OCCOQUAN RESERVOIR

STORAGE RESPONSE CURVES

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Executive Summary

The Washington, D.C. metropolitan area is supplied by three major utilities with a total annual demand of over 450 mgd. The region's water resources, including the Potomac River and several reservoirs, are cooperatively managed during times of drought. Deciding how much water to treat from the river versus the reservoirs is a multi-dimensional problem including variables such as historic reservoir inflows, time of year, historic and current Potomac flows, a regional operating agreement, current regional demands, and current reservoir storage. The challenge was to develop graphical tools that could easily and quickly be used by planners, water managers, and operators in both drought and normal years to maximize the reliability and use of the reservoir resource.

A solution was developed for Fairfax County Water Authority's (FCWA's) Occoquan Reservoir, in collaboration with FCWA planning personnel. The resulting graphical tools describe the maximum safe withdrawal rates for different reservoir storage levels and time of year at given reliabilities as based on historical reservoir inflow. The tools incorporate the flexibility allowed by dual-supply systems, allowing water managers to maximize reservoir water supply withdrawals and hydropower releases from the reservoir in the summer and fall with the understanding that withdrawals may have to be reduced in the winter and spring.

The tools developed are in the form of reservoir response curves, which were used to develop an example operating policy that was tested using simulation models. Results showed that the example operating policy protected:

- Emergency reserve storage (maintain minimum 92' elevation in reservoir).
- Minimum withdrawal rates (minimum 40 mgd withdrawal at all times).
- Reservoir refill at an acceptable reliability (refill to 90 percent full 95 percent of the time by June 1 given a repeat of the historical inflow record).

The response curves were used in the drought of 1999 and allowed managers to fully utilize the reservoirs in the early stages of the drought while maintaining adequate reserve storage. Managers understood that the "cost" of fully utilizing the reservoirs during the drought was to incur a 1% chance that withdrawals would have to be reduced during the winter, when the free flowing Potomac is able to more than meet demands.

Introduction

The objective of this paper is to present graphical tools (reservoir response curves) that can be used to inform operations decisions for reservoir releases given different reservoir storage levels and time of year in both drought and normal hydrology years for the Fairfax County Water Authority's (FCWA's) Occoquan Reservoir. FCWA is a dual-supply utility, withdrawing water from the Potomac River as well as the Occoquan Reservoir. The recommendations developed in this work incorporate the flexibility allowed by dual-supply systems, allowing water managers to maximize water supply withdrawals and hydropower releases from the reservoirs while ensuring adequate reliability of reservoir refill. Prior work has shown that daily operating levels of between 145 and 150 mgd can be maintained with a frequency of 66% over the historical record (Schwartz, 1996). The reservoir response curve provides a quantifiable framework for maximizing the reliability and use of the reservoir resource.

FCWA has entered into a cooperative regional agreement to operate all reservoir storage with a 95 percent probability of refilling to 90 percent of capacity by June 1. Earlier operational procedures provided the *constant* withdrawal rate from the reservoirs that would just satisfy the reliability criteria by June 1. However, since the reservoir is part of a dual-supply system, water managers need not be constrained by the constant withdrawal assumption. Under the reservoir response curve provided here, managers may increase withdrawals from the reservoirs during the summer through fall period with the understanding that during some dry years, spring-time reservoir withdrawals may have to be curtailed so as to ensure 90 percent reservoir refill by June 1.

The tools developed in this work also can be used quickly and effectively during times of drought to estimate sustainable withdrawals for the four-month window when the Potomac may be unable to meet all regional demands.

The response curves were developed in collaboration with water utility personnel to ensure that all operating specifications could be met including maintaining an emergency storage buffer and providing for enough storage to ensure a minimum of 40 mgd withdrawal under a repeat of even the driest refill conditions.

Assumptions/data

Natural flow. The first step in developing the response curve was to determine the Occoquan monthly low and 5th percentile natural inflows. Table 1 shows the lowest six natural inflows to the Occoquan Reservoir for each month and the year in which the low flow occurred. Data were obtained from a 72 year inflow record, Oct. 1927 through Sept. 1999. (Per ICPRB report 98-3 for 1927-1996 data, and data from Occoquan Watershed Monitoring Lab for 1996 through 1999 inflow). Natural flows are those unaffected by human influence such as wastewater return flows or the effects of upstream regulation. The fifth percentile inflows were developed by averaging the lowest six natural inflows (i.e., the lowest ten percent of monthly flow volumes). This fifth percentile flow volume is the flow volume one would expect to exceed in 95 years out of 100 during each month. Note that 1998 and 1999 low flows are shaded in Table 1.

Wastewater return flow. The next step was to estimate how much water could be expected from upstream wastewater treatment plants. The Upper Occoquan Sewage Authority (UOSA) operates a wastewater treatment plant upstream of the Occoquan Reservoir. The plant discharges a significant portion of the inflow to the Occoquan Reservoir during times of drought. Estimates of 1999 monthly UOSA flow are shown in the second column of Table 2. Because there is inter-annual variability in UOSA flow, a low estimate of UOSA flow was determined as shown in the third column of Table 2. The low estimate of the plant's discharge was added to the natural flows to conservatively determine the effects of the UOSA plant on natural inflow.

Effects of Lake Manassas. The City of Manassas operates a reservoir in the Occoquan watershed. The operation of this reservoir can affect the flows entering the Occoquan Reservoir. The effects of Lake Manassas on Occoquan natural inflow were conservatively considered for this analysis. The minimum release is the lesser of 7.5 mgd or inflow to the reservoir. Thus, it was conservatively assumed that Lake Manassas would impound most of the runoff in its sub-watershed during storms. To account for this impoundment, historic record low flows and the 5th percentile monthly inflows were reduced by 10 percent in determining expected Occoquan low and 5th percentile flows. (Ten percent is calculated as the ratio of Lake Manassas drainage area to the Occoquan drainage area, i.e., 60/591.)

Other assumptions are as follows:

- Minimum required downstream release from the reservoir: 0 cfs.
- Emergency storage: 1.07 bg at 92' elevation in reservoir (usable storage = 0.75 bg).
- Minimum withdrawal rate from the reservoir: 40 mgd.
- Total capacity: 8.52 bg (subtract 0.33 bg to determine usable capacity = 8.19 bg).
- 90 percent full (June 1 refill target): 7.37 bg (equals 90% of total usable capacity).

Developing the response curve

The response curves were developed in two major segments, from June 1 through February 28 (drawdown period) and from March 1 through May 31 (the refill period). The two periods were determined by inflow hydrology. The drawdown portion of the response curve can be used to guide operations so as to maintain at least a minimum 40 mgd withdrawal while protecting the emergency storage in the reservoir at greater than 99 percent reliability. The refill portion of the response curve can be used to guide operations so as to fill the reservoir to 90 percent full with 95 % reliability by June 1. Figure 1 shows the complete set of response curves. A complete explanation of the rule curve development and directions in its use are given in subsequent sections of this report.

Developing the June 1 through February 28 portion of the rule curve

The Occoquan manager is not constrained in reservoir operations by regional refill agreements until March 1 because of ample springtime inflow. Therefore, the June 1 through Feb. 28 portion of the response is independent of regional refill requirements. This portion of the response curve was designed solely to help the manager maximize withdrawals, maintain a minimum of 40 mgd withdrawal, and stay above the reservoir's emergency storage levels even under a repeat of the driest (the 1st percentile) inflow conditions. (Reservoir managers would not wish to drop below emergency reserve storage levels even if the minimum historical flow of record were to reoccur. That is why the lowest historical monthly inflow was used to derive the June 1 through Feb. 28 portion of the response curve instead of the 5th percentile inflow.)

For the period June 1 through December 30, the lowest or 1st percentile natural monthly inflow plus UOSA return flow was less than 40 mgd. In February and January, the lowest expected monthly inflow was approximately equal to 40 mgd. Therefore, reservoir storage must be reserved for the months of June through December to meet the minimum 40 mgd demand that cannot be met by inflow to the reservoir. The last column in Table 3 sums the total storage required to meet the 40 mgd withdrawal rate by working backwards from December 30.

To illustrate this point, the total withdrawal for December at 40 mgd equals 1.22 bg. The minimum expected inflow plus UOSA return flow minus Lake Manassas diversion is 1.13 bg. Since expected inflow is less than desired withdrawal by 0.09 bg, 0.09 bg of storage is reserved at the beginning of December to provide for the 40 mgd withdrawal. The 40 mgd response curve is thus based on the last column in Table 3. The 40 mgd response curve for the period June 1 through December 30 defines an area below which a withdrawal greater than 40 mgd cannot be sustained without the risk of either dropping into emergency storage levels during extreme drought events, or cutting back to less than 40 mgd withdrawals.

Note that this portion of the response curve is extremely conservative in that it assumes that the lowest recorded monthly inflow is followed by the subsequent months' lowest recorded flows.

The 50 mgd response curve for this period is determined by using a similar method as used for the 40 mgd zone. Inflow is less than 50 mgd during the period June 1 through the end of February. The total February deficit (minimum inflow plus UOSA return flow minus Lake Manassas diversion and minus a 50 mgd withdrawal) is 0.37 bg. Therefore 0.37 bg of storage is reserved at the beginning of February to provide for the 50 mgd withdrawal. (Working backward from the emergency storage limit of 1.1 bg on March 1 yields a February 1 target of 1.47 bg, i.e., 1.1 + 0.37. This method is repeated in consecutive months to calculate the 50 mgd response curve from June 1 through the end of February.

The 60 mgd response curve can be determined in a similar manner to the method outlined for the 40 and 50 mgd withdrawals.

Developing the March 1 through May 31 (refill) portion of the response curve

The March 1 through May 31 portion of the response curve provides for maximum withdrawal rates while meeting regional refill requirements. The March through May portion of the response curve was based on the 5th percentile Occoquan inflows, adjusted for the effects of Lake Manassas and 1999 UOSA flows, and was determined as follows.

Refill target: The refill target of 7.37 billion gallons was established for June 1 as 90 percent of the total usable capacity of the Reservoir. This refill target was established per regional refill agreements.

40 mgd response curve: The May 1 target was determined by working backwards from the June 1 target of 7.4 bg, given the expected 5th percentile May inflow (1.75 bg), effects of Lake Manassas (0.18 bg) and UOSA return flow (0.6 bg) while allowing for a minimum 40 mgd withdrawal (1.22 bg) as calculated in Table 4. (The May 1 target was 7.37 – 1.75 + 0.18 – 0.6 + 1.22 = 6.42 bg.) This May 1 target is the minimum acceptable storage needed by May 1 in order to refill on June 1 to 90 percent full with 95 percent reliability under a repeat of the historical inflow record while allowing for a minimum withdrawal of 40 mgd each day. The straight line connecting the May 1 and June 1 targets marks the 40 mgd response curve for May 1 through June 1.

The April 1 target was determined for the 40 mgd response curve by working backwards from the May 1 target of 6.42 bg, given the expected 5th percentile April inflow (3.47 bg), effects of Lake Manassas (0.35 bg) and UOSA return flow (0.6 bg) while allowing for a minimum 40 mgd withdrawal (1.22 bg). (The April 1 target was 6.40 – 3.47 + 0.35 – 0.6 + 1.22 = 3.92 bg.)

March is historically the month with the highest values of 5th percentile natural flow, at 6.0 bg. This volume is greater than the volume needed to reach the April 1 target of 3.92 bg, even while allowing for a 40-60 mgd range of withdrawals. The March 1 target need not be any greater than the emergency minimum storage, while meeting regional refill requirements.

50 and 60 mgd response curves: The 50 and 60 mgd response curves were determined using the same accounting process as for the 40 mgd response curve. The only difference was that for the 50 mgd curve, a 50 mgd withdrawal was assumed which is equivalent to a monthly withdrawal volume of 1.53 bg, and a 60 mgd withdrawal is equivalent to 1.83 bg per month. Calculations are shown in Table 4.

Use of reservoir response curve – drawdown period

The reservoir manager can use the curve to quickly predict how the reservoir storage would respond under a repeat of historical low flows given 40, 50 or 60 mgd withdrawal rates. If storage drops below the 50 or 60 mgd response curves and withdrawals are greater than 50 or 60 mgd, the manager knows that if low flow conditions continue the reservoir will be on a trajectory that is unsustainable. In the short term, the manager may wish to take more than 50 or 60 mgd with the understanding that if very dry conditions prevail, reservoir withdrawals can be later reduced to the 40 mgd minimum rate. If wetter conditions prevail (as one might expect in 99 years out of a hundred) reservoir storage would rise into higher withdrawal zones, and higher withdrawal rates could be resumed.

However, if dry conditions continue and reservoir storage continues to drop lower below the 40 mgd response curve, a withdrawal of no greater than 40 mgd should be made. FCWA's preference is to maintain at least a 40 mgd withdrawal at all times. If greater than a 40 mgd withdrawal is made when reservoir storage is below the 40 mgd response curve, managers should understand there is a about a 1 percent probability that either the withdrawal rate will have to be later reduced to less than 40 mgd or the reservoir might drop below emergency storage levels or both.

Use of reservoir response curve – refill period

The reservoir manager can use the curve to quickly determine how the reservoir storage would increase under a repeat of historical 5th percentile flows given 40, 50 and 60 mgd withdrawal rates. The 40, 50 and 60 mgd response curves show the maximum sustainable withdrawal rates at 5th percentile flow conditions. In the short term, the manager may wish to take more than the maximum sustainable withdrawal with the understanding that later withdrawals could be reduced to make up for the difference. If wetter conditions prevail (as one might expect in 95 years out of a hundred) reservoir storage would rise into higher withdrawal zones, and higher withdrawal rates could be resumed.

However, if dry conditions continue and reservoir storage drops below the 40 mgd response curve, a withdrawal of no greater than 40 mgd should be made. FCWA's preference is to maintain at least a 40 mgd withdrawal at all times. If greater than a 40 mgd withdrawal is made when reservoir storage is below the 40 mgd response curve, managers should understand that the reservoir will not refill to 90 percent full at 95 percent reliability.

Development of transparency overlay

A transparency (Figure 2) is included with this report for use with the Occoquan Reservoir response curve (Figure 3). The transparency gives a broader range of reservoir response curves for 5th percentile inflow rates, for withdrawal values of 40, 50, 60, 70, 80, and 90 mgd and for any time of year.

The traces shown in the transparency were developed using the same method used for the refill portion of the response curve. That is, reservoir storage was modeled using the fifth percentile inflows from Table 2 for each month and for selected withdrawal rates for water supply (varying from 40 to 90 mgd).

Use of transparency overlay

The transparency overlay (Figure 2) has the benefit of allowing a prediction of reservoir storage under low flow conditions for several months into the future, given any level of current reservoir storage and a broad range of withdrawal rates. The operator can shift the transparency up or down to estimate how a range of withdrawal rates might affect reservoir storage given future low flow conditions, given today's total reservoir storage. (In shifting the position of the transparency, care must be taken to ensure that the vertical lines that form the left-hand and right-hand side of the graphs are aligned.) The operator or manager can then follow the lines on the transparency to see how different withdrawals might affect reservoir storage several months into the future, if low flow conditions were to occur. The chart can be used to quickly make daily operating decisions that maximize withdrawal rates and meet regional requirements to refill the reservoir to 90% full at a 95% probability, or to devise a release strategy during times of drought in the Potomac basin.

Results—testing an experimental operating policy using a simulation modeling tool

The response curves were used to develop an example operating policy that was tested using simulation models. The example operating policy combined elements of the response curve shown in Figure 1. The example operating policy is shown in Figure 4. Reservoir withdrawals were constrained by the zones shown in Figure 4. Reservoir withdrawals were assumed to be 90 mgd whenever reservoir storage was above the 60 mgd zone. Whenever storage dropped into the 60 mgd zone, withdrawals were assumed to be 60. Similar zones were developed for 50 and 40 mgd withdrawals. Withdrawals were constrained to zero if reservoir storage dropped below emergency storage levels.

The Occoquan Reservoir simulation model developed at ICPRB using *Extend*™ object-oriented software was used to test the example operating policy. Several assumptions were made for the simulation model runs. Natural inflows from ICPRB report 98-3 were used and were extended using Occoquan Watershed Monitoring Laboratory data for 1996 through 1999. Hydropower releases were assumed for the model runs, as determined empirically from data describing hydropower operations during the 1991 through 1996 period and as quantified in Figure 5 and validated in Figure 6. 1999 UOSA return flow was routed into the simulation model's reservoir in addition to natural inflows. Water was routed through Lake Manassas and Lake Manassas withdrawals were simulated in order to estimate the effects of this impoundment. Lake Manassas releases were the minimum of 7.5 mgd or inflow to Lake Manassas.

Reservoir storage was simulated over the entire period of record. A number of metrics were chosen to demonstrate the reservoir performance. The metrics and associated model results are shown below:

- Number of times reservoir storage dropped below emergency storage: **0**
- Minimum total reservoir storage during the period: **1,979 mg**
- Number of times reservoir withdrawals dropped below 40 mgd: **0**

- Average water supply withdrawal: **87.2 mgd**
- Reliability of reservoir refill to 90 percent full on June 1: **94.5 %** [A]
- Average release for hydropower over entire period: **86.3 mgd**

Note [A] If water supply withdrawals are reduced to 50 mgd whenever storage is less than 7 bg during the period May 20 through May 31, then simulated refill reliability is: > 99%.

Reservoir storage for the driest year of the simulation period (1930) is shown in Figure 7. Figure 7 shows that the example operating policy could successfully guide operations through even the worst drought of record while meeting regional reliability requirements, preserving minimum emergency storage, maintaining a minimum withdrawal of 40 mgd, and efficiently using available storage. The reservoir refills in all years of the historical record when operations are guided by the example operating policy.

Results—testing the response curve and transparency tool during the drought of 1999

The Washington metropolitan area depends primarily on the free-flowing Potomac for most of its water. Even under the worst-case flows, the Potomac can meet both environmental flow recommendations (MDNR, 1981) and water supply withdrawals for most of the year. Demands are potentially higher than Potomac flow for only a relatively short period of time (four months) from about mid-July through early–November (Figure 8). Figure 8 was developed by linking the lowest recorded river flow for each day of the year over the course of the last 100 years of gage records.

The transparency tool can be used in conjunction with the response curve to derive an operating policy that maximizes withdrawals during the four-month window of Potomac vulnerability. Similar operating policies using analogous tools have been derived for the other cooperatively operated reservoirs (the Patuxent system) to optimize and balance the regional resources. These tools were used during the drought of 1999 to safely maximize the release decisions for both the Occoquan and Patuxent reservoirs. Managers understood that the “cost” of fully utilizing the reservoirs during the drought was to incur a 1% chance that withdrawals would have to be significantly reduced during the winter, when the free flowing Potomac is able to more than meet demands.

Future work

The effects of changing inflows and reservoir sedimentation will have to be addressed over time. For example, the response curve will need to be refined as UOSA return flows to the Occoquan Reservoir watershed increase, which in turn increases the total flow to the reservoir during low flow periods. The effects of reservoir siltation will shift the elevation of emergency storage on the response curve over time.

Projections by the ICPRB suggest that demand for water could exceed supply in a severe drought early in the 21st century (Mullusky et. al, 1996). The League of Women Voters has suggested options and strategies for dealing with this potential shortage (League of Women Voters of the National Capital Area Water Supply Task Force, 1999). Improved efficiency in the management of the Occoquan and Patuxent reservoirs can be considered an additional strategy for addressing this shortage. The reservoir response curves are an improvement in the efficiency of operations as compared to former overly conservative constant yield operating rules (Schwartz, 1996). The reservoir response curve can be used in future simulation models to safely maximize the use of the Occoquan Reservoir in meeting demands during drought years, thereby extending the prediction of when future resources need to be brought on line.

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Table 1: Ranked Occoquan monthly natural inflow

	January		February		March		April		May		June	
Rank	Year	Inflow	Year	Inflow	Year	Inflow	Year	Inflow	Year	Inflow	Year	Inflow
Lowest natural monthly inflow	1981	0.8	1931	0.6	1931	1.8	1981	2.9	1999	1.2	1986	0.5
2nd Lowest	1966	1.3	1934	1.2	1981	2.8	1985	2.9	1969	1.5	1977	0.7
3rd Lowest	1931	1.6	1954	3.5	1985	6.6	1963	3.7	1941	1.6	1999	0.7
4th Lowest	1942	2.0	1977	4.2	1928	7.8	1931	3.7	1956	1.9	1954	0.9
5th Lowest	1955	2.2	1991	4.5	1945	7.9	1995	3.7	1977	2.1	1964	1.0
6th Lowest	1977	2.3	1947	4.6	1988	8.8	1968	4.0	1963	2.2	1965	1.0
Average (5th percentile flow)		1.69		3.10		5.96		3.47		1.75		0.81

	July		August		September		October		November		December	
Rank	Year	Inflow	Year	Inflow	Year	Inflow	Year	Inflow	Year	Inflow	Year	Inflow
Lowest natural monthly inflow	1966	0.2	1987	0.1	1980	0.1	1986	0.2	1941	0.1	1930	0.6
2nd Lowest	1985	0.3	1966	0.1	1995	0.2	1963	0.2	1930	0.5	1931	0.6
3rd Lowest	1957	0.3	1999	0.2	1988	0.2	1951	0.4	1931	0.5	1965	0.7
4th Lowest	1963	0.4	1980	0.3	1963	0.2	1954	0.4	1965	0.6	1980	1.1
5th Lowest	1965	0.5	1957	0.3	1985	0.2	1962	0.5	1954	0.7	1998	1.2
6th Lowest	1977	0.5	1985	0.3	1983	0.3	1988	0.5	1953	0.7	1958	1.4
Average (5th percentile flow)		0.36		0.21		0.21		0.37		0.50		0.93

Notes: Inflow data is based on ICPRB report 98-3 for 1927-1996, and on data from Occoquan Watershed Monitoring Lab for 1996 through 1999. Method used to generate 1996-1999 inflow data described in ICPRB report 98-3 as used for 1980-1995 data.
1998-1999 flows are shaded for illustrative purpose.

Table 2: 1999 UOSA return flow.

	1993-1998 monthly average production factors [a]	Predicted UOSA annual return flow for 1999 based on 23.9 mgd annual return flow and 1993-1998 monthly average production factors (bg)	Conservative estimate of UOSA 1999 return flow (bg)
January	1.15	0.83	0.6
February	1.14	0.83	0.6
March	1.23	0.89	0.6
April	1.01	0.73	0.6
May	0.96	0.70	0.6
June	0.93	0.67	0.6
July	0.91	0.66	0.6
August	0.93	0.67	0.6
September	0.88	0.64	0.6
October	0.89	0.65	0.6
November	1.01	0.74	0.6
December	0.97	0.70	0.6

Note: [a] Monthly average production factors are based on data provided by Traci Kammer Goldberg, FCWA, of UOSA monthly average influent flows for January of 1993 through March of 1996

Table 3: Determination of response curve for drawdown portion of curve

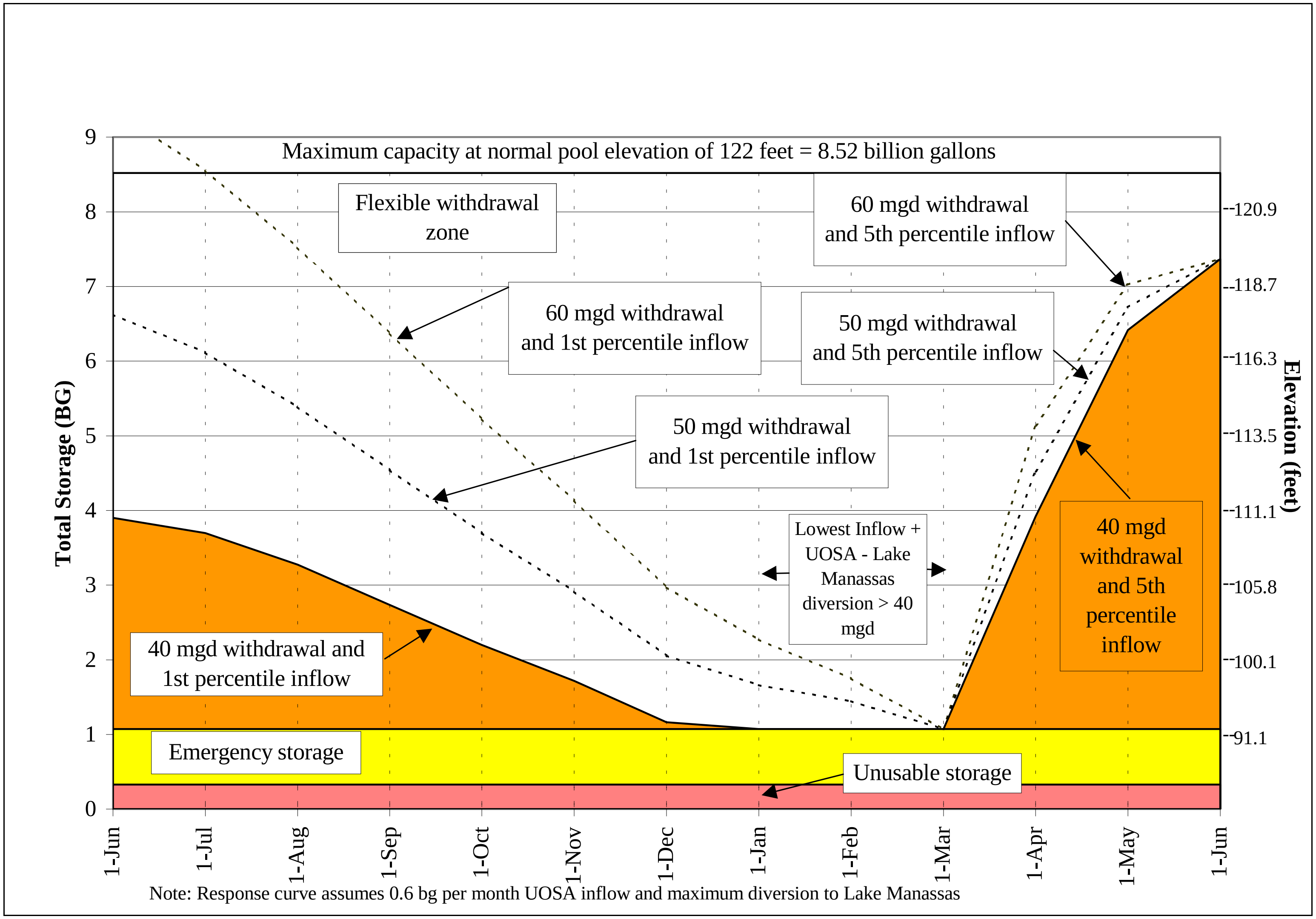
Month	Historical record lowest inflow (bg)	Lake Manassas diversion (est.)	1999 UOSA return flow (bg)	Historical low inflow plus UOSA return flow minus Lake Manassas div. (bg)	40 mgd monthly with-drawal (bg)	Total potential deficit for withdrawal greater than inflow (bg)	Total running deficit, working backwards (bg)
	40 mgd withdrawal						
June	0.5	0.05	0.6	1.02	1.22	-0.20	-2.83
July	0.2	0.02	0.6	0.80	1.22	-0.42	-2.62
August	0.1	0.01	0.6	0.68	1.22	-0.54	-2.20
Sept.	0.1	0.01	0.6	0.68	1.22	-0.54	-1.66
October	0.2	0.02	0.6	0.74	1.22	-0.48	-1.12
Nov.	0.1	0.01	0.6	0.67	1.22	-0.55	-0.64
Dec.	0.6	0.06	0.6	1.13	1.22	-0.09	-0.09
January	0.8	0.08	0.6	1.31	1.22	0.09	0.00
February	0.6	0.06	0.6	1.15	1.22	-0.07	-0.07
March	1.8	0.18	0.6	2.25	1.22		
April	2.9	0.29	0.6	3.17	1.22		
May	1.2	0.12	0.6	1.68	1.22		
	50 mgd withdrawal						
June	0.5	0.05	0.6	1.02	1.5	-0.51	-5.55
July	0.2	0.02	0.6	0.80	1.5	-0.73	-5.04
August	0.1	0.01	0.6	0.68	1.5	-0.85	-4.32
Sept.	0.1	0.01	0.6	0.68	1.5	-0.84	-3.47
October	0.2	0.02	0.6	0.74	1.5	-0.78	-2.63
Nov.	0.1	0.01	0.6	0.67	1.5	-0.86	-1.84
Dec.	0.6	0.06	0.6	1.13	1.5	-0.40	-0.98
January	0.8	0.08	0.6	1.31	1.5	-0.22	-0.59
February	0.6	0.06	0.6	1.15	1.5	-0.37	-0.37
March	1.8	0.18	0.6	2.25	1.5	-	
April	2.9	0.29	0.6	3.17	1.5	-	
May	1.2	0.12	0.6	1.68	1.5	-	
	60 mgd withdrawal						
June	0.5	0.05	0.6	1.02	1.83	-0.81	-8.29
July	0.2	0.02	0.6	0.80	1.83	-1.03	-7.48
August	0.1	0.01	0.6	0.68	1.83	-1.15	-6.45
Sept.	0.1	0.01	0.6	0.68	1.83	-1.15	-5.30
October	0.2	0.02	0.6	0.74	1.83	-1.09	-4.15
Nov.	0.1	0.01	0.6	0.67	1.83	-1.16	-3.06
Dec.	0.6	0.06	0.6	1.13	1.83	-0.70	-1.90
January	0.8	0.08	0.6	1.31	1.83	-0.52	-1.20
February	0.6	0.06	0.6	1.15	1.83	-0.68	-0.68
March	1.8	0.18	0.6	2.25	1.83		
April	2.9	0.29	0.6	3.17	1.83		
May	1.2	0.12	0.6	1.68	1.83	-	

Note: numbers may not compute as shown due to rounding

Table 4: Determination of response curve for refill portion of curve

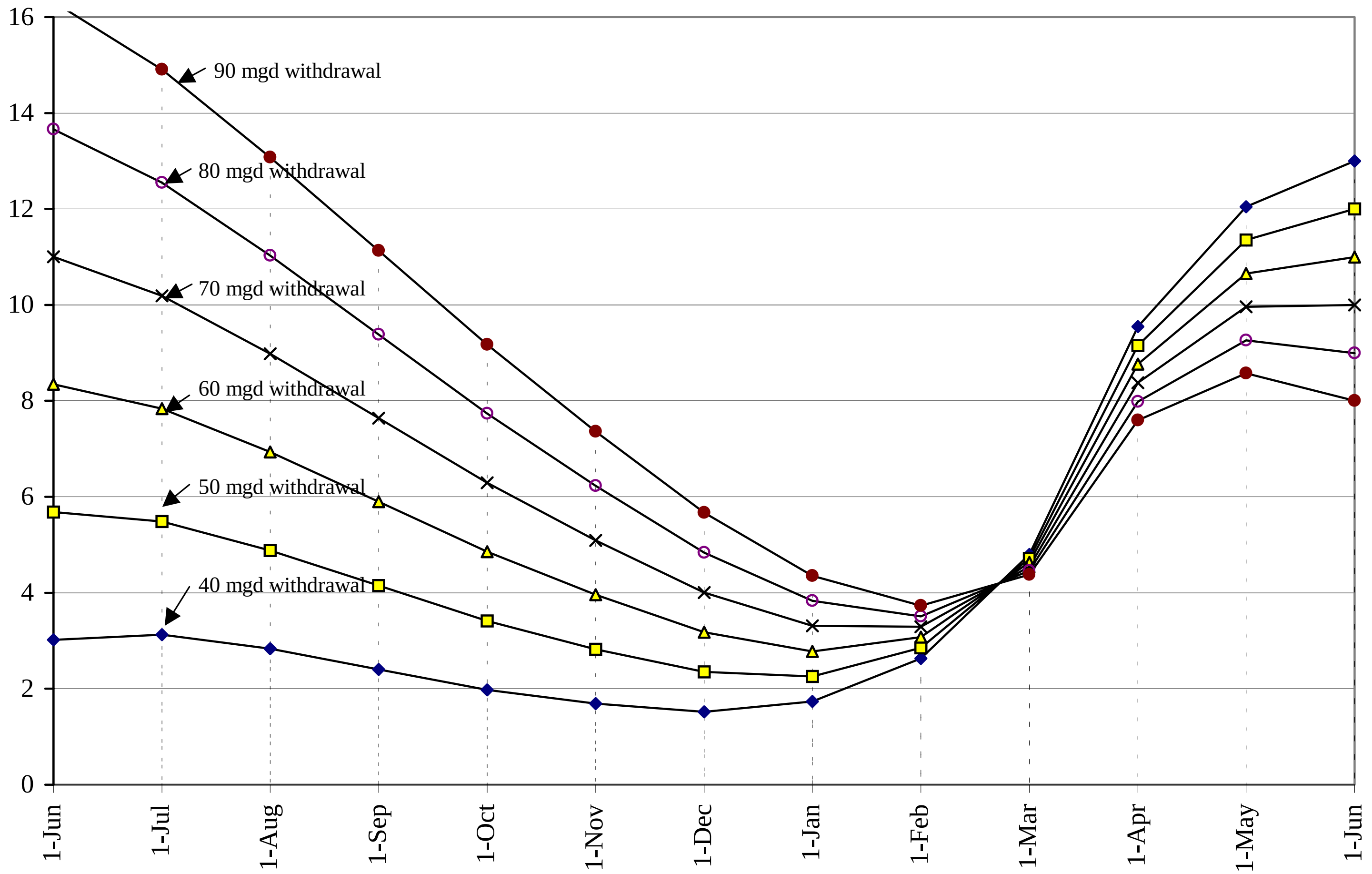
	5th percentile Occoquan monthly natural inflow, bg	Lake Manassas diversion, bg (est.)	1999 UOSA return flow, bg	5th percentile inflow plus UOSA return flow minus Lake Manassas divs., bg	40 mgd monthly withdrawal bg	Required storage to meet target of 90 % full on June 1 at selected withdrawals, bg
	40 mgd withdrawal					
January	1.69	0.17	0.6	2.12	1.22	
February	3.10	0.31	0.6	3.39	1.22	
March	5.96	0.60	0.6	5.97	1.22	-0.83
April	3.47	0.35	0.6	3.72	1.22	3.92
May	1.75	0.18	0.6	2.18	1.22	6.42
June	0.81	0.08	0.6	1.33	1.22	7.37
	50 mgd withdrawal					
January	1.69	0.17	0.6	2.12	1.53	
February	3.10	0.31	0.6	3.39	1.53	
March	5.96	0.60	0.6	5.97	1.53	0.09
April	3.47	0.35	0.6	3.72	1.53	4.53
May	1.75	0.18	0.6	2.18	1.53	6.72
June	0.81	0.08	0.6	1.33	1.53	7.37
	60 mgd withdrawal					
January	1.69	0.17	0.6	2.12	1.83	
February	3.10	0.31	0.6	3.39	1.83	
March	5.96	0.60	0.6	5.97	1.83	1.00
April	3.47	0.35	0.6	3.72	1.83	5.14
May	1.75	0.18	0.6	2.18	1.83	7.03
June	0.81	0.08	0.6	1.33	1.83	7.37

Figure 1: Occoquan Reservoir response curve.



Note: Response curve assumes 0.6 bg per month UOSA inflow and maximum diversion to Lake Manassas

Figure 2: Transparency overlay tool for use with Occoquan Reservoir response curve



Reservoir response curves given 5th percentile inflows, var. withdrawal rates, 0.6bg UOSA monthly inflow, and maximum Lake Manassas Diversion

Figure 3: Occoquan Reservoir response curve for use with transparency overlay

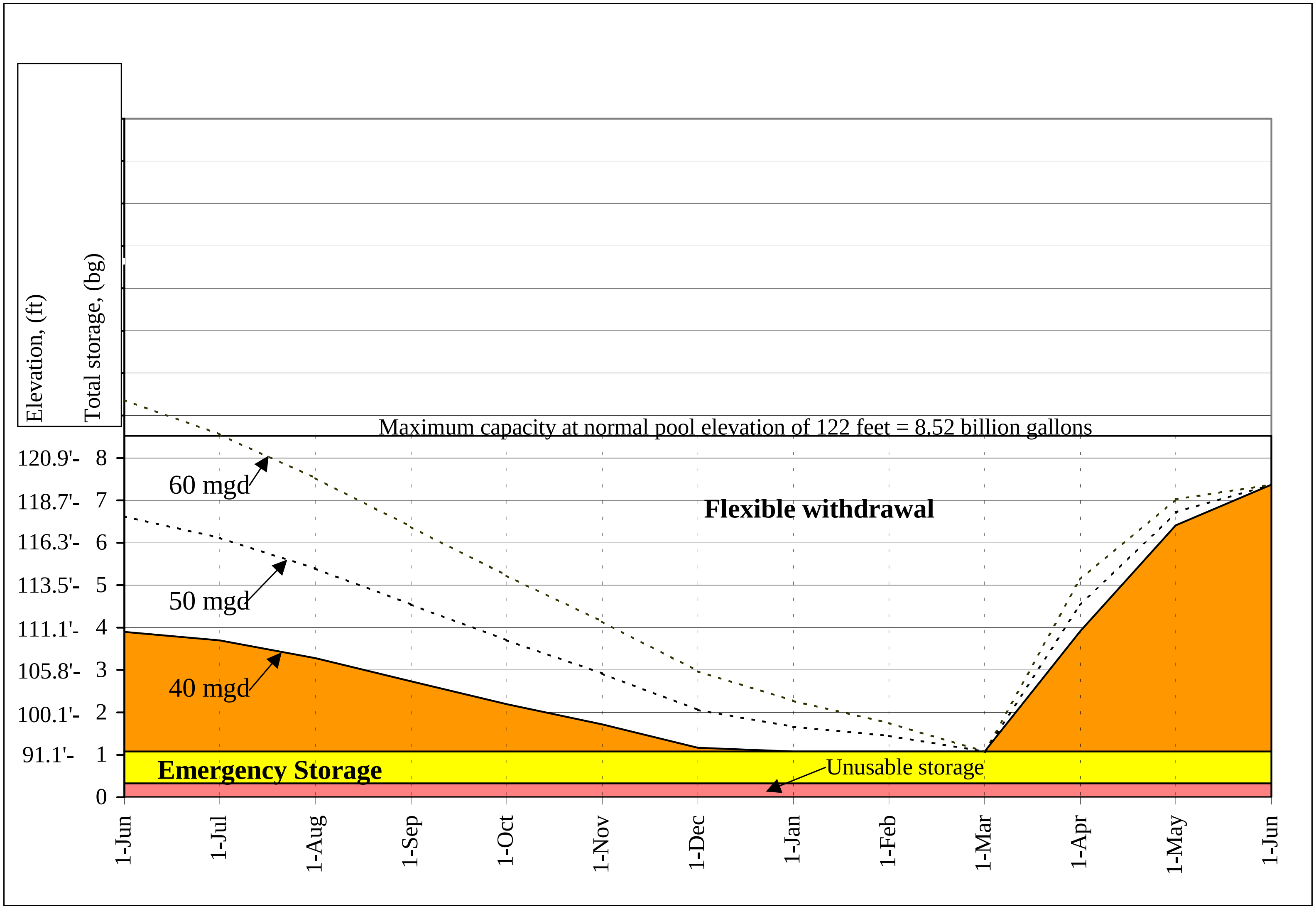


Figure 4: Example operating policy based on reservoir response curve

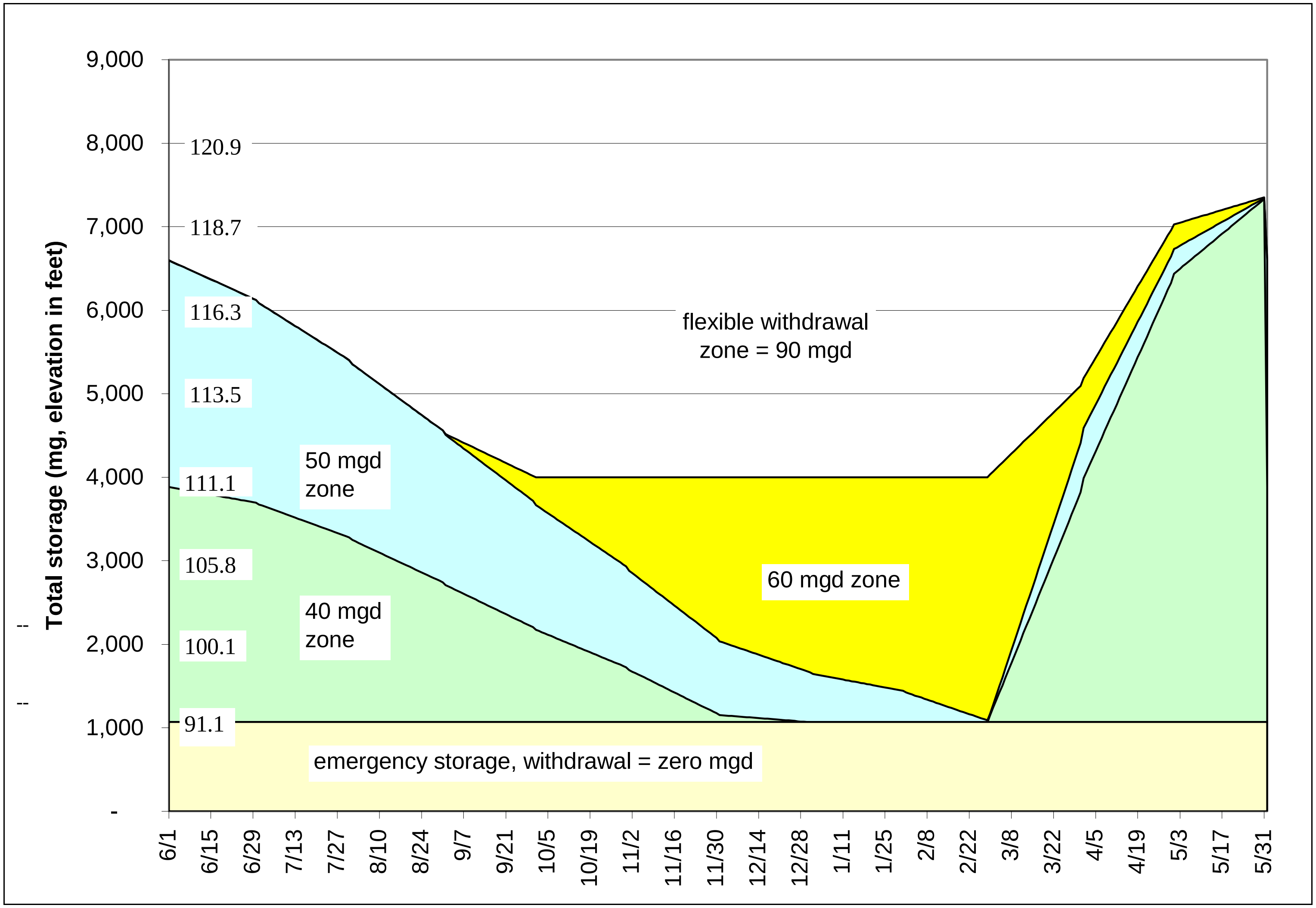
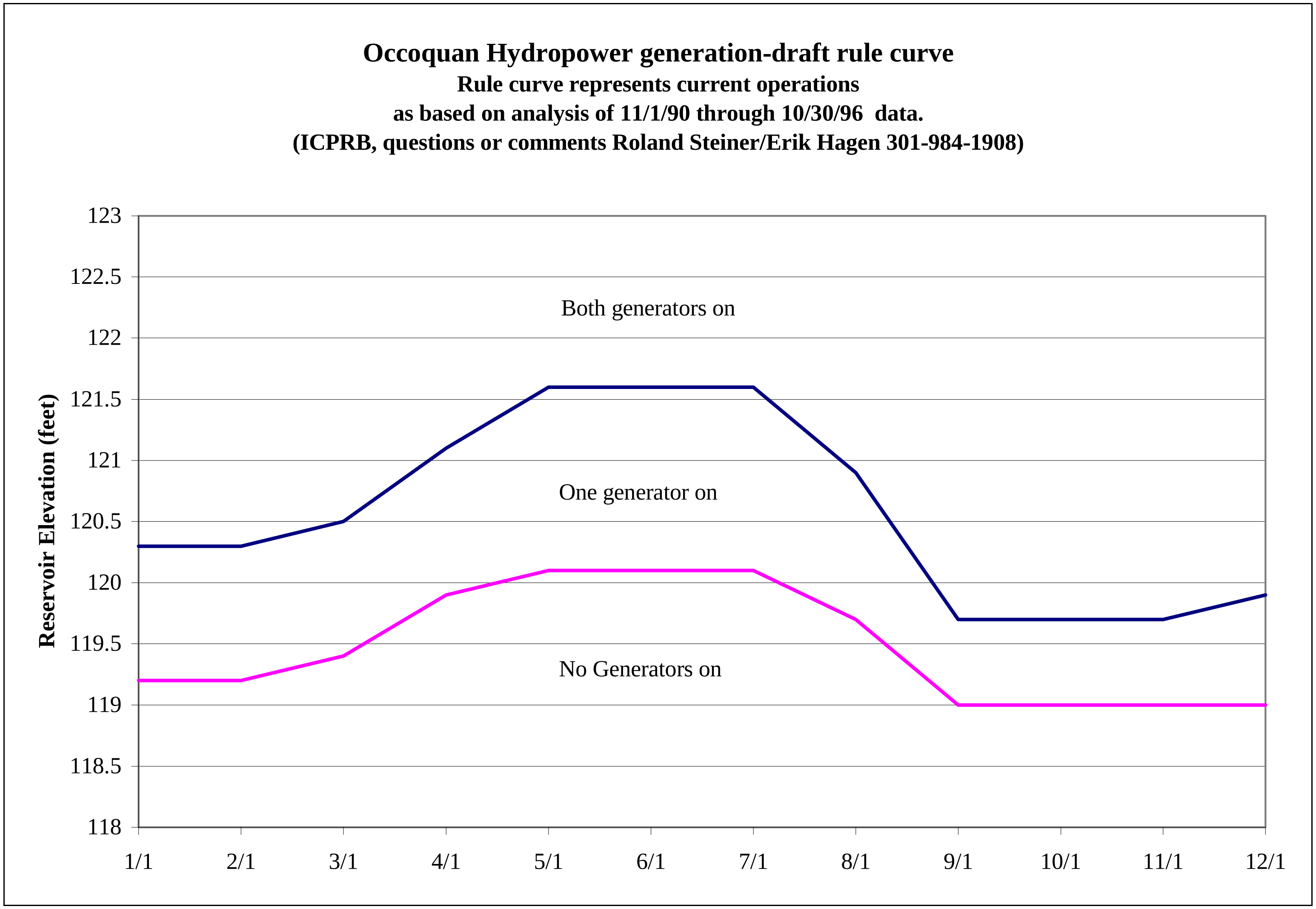


Figure 5: Occoquan hydropower generation: approximation of current operations

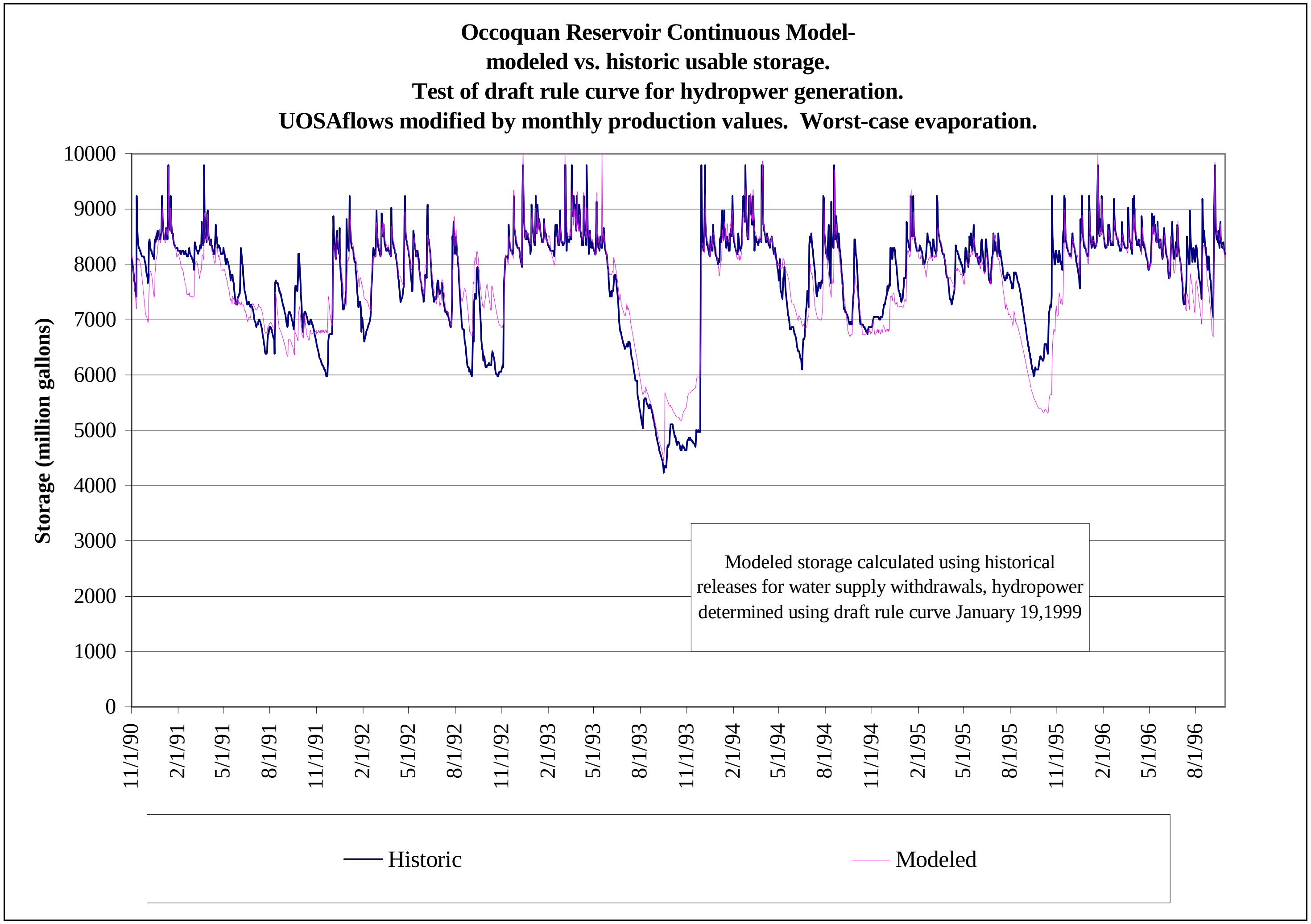


Occoquan Hydropower generation-draft rule curve

Rule curve represents current operations as based on analysis of 11/1/90 through 10/30/96 data.

(ICPRB, questions or comments Roland Steiner/Erik Hagen 301-984-1908)

Figure 6: Model validation of the approximated hydropower operations shown in Figure 5



**Occoquan Reservoir Continuous Model-
modeled vs. historic usable storage.
Test of draft rule curve for hydropwer generation.
UOSAflows modified by monthly production values. Worst-case evaporation.**

Modeled storage calculated using historical releases for water supply withdrawals, hydropower determined using draft rule curve January 19,1999

Figure 7: Occoquan Reservoir critical period storage using an example operating policy

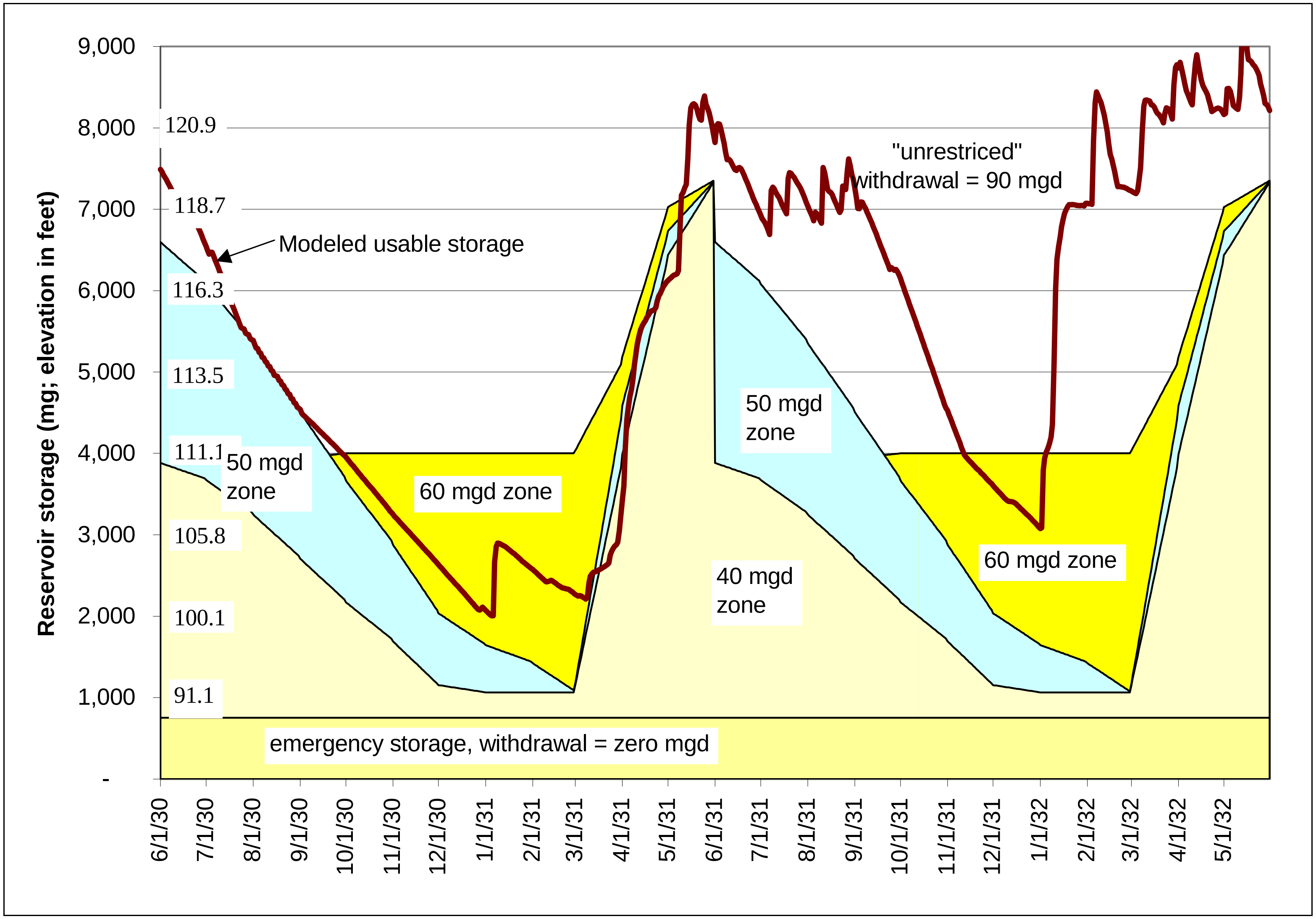
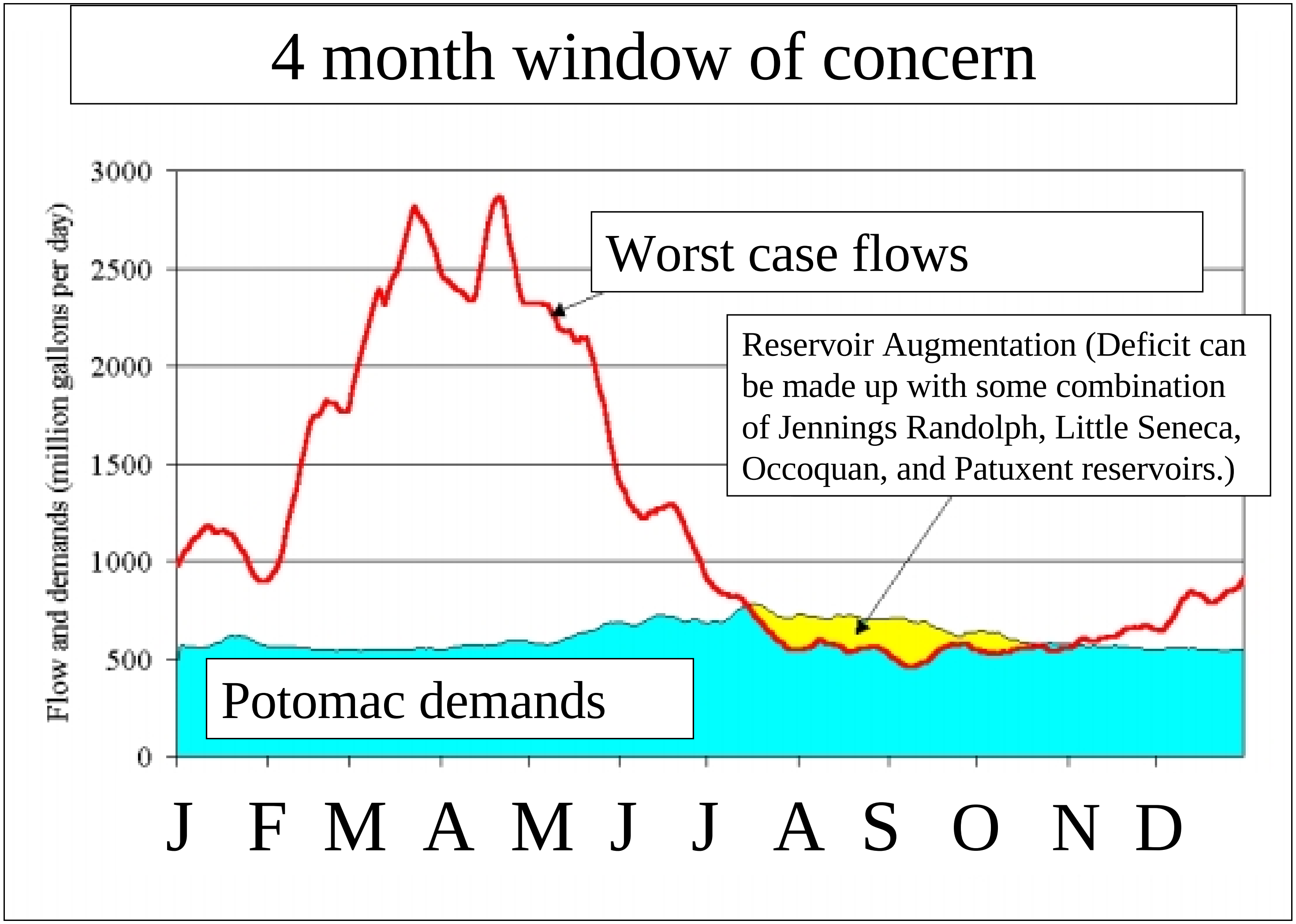


Figure 8: Potomac worst-case flows and current 1999 demands



4 month window of concern

Worst case flows

Reservoir Augmentation (Deficit can be made up with some combination of Jennings Randolph, Little Seneca, Occoquan, and Patuxent reservoirs.)

Potomac demands