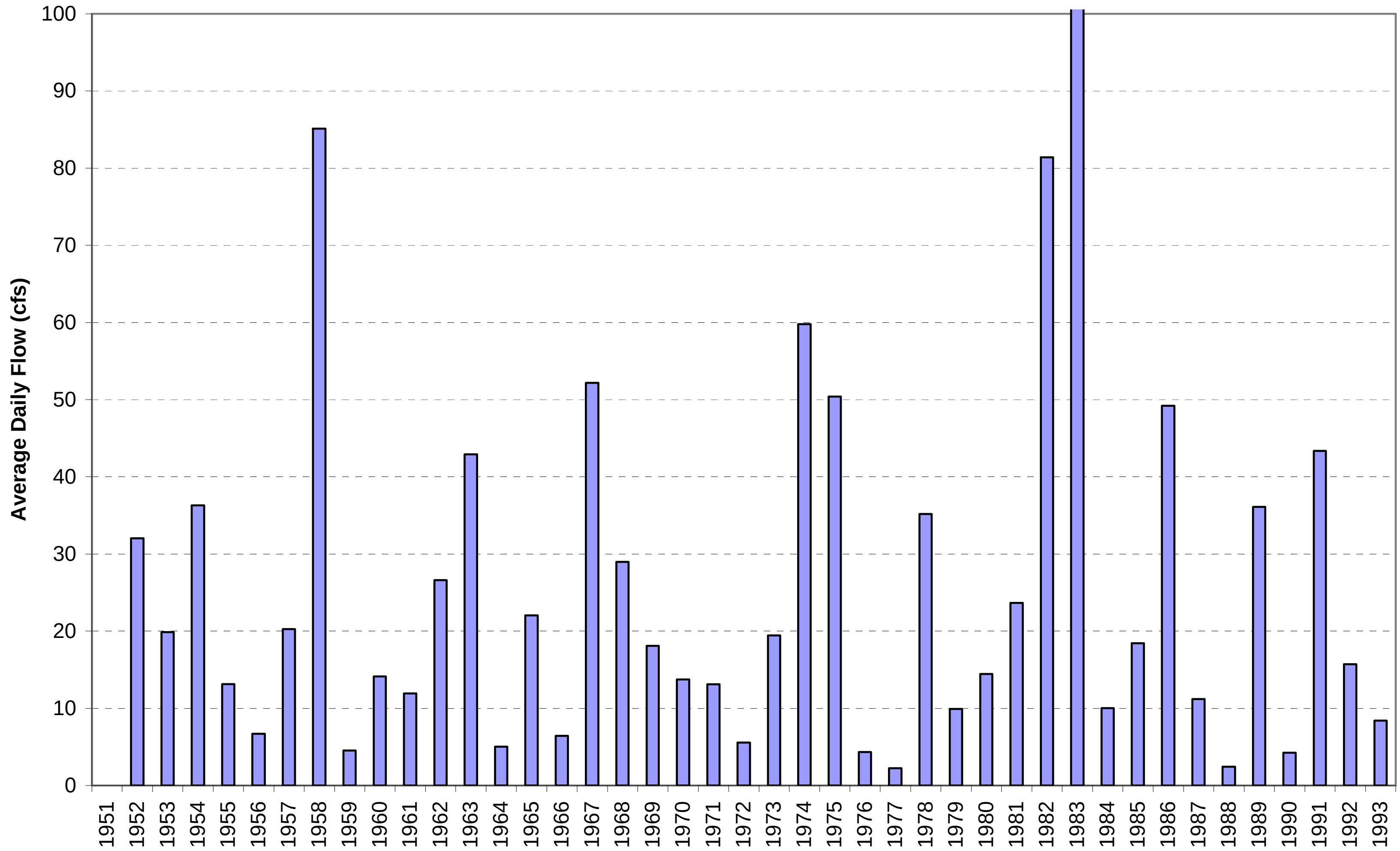


Figure 2b Average Daily Flow at Ross Gage from April 1 to May 31

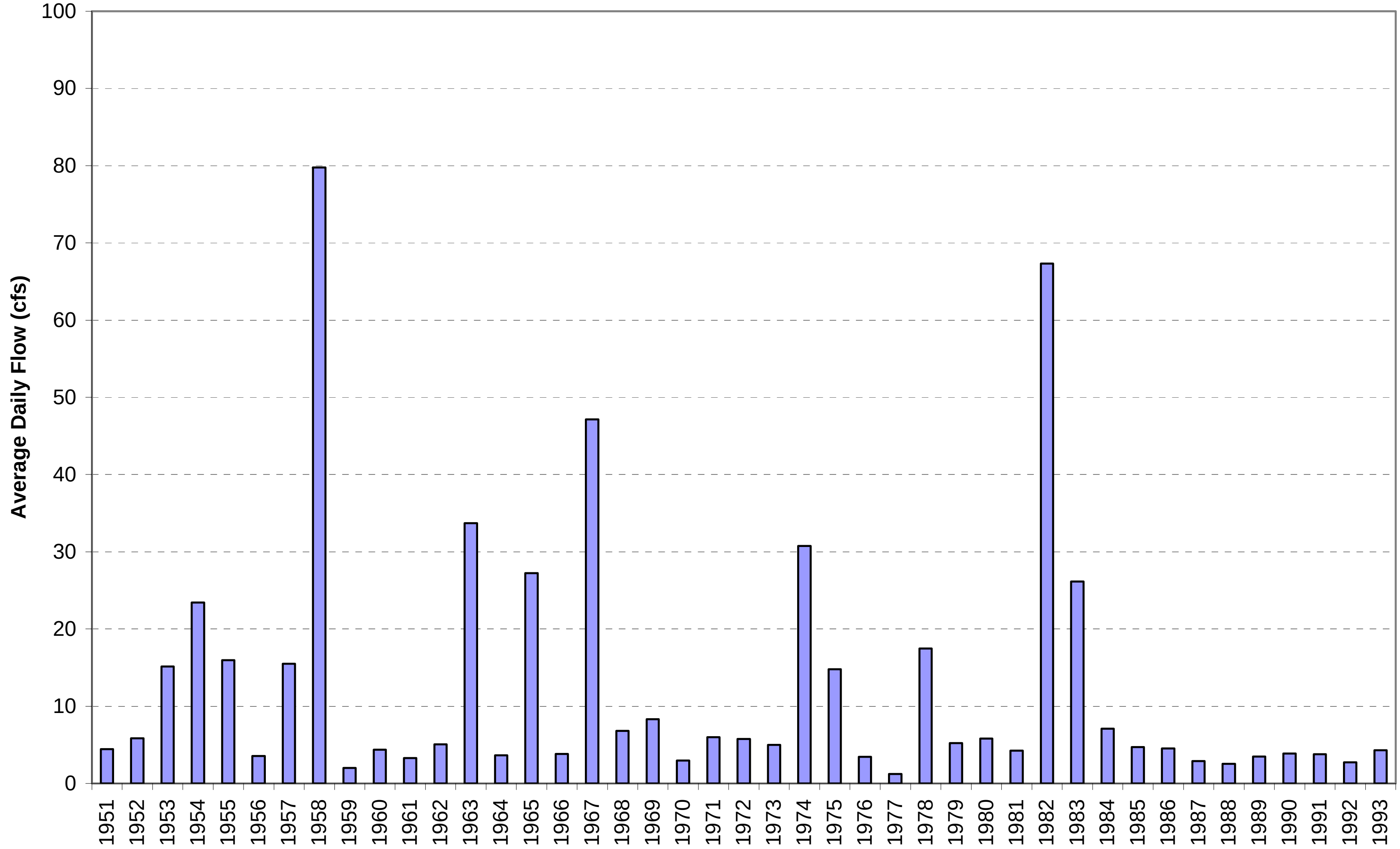
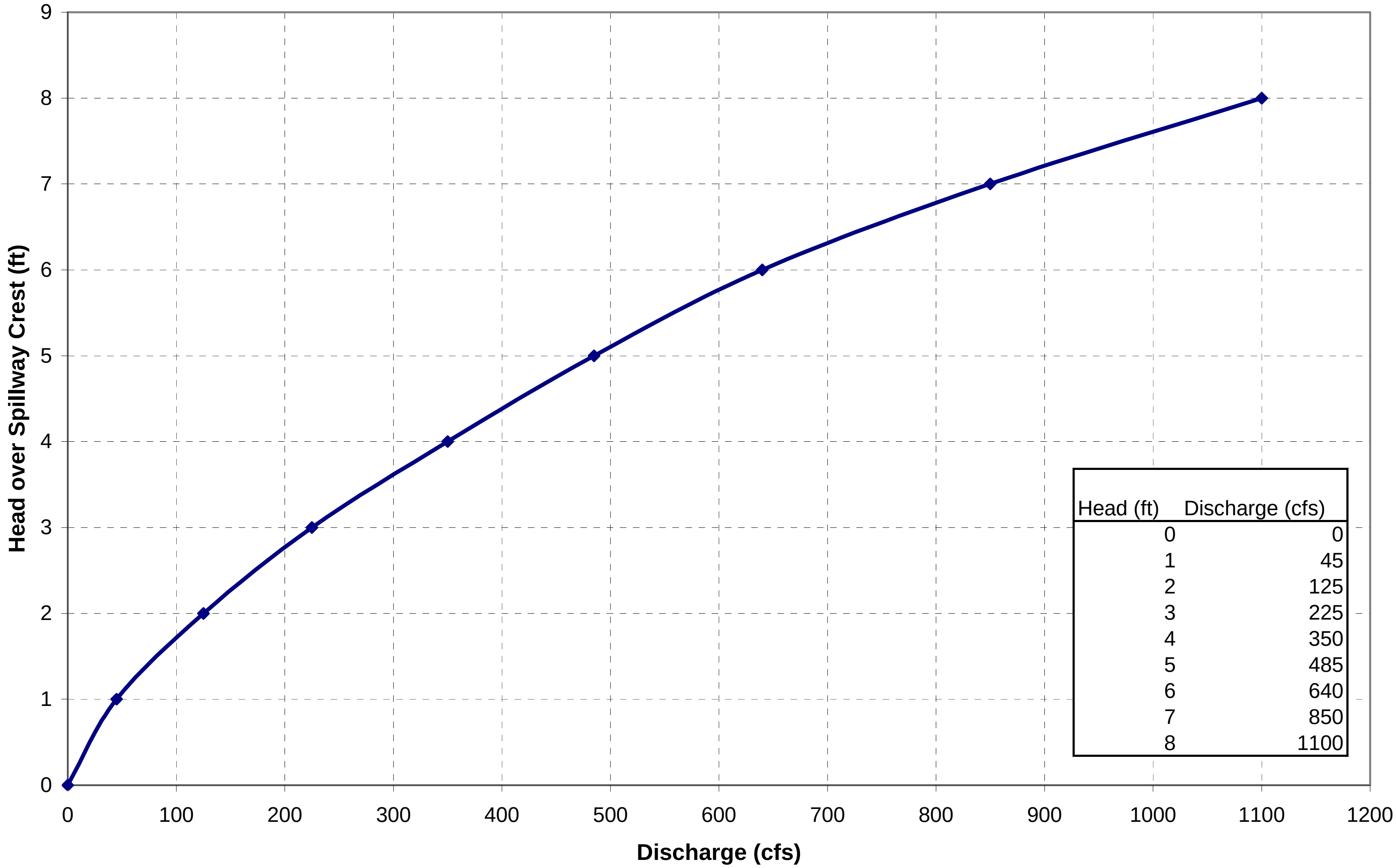


Figure 3 Phoenix Lake Spillway Discharge Rating Curve



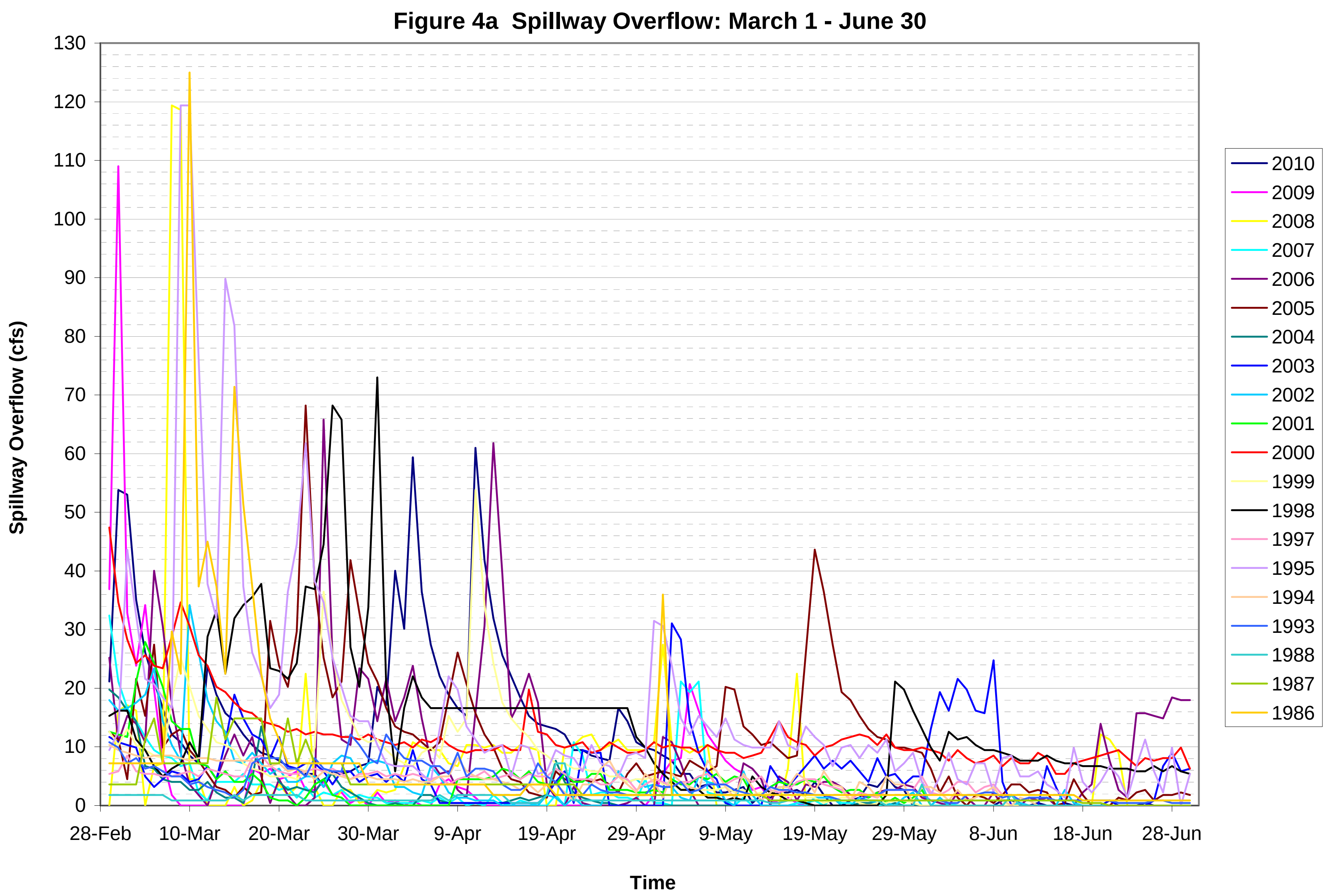


Figure 4a Spillway Overflow: March 1 - June 30
Spillway Overflow (cfs)
130
120
110
100
90
80
70
60
50
40
30
20
10
0
28-Feb
10-Mar
20-Mar
30-Mar
9-Apr
19-Apr
29-Apr
9-May
19-May
29-May
8-Jun
18-Jun
28-Jun
Time
2010
2009
2008
2007
2006
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1993
1988
1987
1986

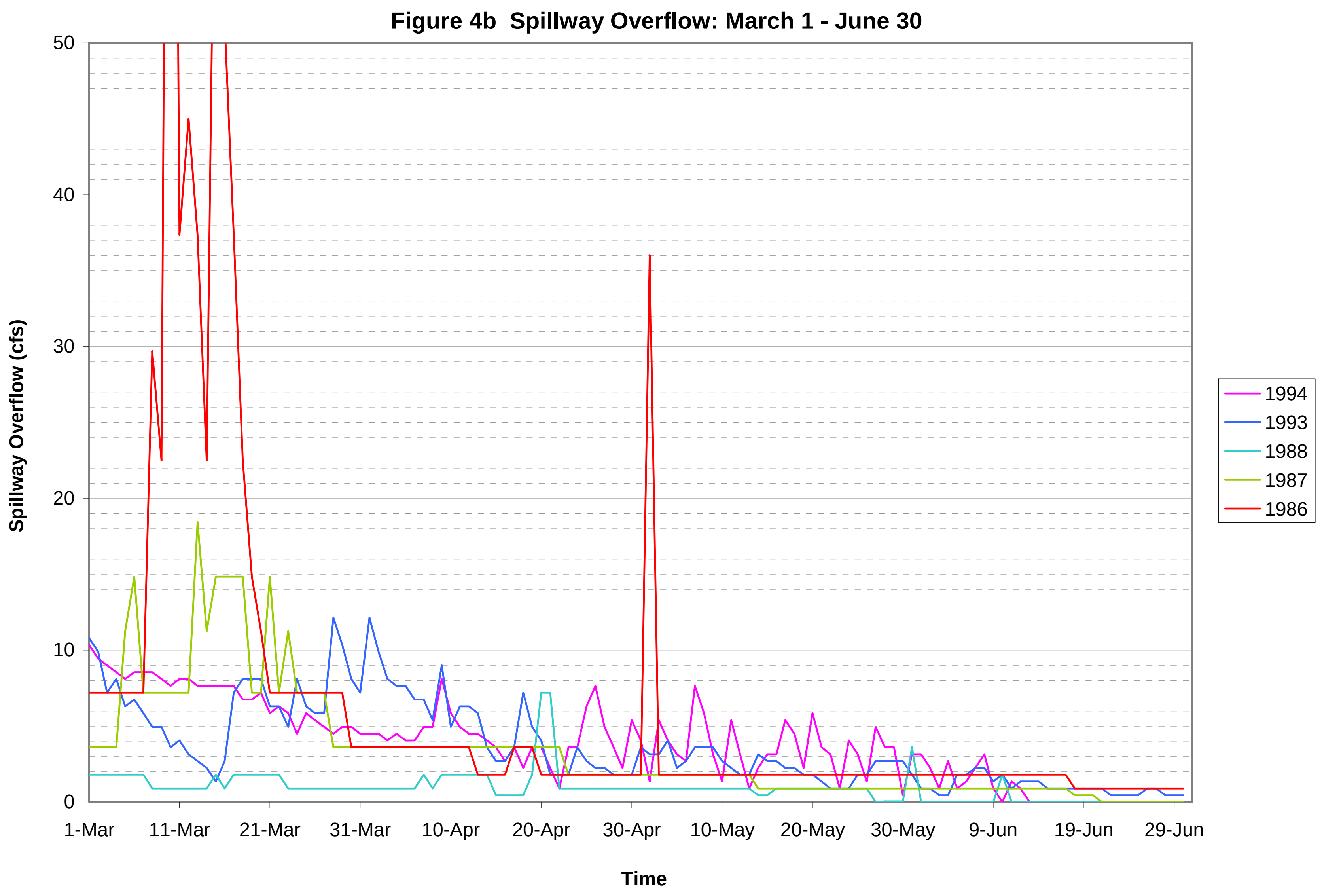


Figure 4b Spillway Overflow: March 1 - June 30
Spillway Overflow (cfs)
50
40
30
20
10
0
1-Mar
11-Mar
21-Mar
31-Mar
10-Apr
20-Apr
30-Apr
10-May
20-May
30-May
9-Jun
19-Jun
29-Jun
Time
1994
1993
1988
1987
1986

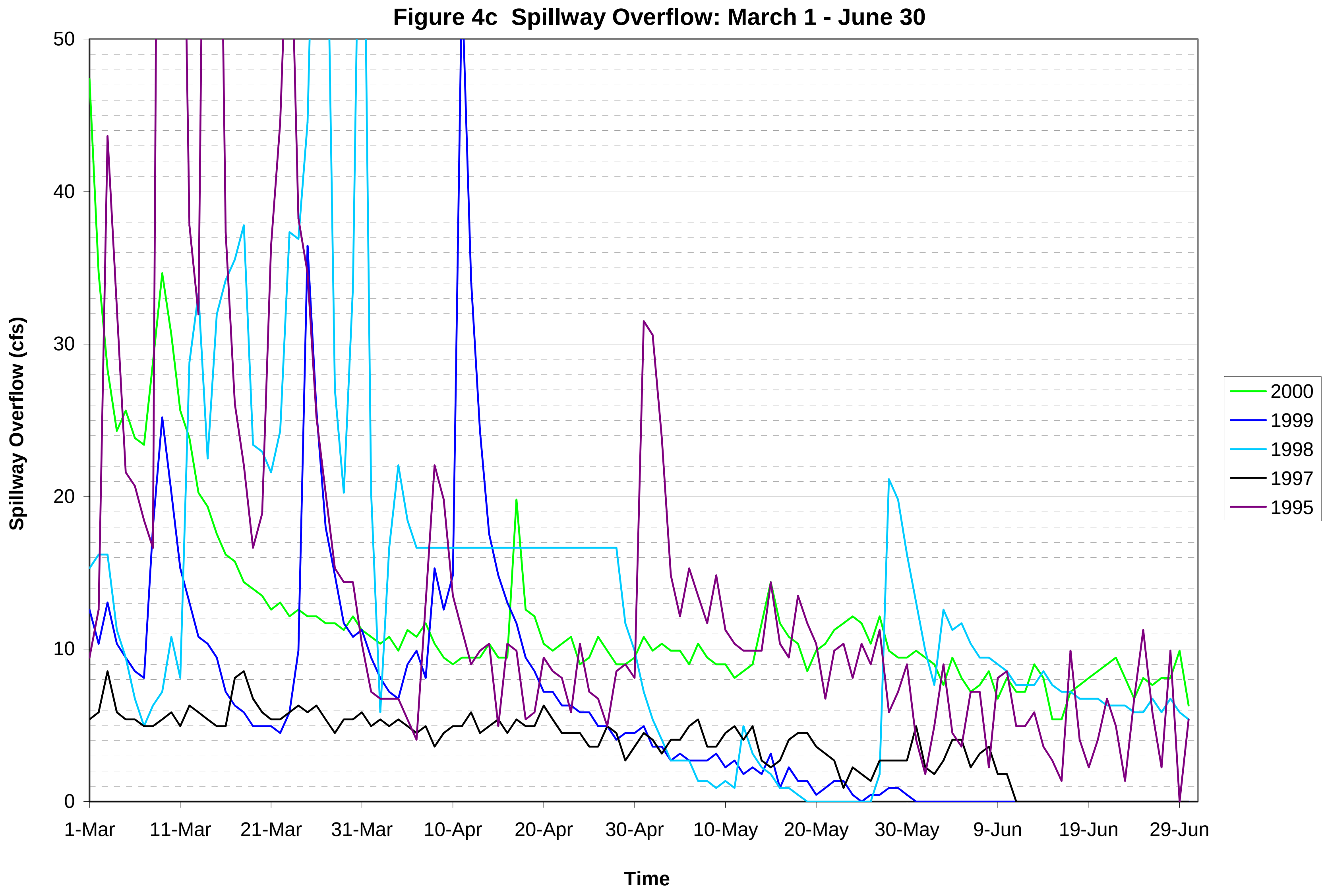


Figure 4c Spillway Overflow: March 1 - June 30
Spillway Overflow (cfs)
50
40
30
20
10
0
1-Mar
11-Mar
21-Mar
31-Mar
10-Apr
20-Apr
30-Apr
10-May
20-May
30-May
9-Jun
19-Jun
29-Jun
Time
2000
1999
1998
1997
1995

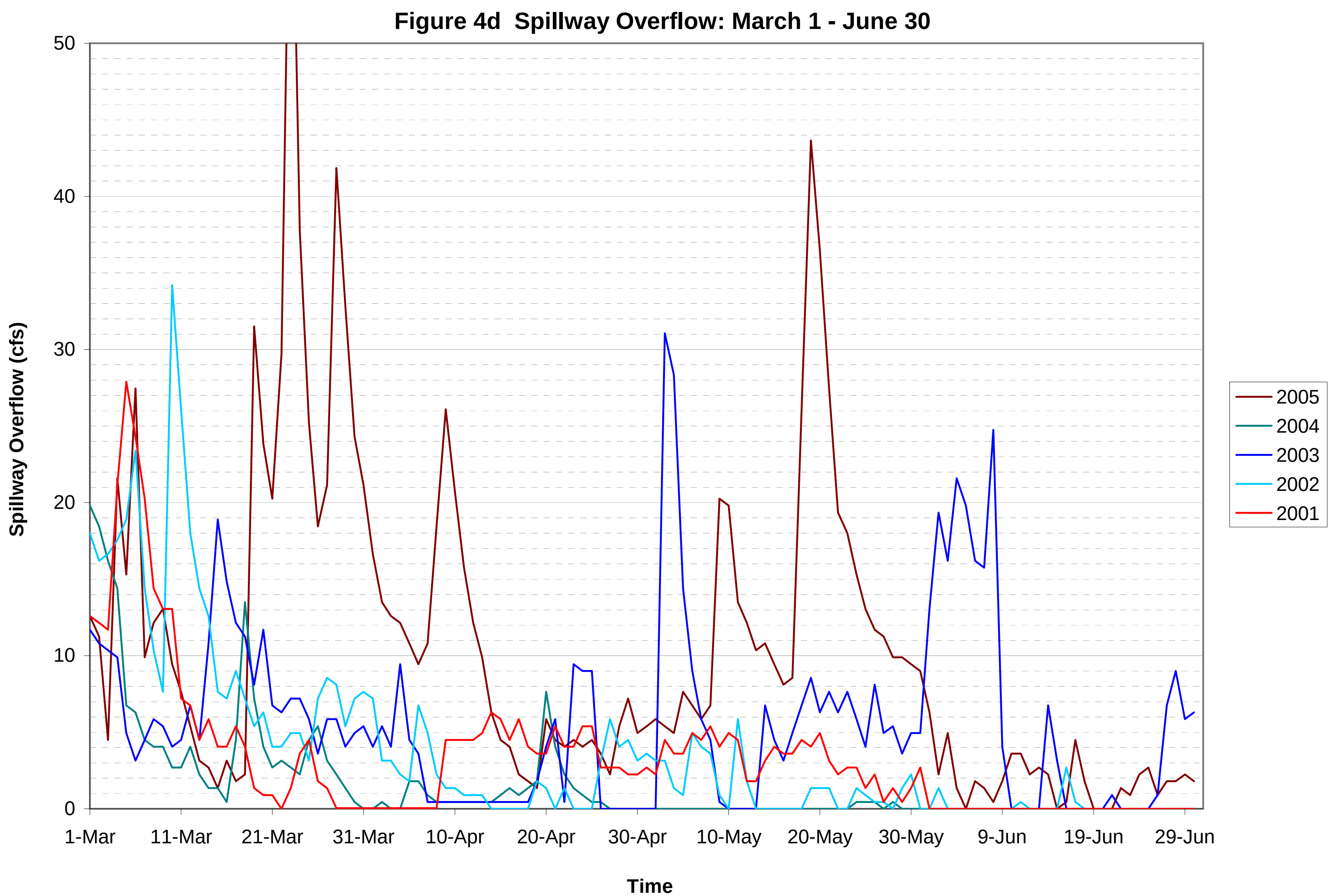


Figure 4d Spillway Overflow: March 1 - June 30
Spillway Overflow (cfs)
50
40
30
20
10
0
1-Mar
11-Mar
21-Mar
31-Mar
10-Apr
20-Apr
30-Apr
10-May
20-May
30-May
9-Jun
19-Jun
29-Jun
Time
2005
2004
2003
2002
2001

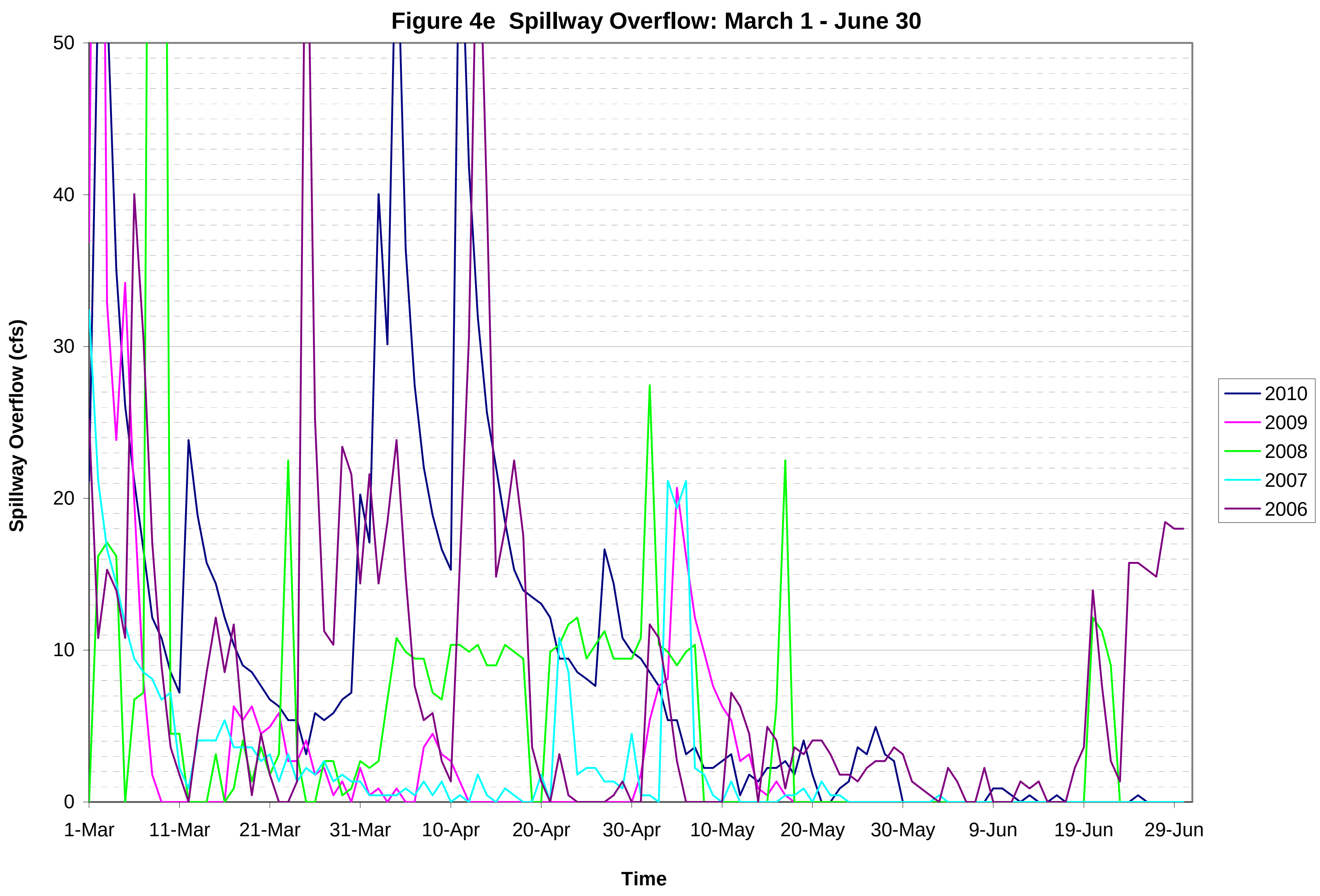
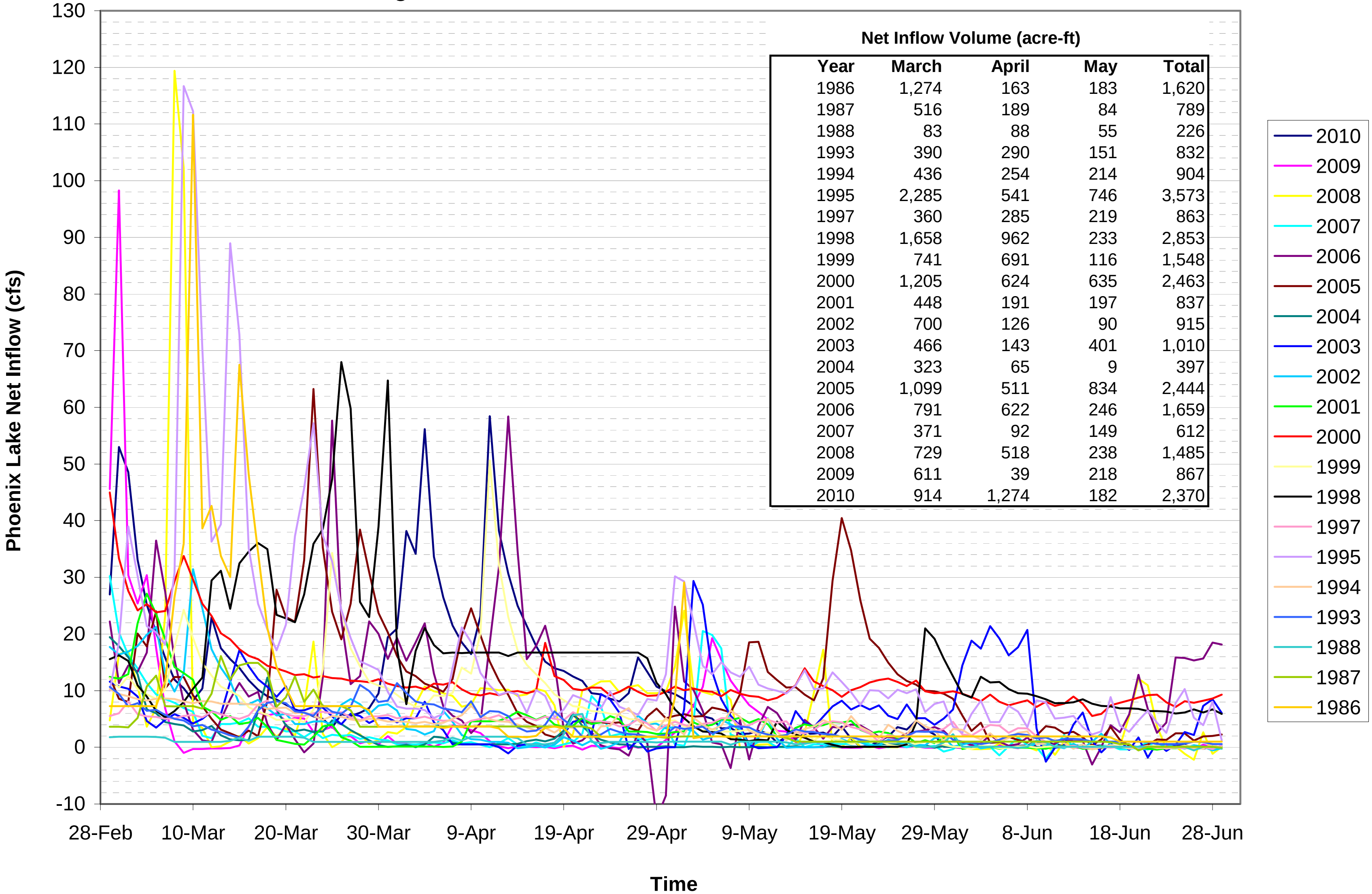


Figure 4e Spillway Overflow: March 1 - June 30
Spillway Overflow (cfs)
50
40
30
20
10
0
1-Mar
11-Mar
21-Mar
31-Mar
10-Apr
20-Apr
30-Apr
10-May
20-May
30-May
9-Jun
19-Jun
29-Jun
Time
2010
2009
2008
2007
2006

Figure 5a Phoenix Lake Net Infow: March 1 - June 30



Net Inflow Volume (acre-ft)

Year	March	April	May	Total
1986	1,274	163	183	1,620
1987	516	189	84	789
1988	83	88	55	226
1993	390	290	151	832
1994	436	254	214	904
1995	2,285	541	746	3,573
1997	360	285	219	863
1998	1,658	962	233	2,853
1999	741	691	116	1,548
2000	1,205	624	635	2,463
2001	448	191	197	837
2002	700	126	90	915
2003	466	143	401	1,010
2004	323	65	9	397
2005	1,099	511	834	2,444
2006	791	622	246	1,659
2007	371	92	149	612
2008	729	518	238	1,485
2009	611	39	218	867
2010	914	1,274	182	2,370

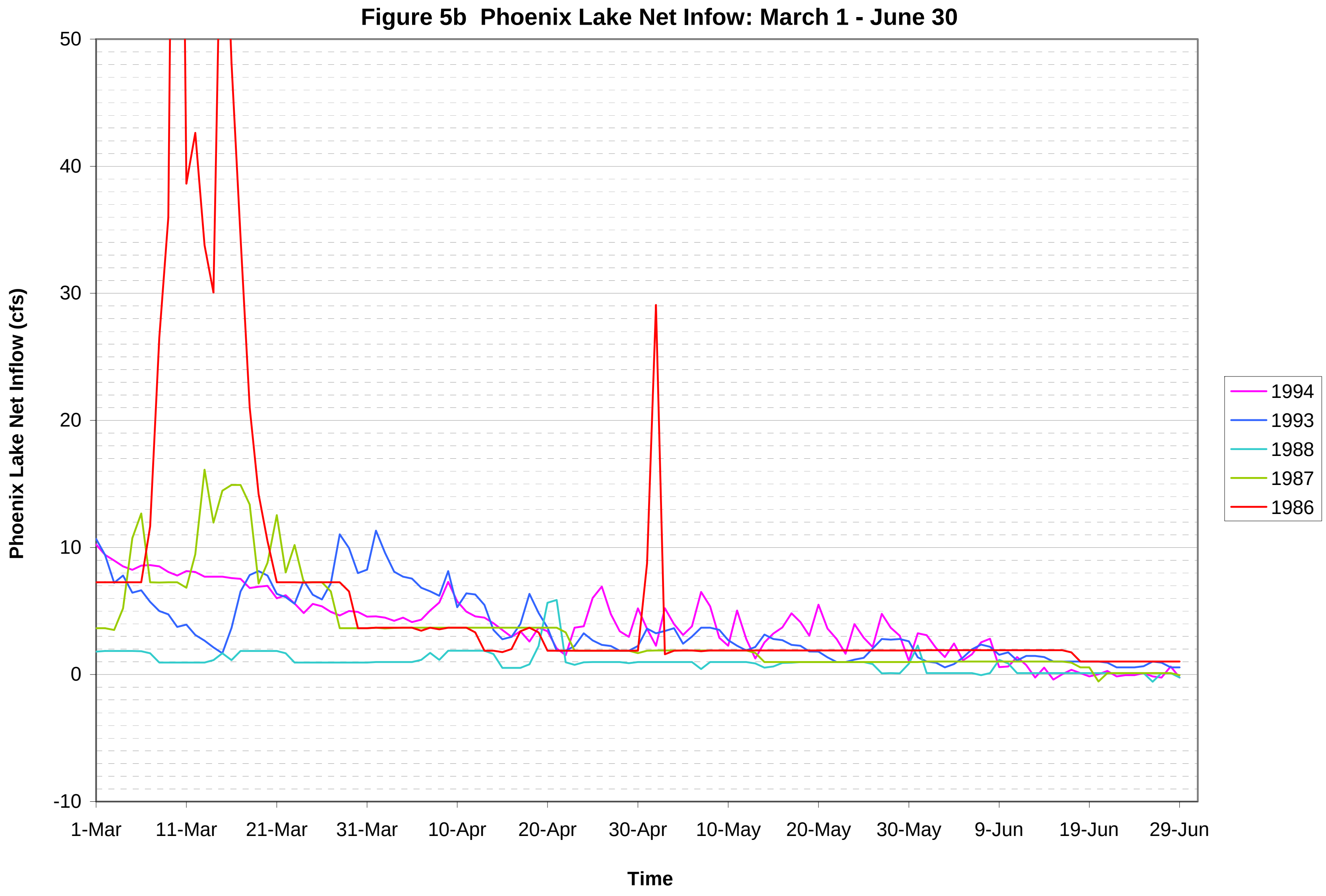


Figure 5b Phoenix Lake Net Infow: March 1 - June 30
Phoenix Lake Net Inflow (cfs)
50
40
30
20
10
0
-10
1-Mar
11-Mar
21-Mar
31-Mar
10-Apr
20-Apr
30-Apr
10-May
20-May
30-May
9-Jun
19-Jun
29-Jun
Time
1994
1993
1988
1987
1986

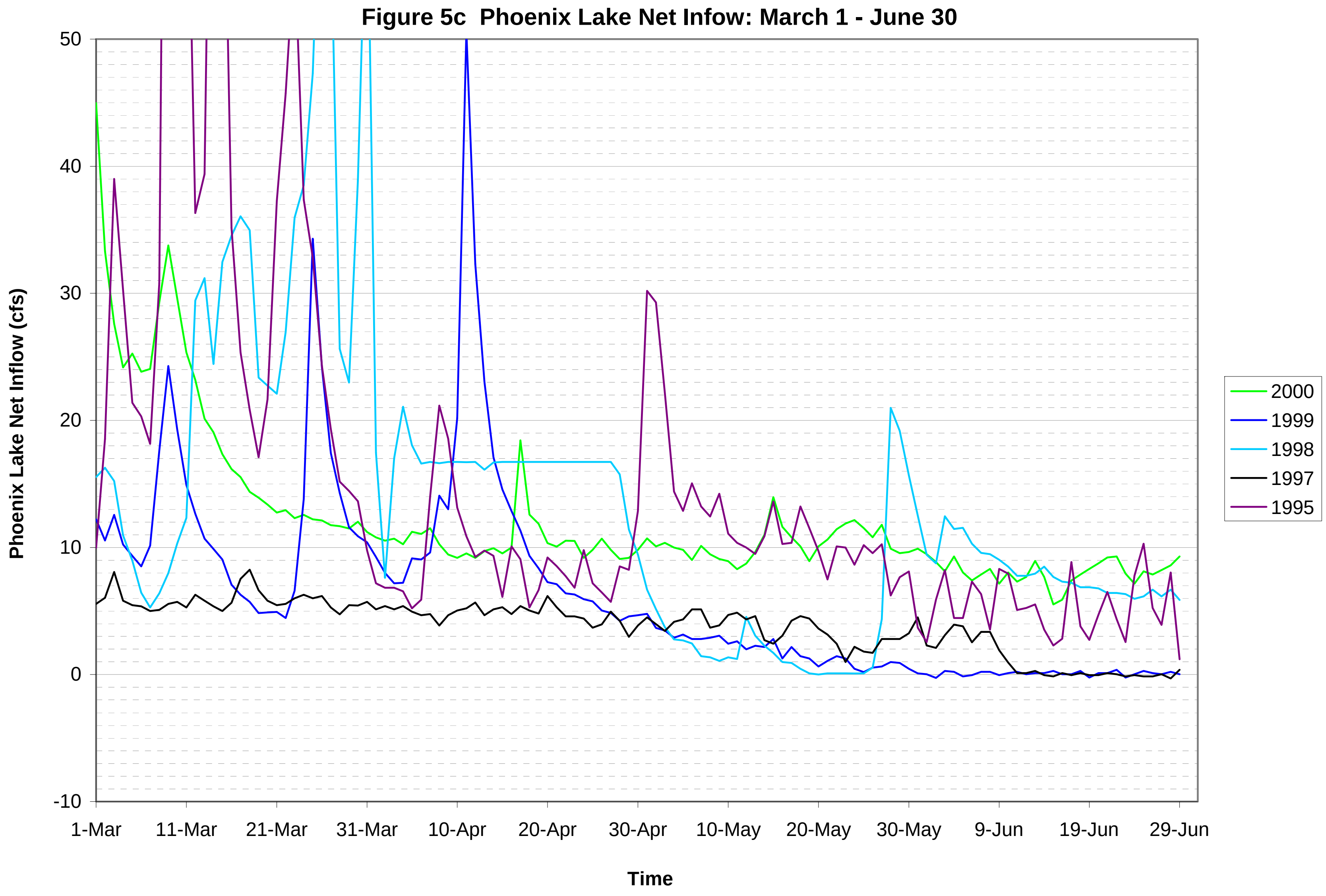


Figure 5c Phoenix Lake Net Infow: March 1 - June 30
Phoenix Lake Net Inflow (cfs)
50
40
30
20
10
0
-10
1-Mar
11-Mar
21-Mar
31-Mar
10-Apr
20-Apr
30-Apr
10-May
20-May
30-May
9-Jun
19-Jun
29-Jun
Time
2000
1999
1998
1997
1995

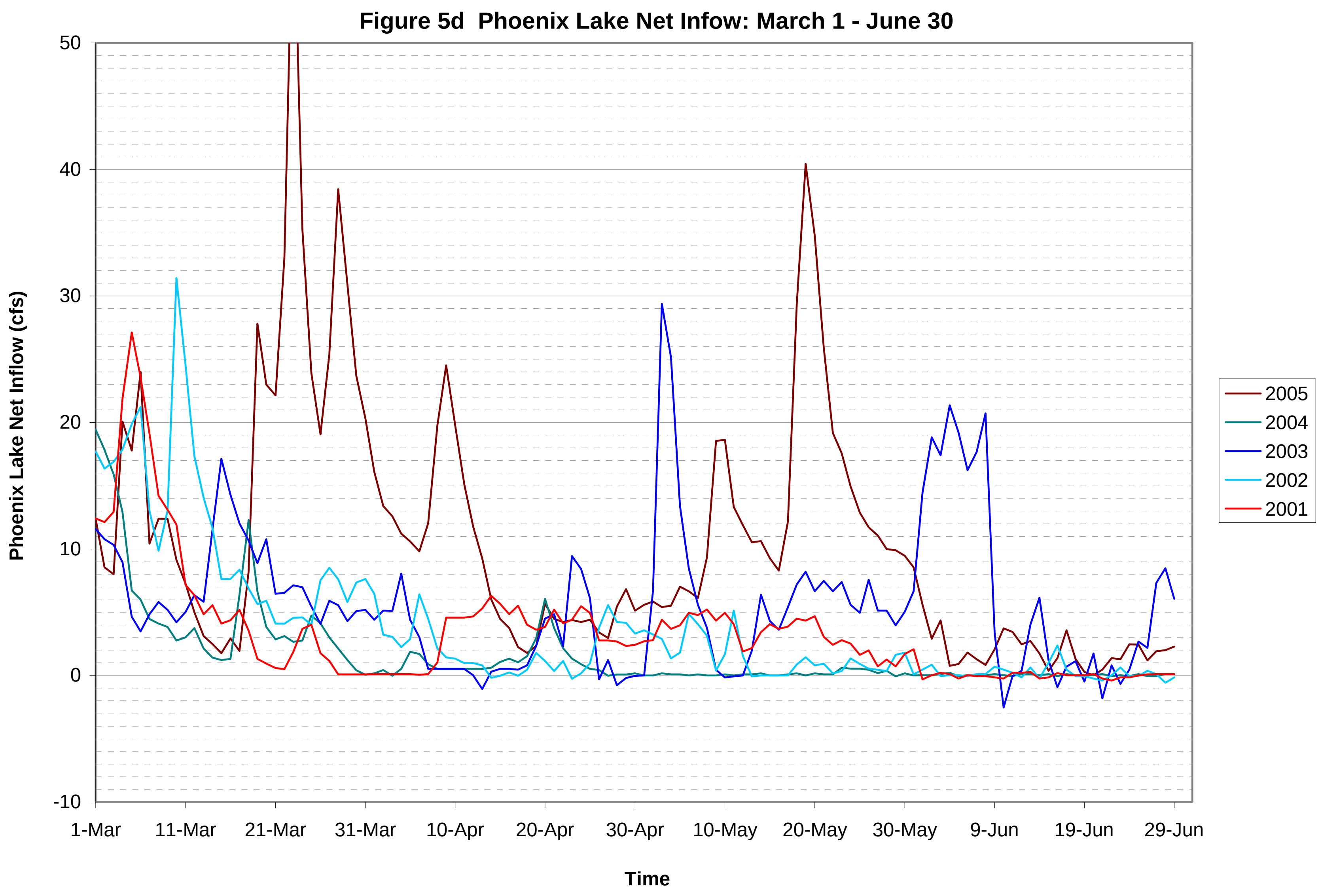


Figure 5d Phoenix Lake Net Infow: March 1 - June 30
Phoenix Lake Net Inflow (cfs)
50
40
30
20
10
0
-10
1-Mar
11-Mar
21-Mar
31-Mar
10-Apr
20-Apr
30-Apr
10-May
20-May
30-May
9-Jun
19-Jun
29-Jun
Time
2005
2004
2003
2002
2001

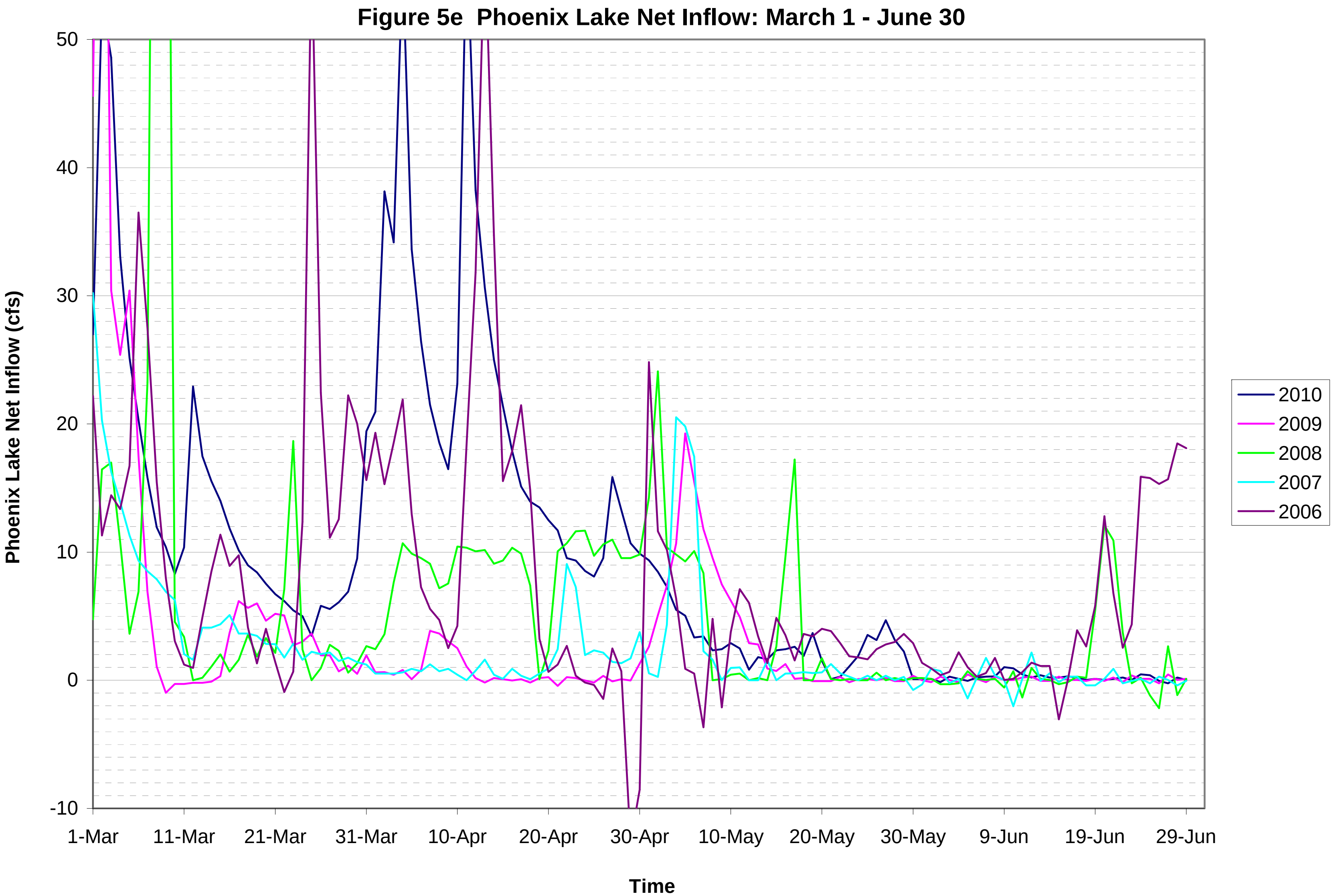
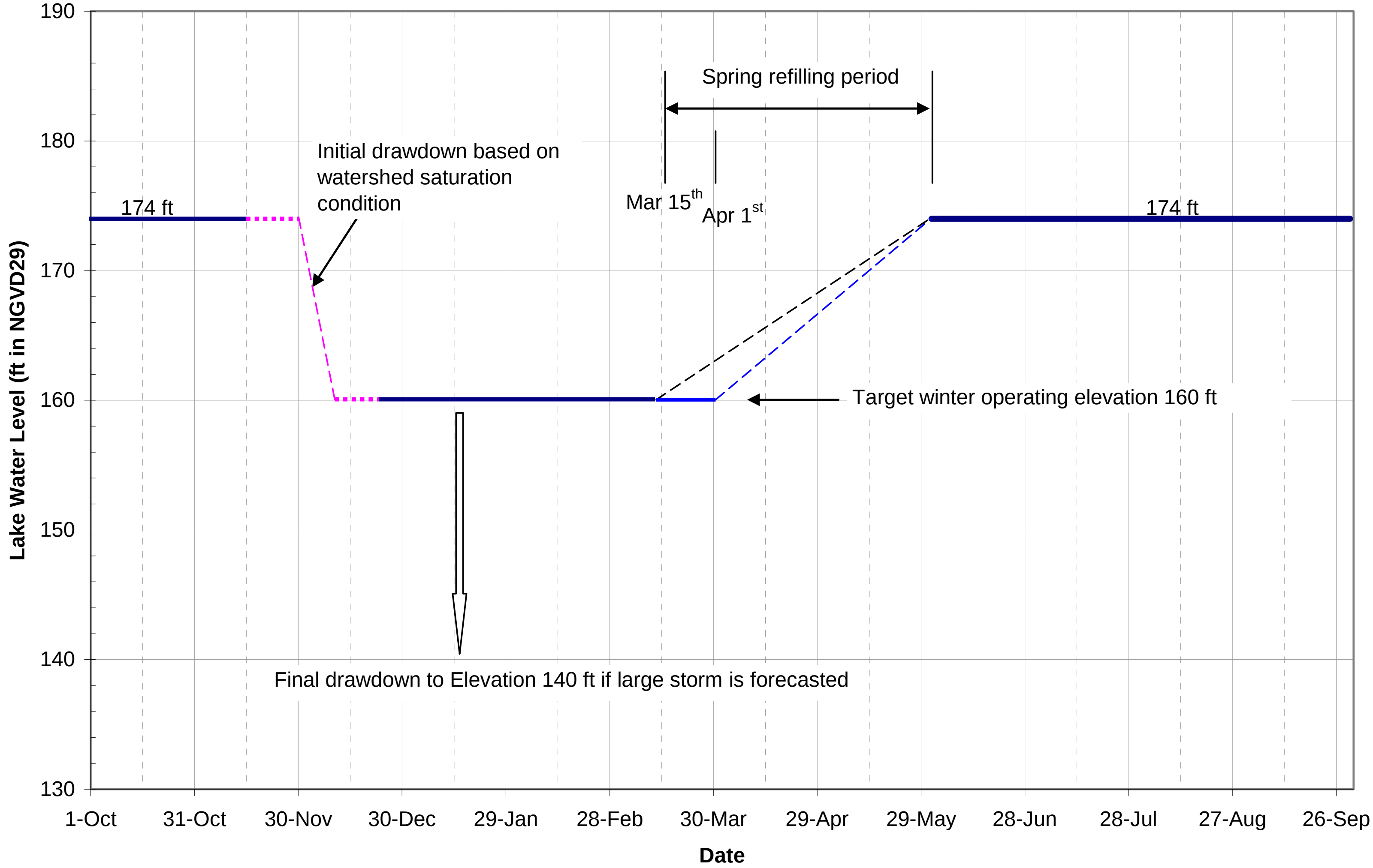


Figure 5e Phoenix Lake Net Inflow: March 1 - June 30
Phoenix Lake Net Inflow (cfs)
50
40
30
20
10
0
-10
1-Mar
11-Mar
21-Mar
31-Mar
10-Apr
20-Apr
30-Apr
10-May
20-May
30-May
9-Jun
19-Jun
29-Jun
Time
2010
2009
2008
2007
2006

Figure 6 Rule Curve Used in Reservoir Re-Operations Analysis



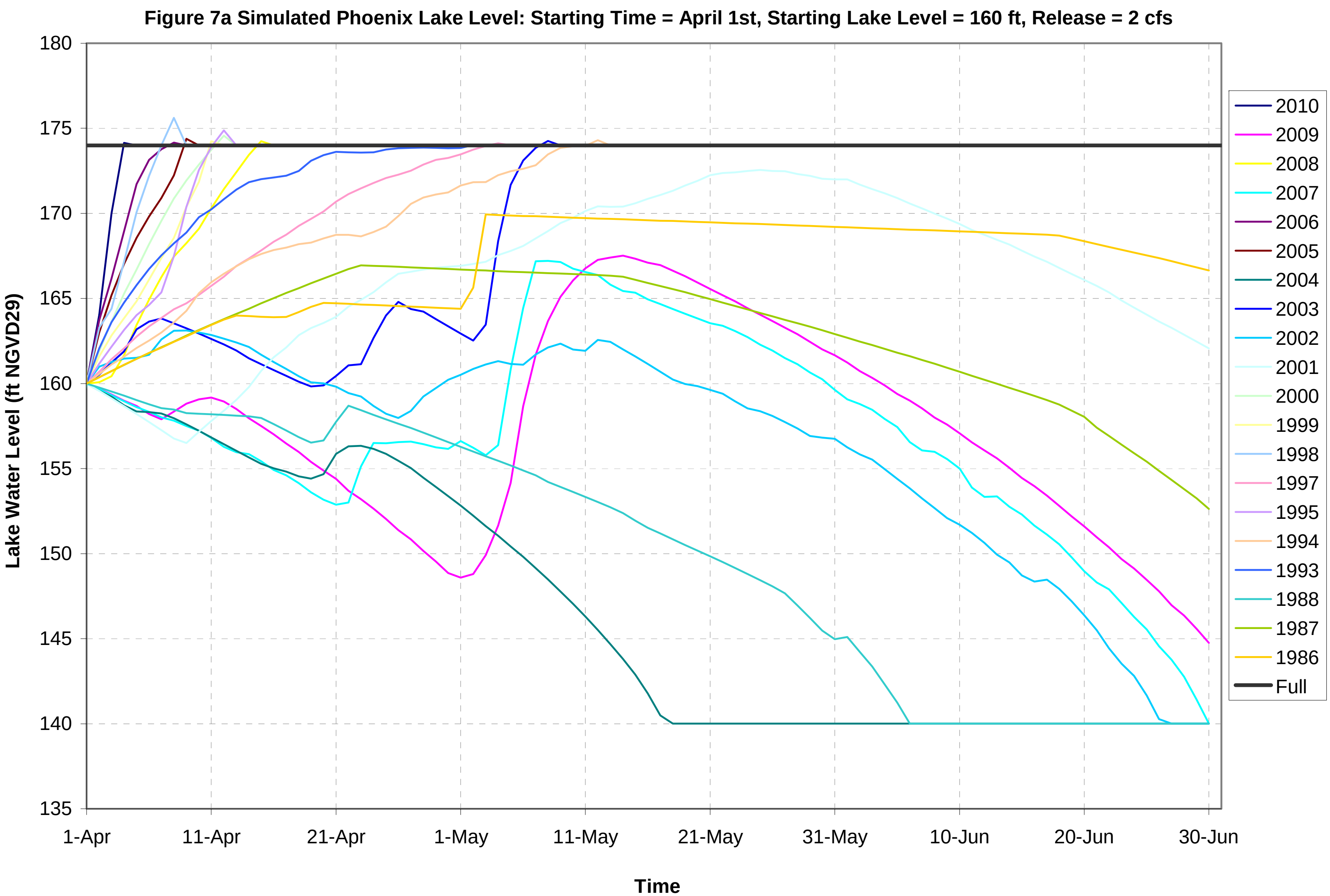


Figure 7a Simulated Phoenix Lake Level: Starting Time = April 1st, Starting Lake Level = 160 ft, Release = 2 cfs
Lake Water Level (ft NGVD29)
180
175
170
165
160
155
150
145
140
135
1-Apr
11-Apr
21-Apr
1-May
11-May
21-May
31-May
10-Jun
20-Jun
30-Jun
Time
2010
2009
2008
2007
2006
2005
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1993
1988
1987
1986
Full

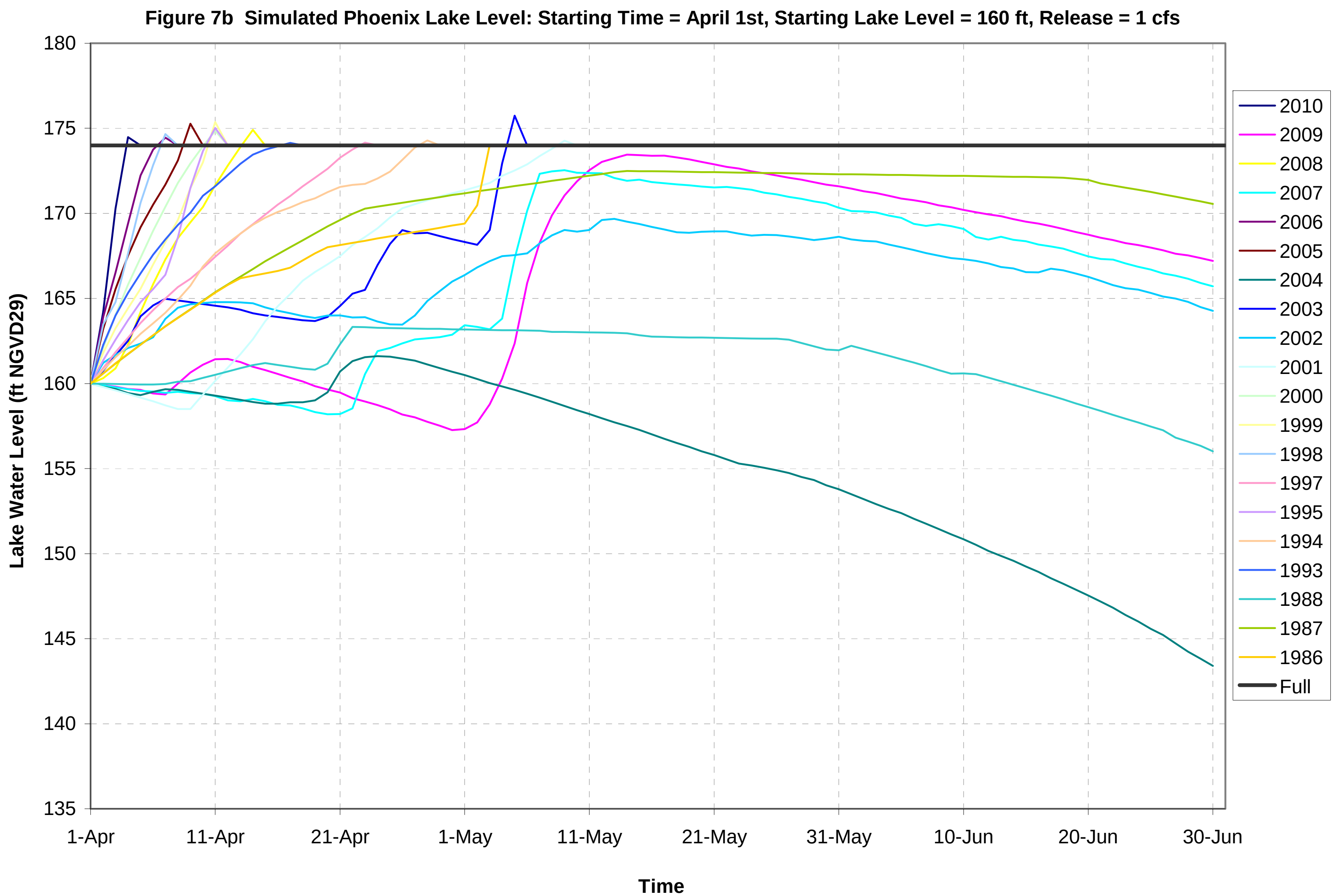
Figure 7b Simulated Phoenix Lake Level: Starting Time = April 1st, Starting Lake Level = 160 ft, Release = 1 cfs
Lake Water Level (ft NGVD29)
180
175
170
165
160
155
150
145
140
135
1-Apr
11-Apr
21-Apr
1-May
11-May
21-May
31-May
10-Jun
20-Jun
30-Jun
Time
2010
2009
2008
2007
2006
2005
2004
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1993
1988
1987
1986
Full

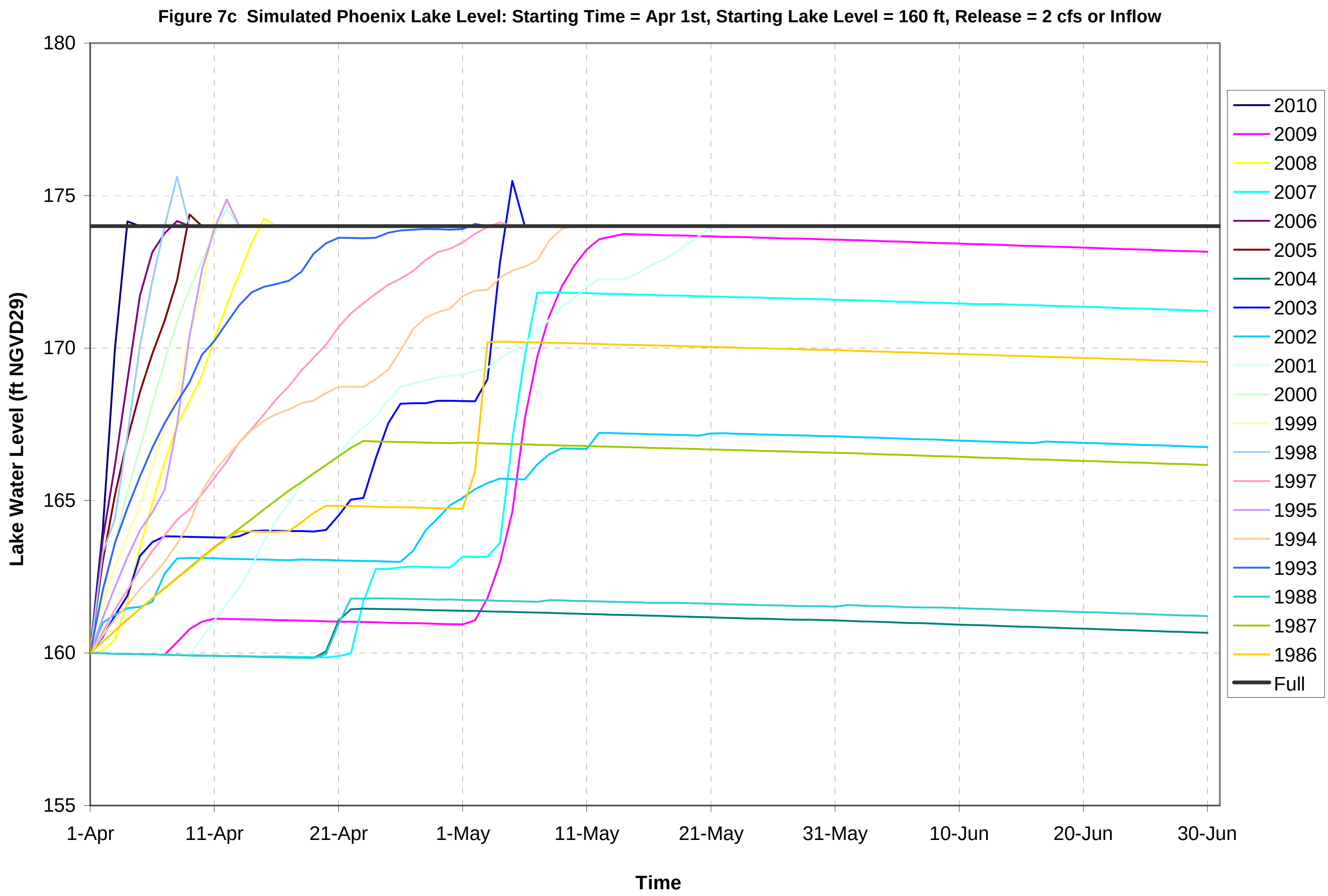


Figure 7c Simulated Phoenix Lake Level: Starting Time = Apr 1st, Starting Lake Level = 160 ft, Release = 2 cfs or Inflow
Lake Water Level (ft NGVD29)
180
175
170
165
160
155
1-Apr
11-Apr
21-Apr
1-May
11-May
21-May
31-May
10-Jun
20-Jun
30-Jun
Time
2010
2009
2008
2007
2006
2005
2004
2003
2002
2001
2000
1999
1998
1997
1995
1994
1993
1988
1987
1986
Full

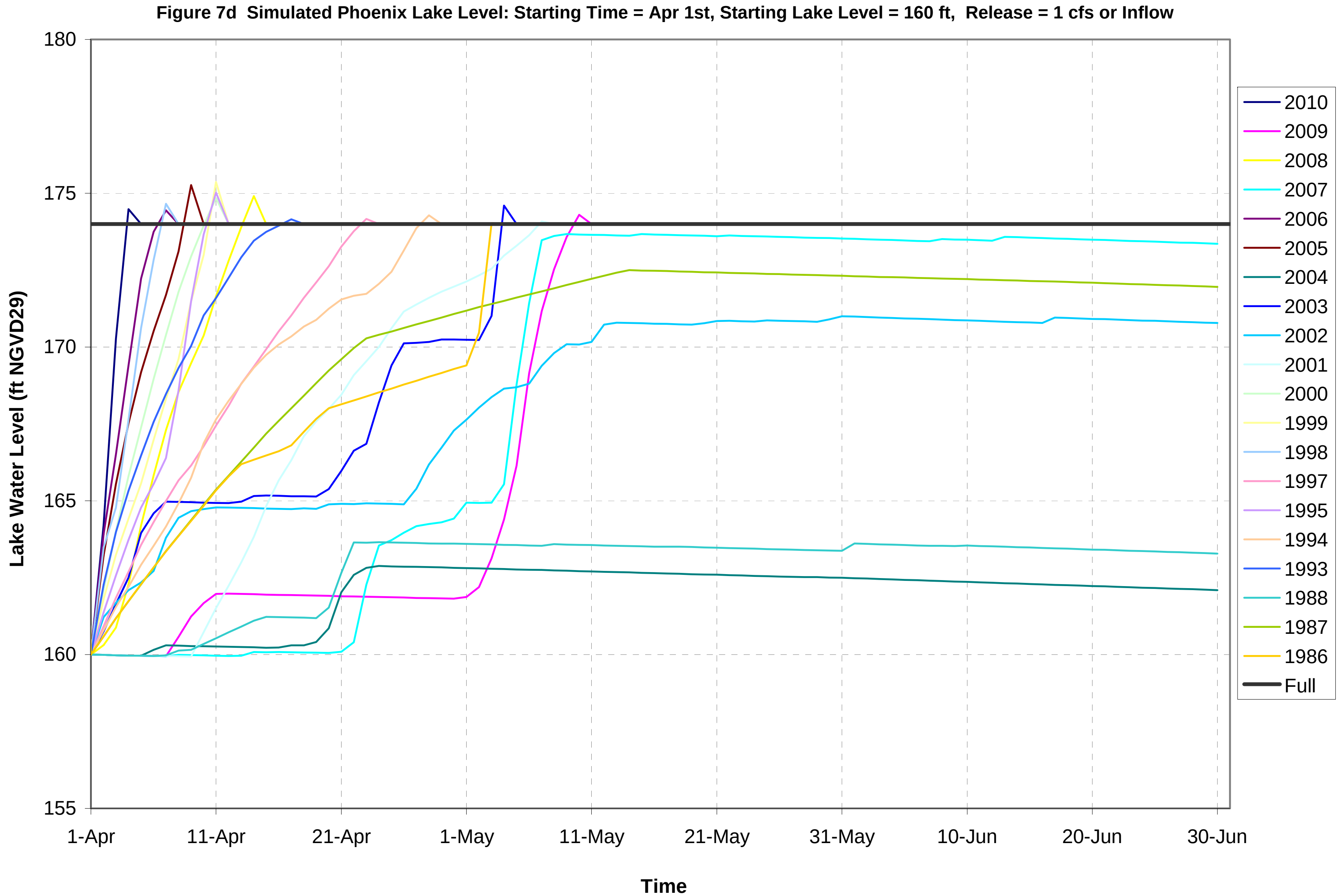
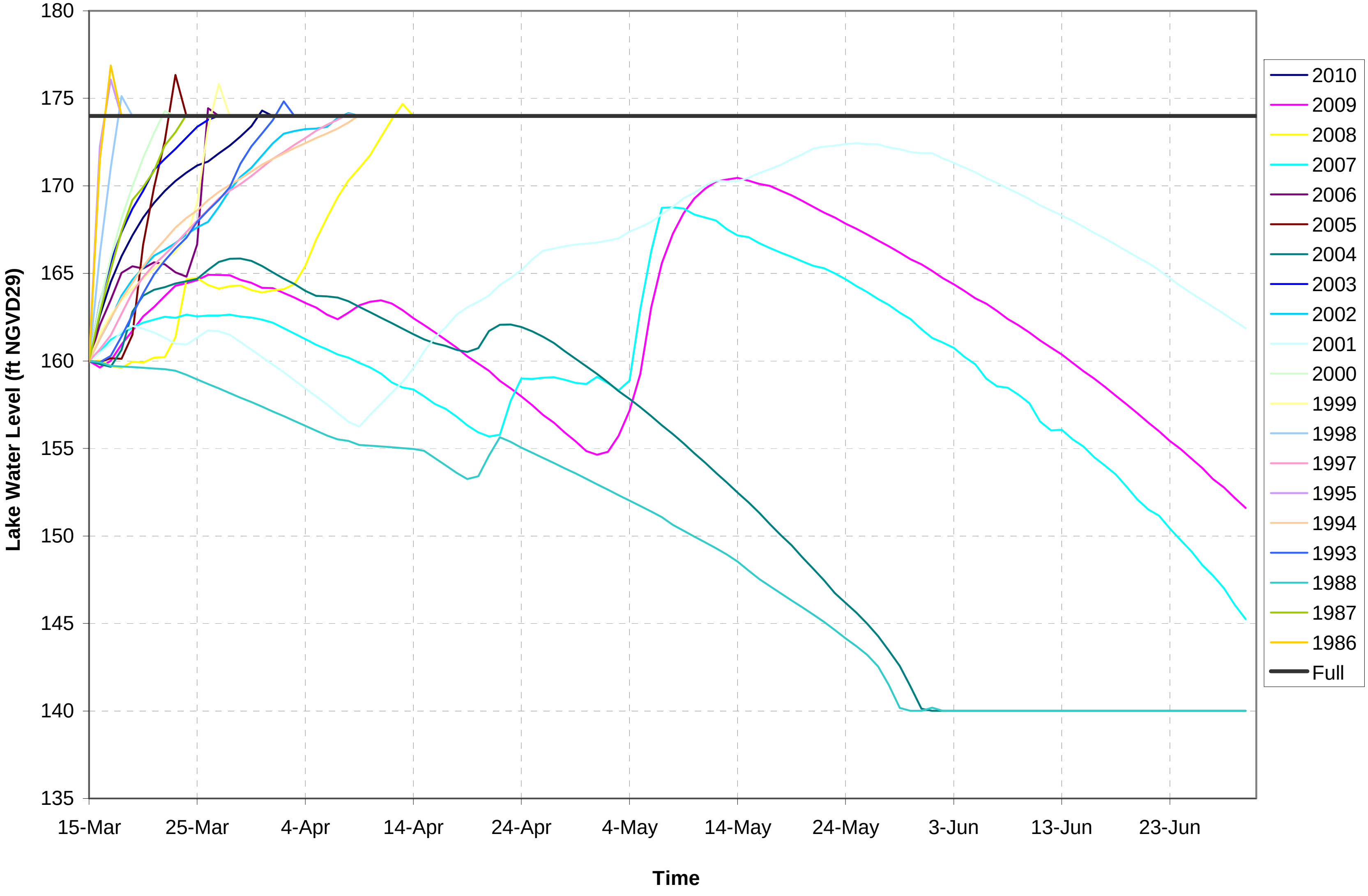


Figure 7d Simulated Phoenix Lake Level: Starting Time = Apr 1st, Starting Lake Level = 160 ft, Release = 1 cfs or Inflow
Lake Water Level (ft NGVD29)
180
175
170
165
160
155
1-Apr
11-Apr
21-Apr
1-May
11-May
21-May
31-May
10-Jun
20-Jun
30-Jun
Time
2010
2009
2008
2007
2006
2005
2004
2003
2002
2001
2000
1999
1998
1997
1995
1994
1993
1988
1987
1986
Full

Figure 8a Simulated Phoenix Lake Level: Starting time = Mar 15th, Starting Lake Level = 160 ft, Release = 2 cfs



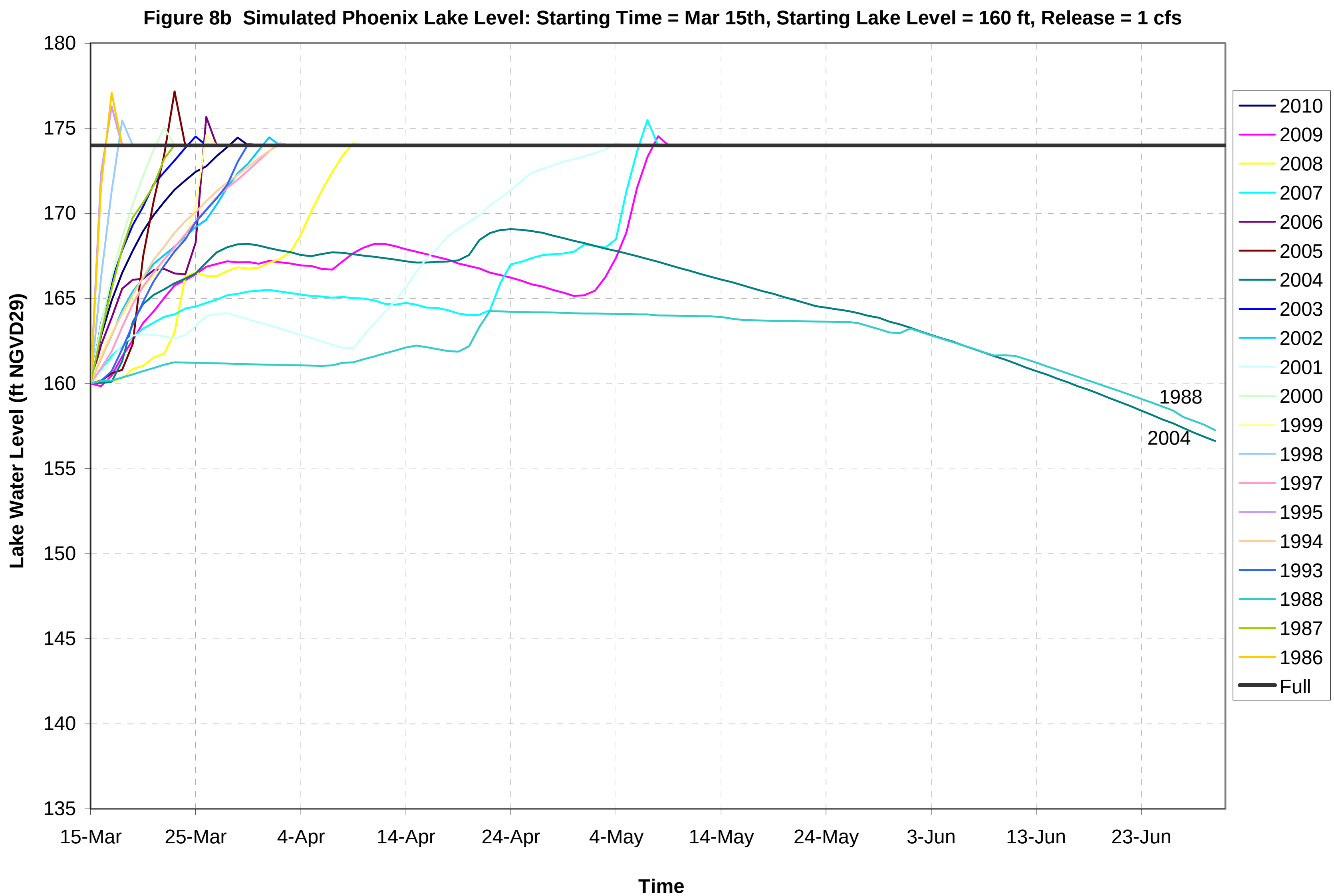


Figure 8b Simulated Phoenix Lake Level: Starting Time = Mar 15th, Starting Lake Level = 160 ft, Release = 1 cfs
Lake Water Level (ft NGVD29)
180
175
170
165
160
155
150
145
140
135
15-Mar
25-Mar
4-Apr
14-Apr
24-Apr
4-May
14-May
24-May
3-Jun
13-Jun
23-Jun
Time
1988
2004
2010
2009
2008
2007
2006
2005
2004
2003
2002
2001
2000
1999
1998
1997
1995
1994
1993
1988
1987
1986
Full

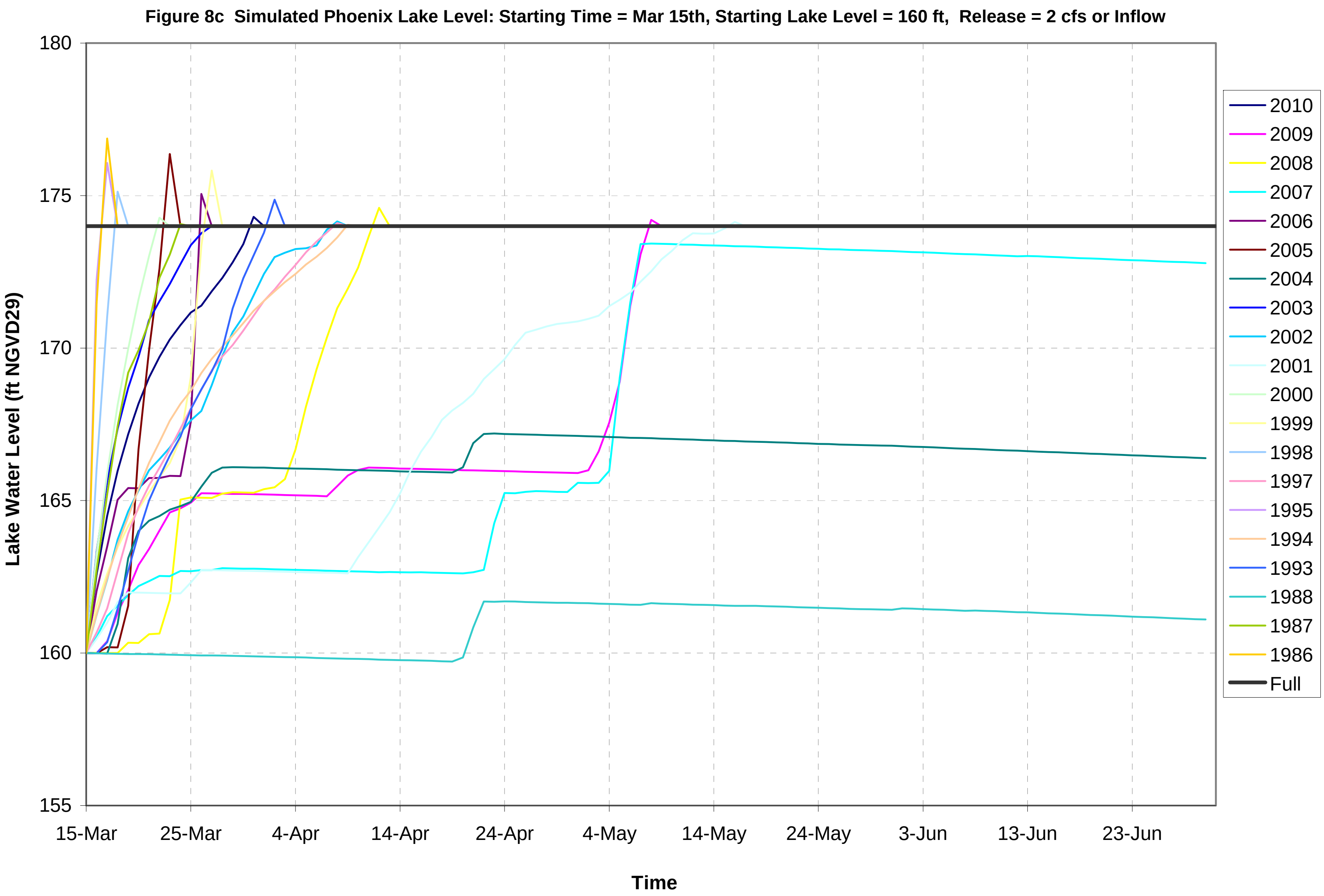


Figure 8c Simulated Phoenix Lake Level: Starting Time = Mar 15th, Starting Lake Level = 160 ft, Release = 2 cfs or Inflow
Lake Water Level (ft NGVD29)
180
175
170
165
160
155
15-Mar
25-Mar
4-Apr
14-Apr
24-Apr
4-May
14-May
24-May
3-Jun
13-Jun
23-Jun
Time
2010
2009
2008
2007
2006
2005
2004
2003
2002
2001
2000
1999
1998
1997
1995
1994
1993
1988
1987
1986
Full

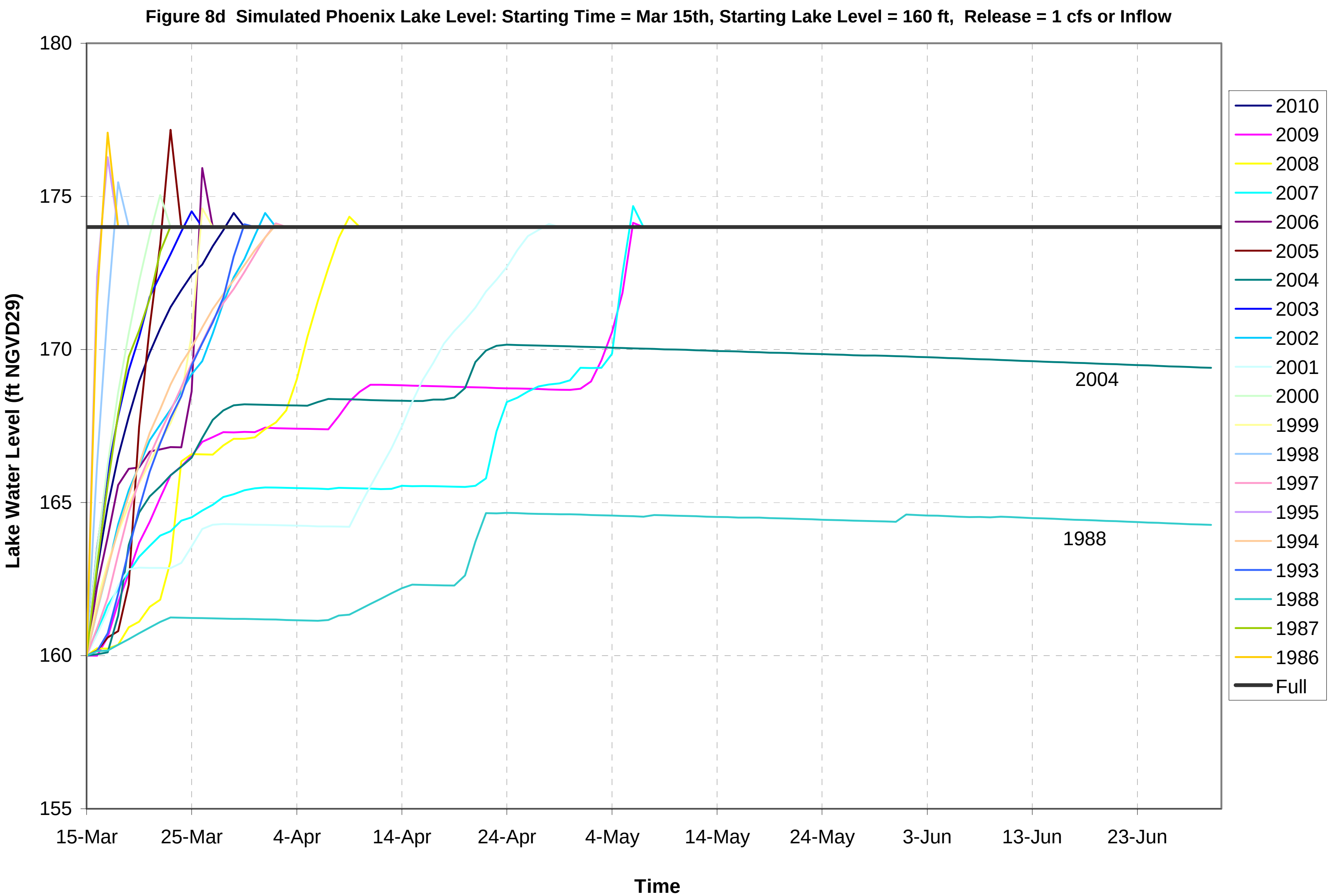


Figure 8d Simulated Phoenix Lake Level: Starting Time = Mar 15th, Starting Lake Level = 160 ft, Release = 1 cfs or Inflow
Lake Water Level (ft NGVD29)
180
175
170
165
160
155
15-Mar
25-Mar
4-Apr
14-Apr
24-Apr
4-May
14-May
24-May
3-Jun
13-Jun
23-Jun
Time
2004
1988
2010
2009
2008
2007
2006
2005
2004
2003
2002
2001
2000
1999
1998
1997
1995
1994
1993
1988
1987
1986
Full

Figure 9 Analysis Results of Routing Baseflows That Occurred on December 31, 2005 through the Dam with the 30" Low-Level Outlet Open