2002 Drought Operations and Lessons Learned
Washington Metropolitan Area

Prepared by

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The Section for Cooperative Water Supply Operations on the Potomac

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2002 Drought Operations Report and Lessons Learned Washington Metropolitan Area

Photo credit: Woody Peterson, Washington Aqueduct. View towards Snake Island from the balcony of the Little Falls Intake during low flow conditions on August 19, 2002 (flow of approximately 170 mgd)

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1 Introduction

The Potomac River supplies most of the water for residents of the Washington, D.C. metropolitan area. Drought conditions in summer 2002 required augmentation of flow in the Potomac River from upstream reservoirs for only the second season since the reservoirs were constructed in the early 1980's. Reservoir releases were first required in 1999. Coordination between the three major water suppliers and the Interstate Commission on the Potomac River Basin (ICPRB) went smoothly, and sufficient water was available in the river at all times to meet water supply needs and to maintain the environmental flow recommendation at Little Falls. However, several issues emerged early in the summer and created difficult challenges for managing the Potomac River to meet operational goals.

This report summarizes drought management activities which took place during 2002 and outlines recommendations for improved management in the future. This report is intended to be a resource for utility and CO-OP personnel, who can use the report as a primer to help prepare for future droughts and drought exercises. Personnel change, memories fade, and it is hoped that this report will preserve and archive the lessons learned in 2002 so that future operations can build on the experience of the 2002 operations.

1.1 Overview of metropolitan area water supply system

Three major water suppliers serve the Washington metropolitan area. The U.S. Army Corps of Engineers Washington Aqueduct Division (Aqueduct) wholesales water to the District of Columbia and portions of suburban Virginia. The Fairfax County Water Authority (FCWA) serves most of the remaining Virginia suburbs. The Maryland suburbs in Montgomery and Prince George's counties are served by the Washington Suburban Sanitary Commission (WSSC). These three water utilities share the Potomac River as a source of water. The Potomac is the sole source of water for the Aqueduct. The Patuxent Reservoirs and the Occoquan Reservoir are additional sources of water for WSSC and FCWA, respectively. These reservoirs are located outside of the portion of the Potomac River watershed upstream of Little Falls dam, the site of the most downstream water withdrawal.

Under normal conditions, the three utilities operate independently. However, they have entered into agreements to coordinate operations during drought conditions so that Potomac River water can be shared in the most efficient manner possible. The Section for Cooperative Water Supply Operations of the Interstate Commission on the Potomac River Basin (ICPRB CO-OP) provides technical support to the three utilities to coordinate drought operations.

Two additional reservoirs, Jennings Randolph Reservoir and Little Seneca Reservoir, are available to augment flow in the Potomac when the flow would otherwise be insufficient to meet environmental needs or water supply demand. These reservoirs are shared resources, and the three major water suppliers each contribute to the cost of these facilities. Jennings Randolph Reservoir is the larger of the two, holding 13.4 billion gallons (bg) of water supply storage. The reservoir is over 200 miles upstream of the most downstream water supply intake[1], and releases take over a week to travel that distance. Little Seneca Reservoir is smaller, holding 3.9 bg, but is significantly closer to the metropolitan area's water intakes. Releases from Little Seneca Reservoir take approximately one day to reach the intake locations. This reservoir is used to "fine tune" the larger releases from Jennings Randolph Reservoir, which can then be operated more conservatively.

The Savage Reservoir is located on the Savage River, about 4.4 miles upstream of its confluence with the North Branch Potomac River. The Savage Reservoir is used primarily for water quality purposes. Together, Jennings Randolph Reservoir and Savage Reservoir make up the North Branch system. In 2002, a percentage of the Jennings Randolph water supply release was matched by a concurrent water quality release from Savage Reservoir. The Savage release amounted to approximately 20% of the total water supply request. The Savage matching policy is based on the COE master manuals for the North Branch system, in which a concurrent Savage release during Jennings Randolph releases is authorized for water quality purposes. The continuing implementation of this policy has been formally approved by the Upper Potomac River Commission (UPRC), the owners of Savage Reservoir.

Releases from the jointly owned Jennings Randolph and Little Seneca Reservoirs are recommended by ICPRB CO-OP based on existing and projected water demand, the status of the other reservoirs, and streamflow and weather conditions. The CO-OP Operations Committee, made up of representatives from each utility, provide formal approval of ICPRB CO-OP's recommendations and concurrence is sought before major operational changes.

2 Overview of 2002 Drought Operations

2.1 Hydrometeorological conditions

The 2002 drought had its roots in a large precipitation deficit which grew out of below normal precipitation beginning in September 2001. As seen in Figure 2-1, below normal precipitation occurred from September 2001 through February 2002, resulting in a precipitation deficit of 9.4 inches by the end of February. The precipitation deficit peaked at 10.4 inches below normal at the end of August.

[1] The distance from Aqueduct's Little Falls intake to the North Branch Potomac River at Luke gage is 221.2 miles, to the confluence with the Savage River is 221.4 miles, and to Jennings Randolph Reservoir is 230.4 miles as determined using USGS publication "Water Resources Data Maryland and Delaware," supplemented with a computer mapping program.

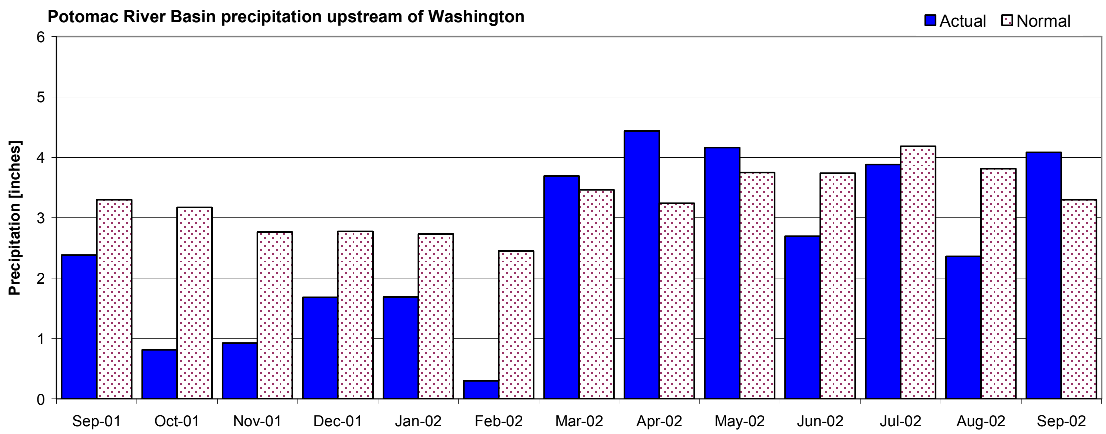

Figure 2-1 Monthly precipitation in the Potomac River Basin, observed in 2001 - 2002 vs. normal. Data courtesy Middle Atlantic River Forecast Center.

Fall and winter rains are generally the most effective for recharging groundwater because evapotranspiration is lowest during these months, allowing water to infiltrate deep into the soils and recharge groundwater. Groundwater responds more slowly than streamflow to precipitation, and low groundwater conditions take many months to develop. Likewise, it can take many months for groundwater levels to recover from low levels. The severe precipitation deficit in fall and winter 2001-2002 resulted in low groundwater levels, and record low levels were being seen by December 2001 at some basin locations. Slightly above normal spring rains were unable to replenish the groundwater and record low groundwater levels persisted into the summer season. Figure 2-2 shows groundwater levels at a monitoring well in Montgomery County. As was typically the case in observation wells throughout the basin, groundwater levels began the calendar year at low levels and did not begin to recover significantly until late in the year.

In the absence of rain, baseflow from groundwater is the main source of streamflow in rivers and low groundwater levels were reflected in streamflow levels in 2002. Figure 2-3 shows streamflow in the Potomac River at Point of Rocks for September 2001 – December 2002. Point of Rocks is the most downstream gaging station before reaching the metropolitan Washington water supply intakes on the Potomac River. Streamflow at Point of Rocks fell below 2000 cfs in September 2001, triggering enhanced monitoring of river flow and water demand which was not lifted until October 2002. Record low flows were seen at Point of Rocks in February and March of 2002. Near record low flows were seen in the summer during dry periods with little rainfall.

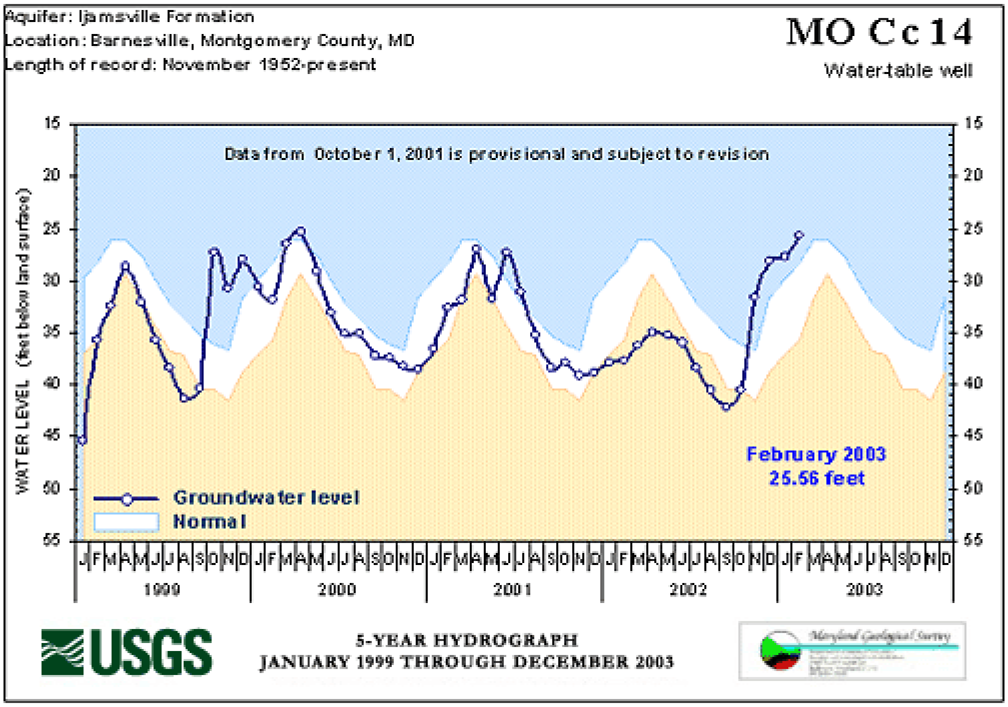

Figure 2-2 Groundwater at a monitoring well in Montgomery County. Groundwater levels were well below normal through most of 2002 and did not begin recovering until late in the year. Figure courtesy United States Geological Survey.

The experience of 2002 verified previous observations that low summer streamflow in the Potomac basin is the product of both low summer rainfall and low antecedent groundwater levels. The dual requirement is illustrated by the events of 1951 and 1966:

> "During the period July through September, nearly identical rainfall totals were recorded in 1951 and 1966, yet in 1966 Potomac River streamflow at Point of Rocks reached a daily minimum of 547 cfs while in 1951 (following a wet fall and winter), the minimum daily flow was 1170 cfs."
>
> *Jim Smith, Dan Sheer, and John Schaake, Jr., "The Use of Hydrometeorological Data in Drought Management: Potomac River Basin Case Study, International Symposium on Hydrometeorology, AWRA, p. 350, June 1982.*

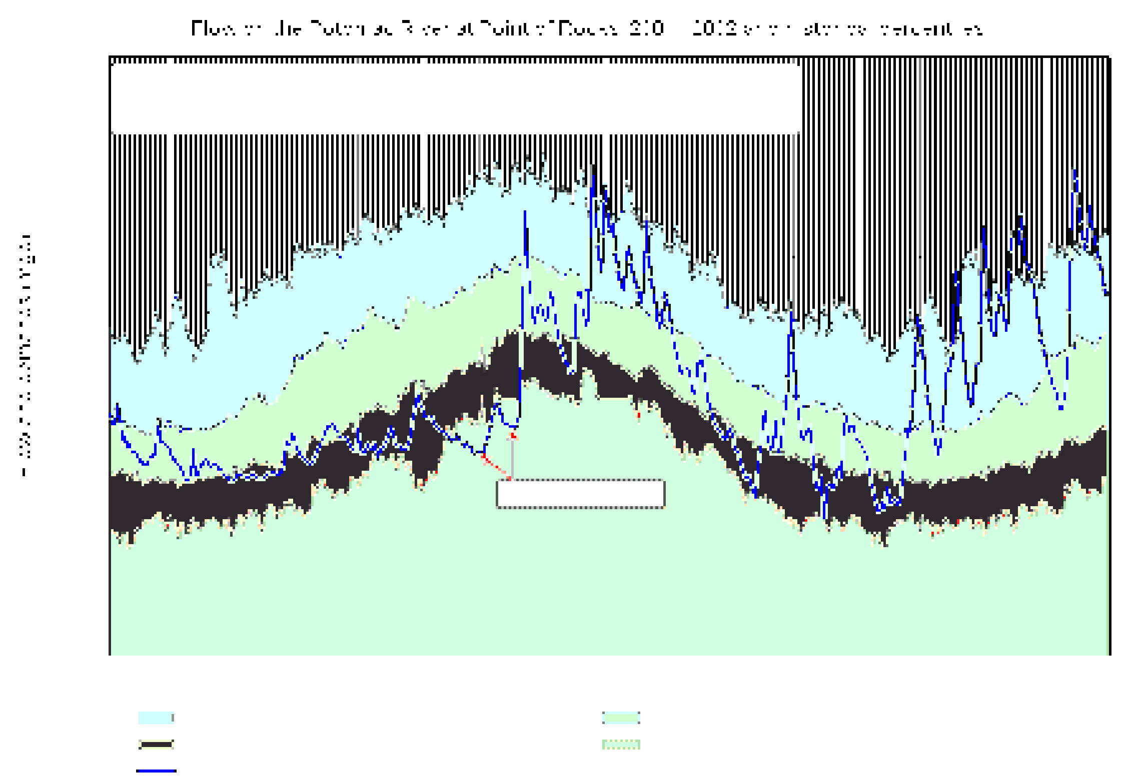

Figure 2-3 Streamflow on the Potomac at Point of Rocks, MD. Flow fell below 2000 cfs in September 2001, triggering enhanced flow monitoring. While springtime flow was in the normal range, low baseflow brought the river back down to near record low levels during dry periods during the summer.

2.2 Reservoir releases

During the summer, low streamflow at times necessitated augmentation of Potomac River flow from upstream reservoirs. The first release was made on July 12, 2002. This small release was discontinued on July 14, 2002 due to a basin wide rain event. Releases began in earnest on August 13, 2002 and continued, off and on, from both Jennings Randolph and Little Seneca Reservoirs through September 22, 2002. From late September until the end of the calendar year, many runoff producing rain and snowmelt events kept streamflow above levels requiring flow augmentation. The complete schedule of releases from each reservoir is given in Table 2-1. The table also shows water quality releases from Savage Reservoir which were made to match a percentage of the Jennings Randolph water supply releases. The release rates shown for both Jennings Randolph and Savage Reservoir are estimates based on the Luke flow target requested by ICPRB. The release rates recorded by the COE were not always the same as those listed here. These differences arise because of differences between the gage flow at Luke and measured outflow rates from the reservoirs. In part, the discrepancies between measured flow at Luke and measured reservoir outflow rates can be attributed to different 24-hour periods used to calculate daily averages by the USGS at the Luke gage and by the COE at the reservoir outflow facilities.

Table 2-1 Releases from Jennings Randolph and Little Seneca Reservoirs in 2002 (mg).

	Water Supply Releases [mg]		Water Quality [mg]		Water Supply Releases [mg]		Water Quality [mg]
	Jennings Randolph	*Little Seneca*	*Savage WS match*		*Jennings Randolph*	*Little Seneca*	*Savage WS match*
7/1/02	0	0	0	8/16/02	79	47	20
7/2/02	0	0	0	8/17/02	0	45	0
7/3/02	0	0	0	8/18/02	0	0	0
7/4/02	0	0	0	8/19/02	187	15	47
7/5/02	0	0	0	8/20/02	270	86	68
7/6/02	0	0	0	8/21/02	270	78	68
7/7/02	0	0	0	8/22/02	230	25	58
7/8/02	0	0	0	8/23/02	230	0	58
7/9/02	0	0	0	8/24/02	230	0	58
7/10/02	0	0	0	8/25/02	196	0	49
7/11/02	0	0	0	8/26/02	161	0	40
7/12/02	0	10	0	8/27/02	161	0	40
7/13/02	0	65	0	8/28/02	161	0	40
7/14/02	0	25	0	8/29/02	109	0	27
7/15/02	0	0	0	8/30/02	109	0	27
7/16/02	0	0	0	8/31/02	109	0	27
7/17/02	0	0	0	9/1/02	0	0	0
7/18/02	0	0	0	9/2/02	0	0	0
7/19/02	0	0	0	9/3/02	0	0	0
7/20/02	0	0	0	9/4/02	0	0	0
7/21/02	0	0	0	9/5/02	0	0	0
7/22/02	0	0	0	9/6/02	120	0	30
7/23/02	0	0	0	9/7/02	120	0	30
7/24/02	0	0	0	9/8/02	120	0	30
7/25/02	0	0	0	9/9/02	240	75	60
7/26/02	0	0	0	9/10/02	240	125	60
7/27/02	0	0	0	9/11/02	187	100	47
7/28/02	0	0	0	9/12/02	187	50	47
7/29/02	0	0	0	9/13/02	187	100	47
7/30/02	0	0	0	9/14/02	187	50	47
7/31/02	0	0	0	9/15/02	135	0	34
8/1/02	0	0	0	9/16/02	135	0	34
8/2/02	0	0	0	9/17/02	135	0	34
8/3/02	0	0	0	9/18/02	135		34
8/4/02	0	0	0	9/19/02	135		34
8/5/02	0	0	0	9/20/02	135	0	34
8/6/02	0	0	0	9/21/02	103	0	26
8/7/02	0	0	0	9/22/02	103	0	26
8/8/02	0	0	0	9/23/02	0	0	0
8/9/02	0	0	0	9/24/02	0	0	0
8/10/02	0	0	0	9/25/02	0	0	0
8/11/02	0	0	0	9/26/02	0	0	0
8/12/02	0	0	0	9/27/02	0	0	0
8/13/02	0	10	0	9/28/02	0	0	0
8/14/02	0	35	0	9/29/02	0	0	0
8/15/02	0	35	0	9/30/02	0	0	0
				TOTAL	5,105	976	1277

Flow is measured on the Potomac River at Little Falls. This gage measures streamflow just after the most downstream water supply withdrawal has been made. A minimum flow recommendation of 100 mgd applies to flow in the Potomac just downstream of Little Falls and is included within WSSC's permit for water withdrawal. As shown in Figure 2-4, the flow at Little Falls exceeded the environmental flow recommendation throughout the 2002 reservoir release period. The minimum daily average streamflow observed at Little Falls during 2002 was 166 mgd, experienced on August 20. There is also a minimum flow recommendation for the Potomac River between Great Falls and Little Falls. Drought impacts on this stretch of the river are discussed more fully in Section 4.8.

Reservoir releases used to augment Potomac flow lowered the water supply storage in Jennings Randolph and Little Seneca Reservoirs. The cumulative amount of water released from both reservoirs was 6.1 bg and dropped combined storage to a minimum of 11.1 bg (65% full) on September 22, 2002. Figure 2-5 shows the combined water supply storage in both reservoirs throughout 2002, and compares reservoir storage in 2002 with modeled storage under hydrological conditions experienced during the worst recorded historical drought of 1930. The figure shows that the drought of 1930 would have caused reservoir storage to drop lower than it did in the 2002 drought, and that reservoirs would not have refilled as quickly.

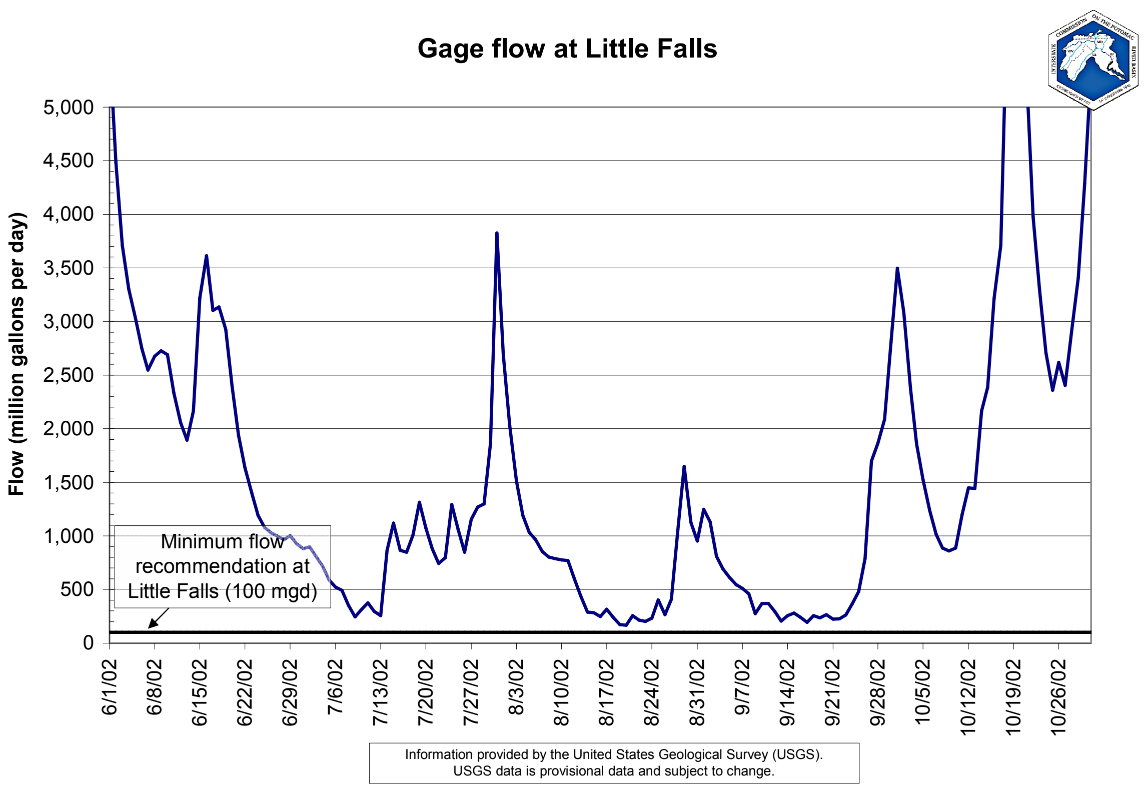

Figure 2-4 Summer and fall gage flow at Little Falls. Flow in the Potomac River at Little Falls exceeded the environmental flow recommendation throughout the reservoir release season.

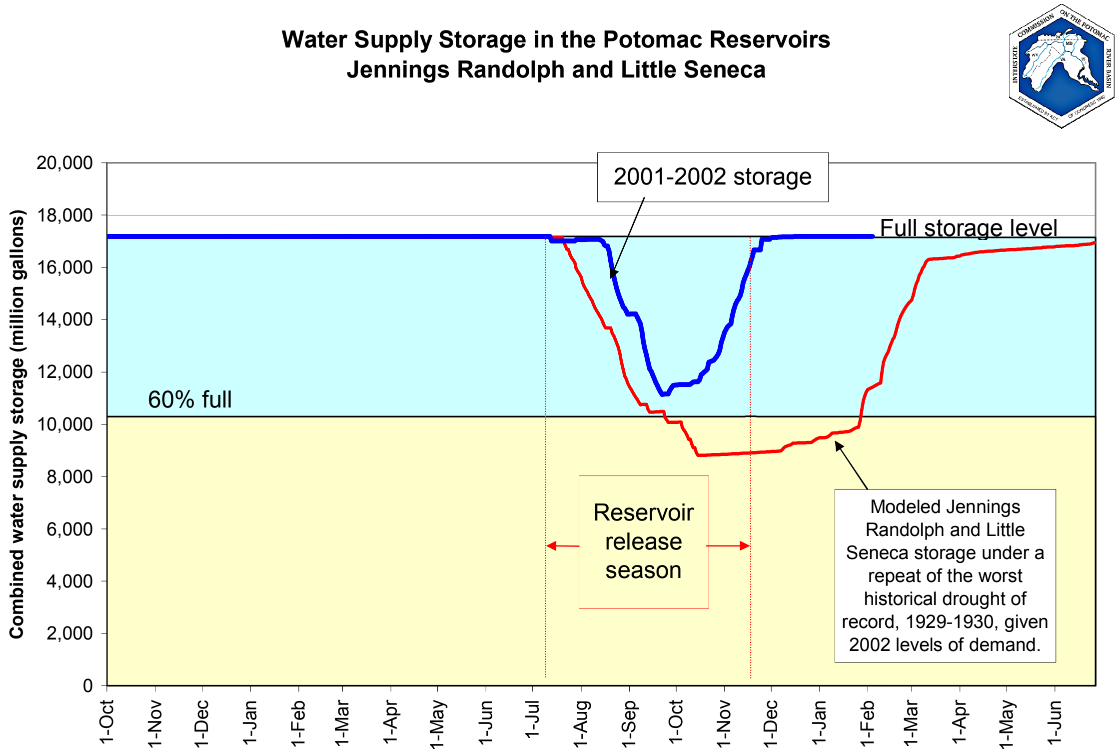

Figure 2-5 Water supply storage at Jennings Randolph and Little Seneca Reservoirs, 2002. Combined storage reached a minimum of 11.1 bg (65% full) on September 22, 2002.

Figure 2-6 shows the flow that would have occurred at Little Falls in the absence of any reservoir releases. The calculation of the relative contributions of water quality and water supply releases to flow at Little Falls is somewhat inexact because of the travel time between the North Branch system and Little Falls. The operational flow target of 200 mgd that was used at Little Falls in 2002 incorporated a large safety factor of 100 mgd because of the operational issues that are discussed in subsequent sections of this report.

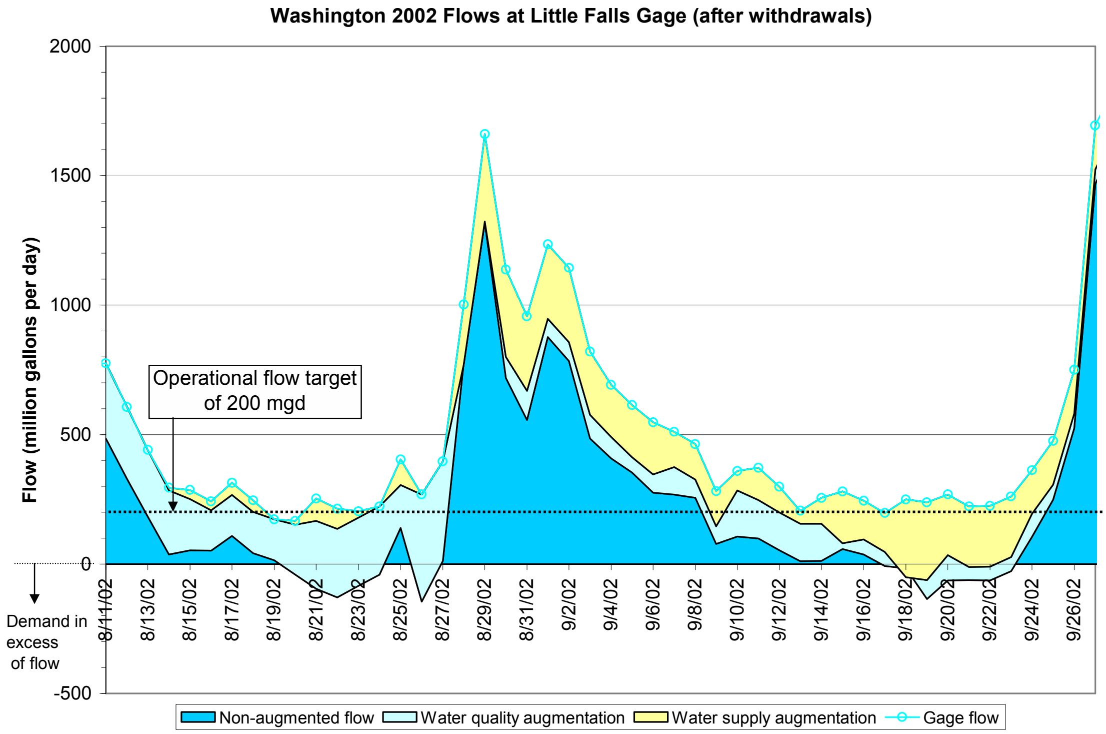

Figure 2-6 Flow that would have occurred at Little Falls in the absence of water quality and water supply releases augmenting Potomac River flow.

In 2002, the efficiency of water supply releases was about 33 percent, i.e., about 33 percent of the water released from the reservoirs for water supply purposes was actually needed to meet the Little Falls flow target being used. This level of efficiency is in line with that modeled by the Potomac Reservoir and River Simulation Model (PRRISM) for other historical drought events. The augmentation of river flow to meet water supply and environmental flow requirements is inherently inefficient because of the travel time between the reservoirs and the water supply intakes. In the intervening time between a water supply release and the release's arrival at the water supply intakes, flow conditions or the level of demand may develop differently than was forecast because of rain or other factors.

2.3 Natural Potomac River flow at Little Falls

The gage record at Little Falls for 2002 was adjusted to remove the effects of upstream human influence, including effects from upstream withdrawals, upstream regulation by Savage, Jennings Randolph, and Little Seneca reservoirs, and upstream augmentation by Little Seneca wastewater treatment plant. The lowest natural daily low flow calculated for the drought of 2002 was 385 mgd on September 19, 2002.

Prior to 2002, the USGS reported minimum flow at Little Falls, adjusted for diversion but not upstream regulation, was 388 mgd, occurring on September 10, 1966 (USGS, Water

Resources Data, Maryland and Delaware, 2000)[2]. ICRPB further adjusted this 1966 flow to simulate natural flows by adjusting the record to account for upstream regulation by Savage Reservoir. The resulting natural low flow in 1966 was approximately 351 mgd. Thus, while natural 2002 flow approached the low flow record set in 1966, it did not fall below it.

Additional details of this analysis are included as Appendix B.

2.4 Public information

One of the lessons learned in the 1999 drought was the necessity for education and sharing of information to as wide an audience as possible. Proactively sharing this information via an electronic mail distribution list in 2002 greatly reduced time spent on the phone answering drought related questions from reporters, state and local government agency personnel, and the general public. Getting information out early and often also helped ensure that drought related policy developed by local jurisdictions was consistent with and informed by the hydrology and science. Public information was a critical part of drought operations.

Throughout drought operations, the public and interested parties were updated on a daily basis through information posted on the ICPRB website and through daily emails describing current conditions. In addition, a press release was prepared by ICPRB when the first reservoir release was made on July 12, 2002. Appendix A contains this press release, a distribution list for the daily water supply status reports issued by electronic mail, and all of the daily updates for the 2002 release season.

ICPRB CO-OP and the metro area water suppliers coordinated with the Metropolitan Washington Council of Governments (MWCOG) on drought response plans. The drought plan includes various stages of alert, the first of which is a WATCH phase. The WATCH phase was entered into on February 20, 2002 and lifted November 22, 2002. The area served by the CO-OP water utilities never reached a higher level of alert during the 2002 drought event.

3 Daily operational procedures

A number of management decisions were made daily in order to ensure an adequate flow of water in the Potomac River to meet water supply needs and the minimum environmental flowby. These decisions included reservoir releases from either Jennings Randolph Reservoir or Seneca Reservoir, load shifting at Occoquan or Patuxent Reservoirs, and load shifting between the Aqueduct's Great Falls and Little Falls intakes. This section outlines the daily operational procedures for making these decisions in 2002.

[2] The daily discharge observed at the Little Falls gaging station on the same day (September 10 1966) was lower at 152 cfs (98 mgd), but this measurement did not include upstream diversions of 449 cfs (290 mgd). The minimum flow, adjusted for diversion, is simply the measured gage flow of 152 cfs (98 mgd) plus upstream water supply diversions not yet returned to the river at Little Falls of 449 cfs (290 mgd), equaling the reported minimum flow of 388 mgd.

Each day, management activities began with the collection of demand estimates from each water utility and the latest flow conditions from the USGS. Each utility assigned personnel to email the day's predicted demand to ICPRB CO-OP staff. Real time flow at Little Falls and other Potomac watershed gaging stations was available from the USGS web site. Depending on the station, flow was updated approximately every 4 hours. In addition, river stage at Little Falls could be accessed by phone via the automated Handar reporting unit. The Handar unit could be used to obtain current stage and recorded stage at 15-minute increments. The Handar unit's reported stage tended to drift slowly, by perhaps a few hundredths of a foot over a few days. While this led to uncertainty in translating the Handar stage to an absolute flow value, the information provided by the Handar unit provided useful information on the latest trend in flow. In addition, the Handar unit was set up to automatically alert ICPRB when flow conditions fell below a specified threshold. The Handar unit was set up to dial WSSC's operations control center, and WSSC personnel were then to contact ICPRB COOP staff. This system of alert was tested successfully.

After obtaining morning demand estimates and flow data, a prediction of the day's average daily flow was made. This prediction was used to adjust the Aqueduct's withdrawals from Great Falls and Little Falls, set the previous night, if necessary. Next, the flow for the following day was estimated and used to adjust the Little Seneca release, if necessary. Changes in Little Seneca release rates were communicated to WSSC staff by telephone.

Load shifting from the Potomac River to WSSC's Patuxent reservoirs or FCWA's Occoquan Reservoir was also adjusted based on daily flow predictions. Load shifting between the Potomac and off-Potomac resources attempted to minimize drawdown of the off-Potomac reservoirs when water was available in the Potomac (for example, after a runoff producing rain event), and to balance the use of storage in the Potomac water supply reservoirs and the off-Potomac reservoirs. The overall drawdown of the off-Potomac reservoirs was set so that sustainable withdrawals estimated from rule curves were not exceeded. Load shifting at either WSSC or FCWA was communicated by telephone.

Predictions of both the current day's and next day's flows were based on recent trends in flow, and any changes to that trend that could be expected due to recent precipitation or alterations to reservoir release rates. Stage data at the FCWA intake was requested as an additional management tool. This gage could not be directly related to flow until after the drought and a stage-rating curve could be established. However, it was useful as an intermediate gaging location between Point of Rocks and Little Falls and when possible, was used as an aid to tracking peaks and dips in the hydrograph as they moved downstream. Stage data was also available at WSSC, but the stage levels did not vary as flow changed during the days for which data were provided. WSSC stage data did not yield useful information and subsequently were not used.

Jennings Randolph Reservoir is 230.4 miles upstream of the Aqueduct's Little Falls intake, and releases take about 9 days to travel that distance. In order to determine necessary releases from the North Branch system, the flow at Little Falls in 9-days time was forecast every morning. This forecast was based on current release rates in the North Branch system and trends in tributary and main stem flows on the Potomac. (See also Section 4.9, Predicting Little Falls flow…) If necessary, release rates from water supply storage in Jennings Randolph Reservoir were adjusted. Recent rainfall was also considered in making these decisions. To some degree, forecasted precipitation influenced release decisions from Jennings Randolph Reservoir. However, precipitation forecasts for the summer months are often highly uncertain. For example, the storm on July 13-14, 2002 brought 1 to 2 inches of precipitation basin wide, allowing the suspension of water supply releases. The day before the rain commenced, forecasters were predicting only about 1/10th of an inch of rain. In other cases, early forecasts of significant rain did not materialize due to changing meteorological conditions.

Based on the factors discussed above, a target flow rate for the North Branch Potomac River at Luke, MD was determined that would be sufficient to meet water supply needs. If the target flow was larger than the current water quality release, a new Luke target for water supply purposes was communicated by phone to staff at the U.S. Army Corps of Engineers, Water Quality Control Section in Baltimore, MD. Corps of Engineers staff then relayed operational changes to operators at North Branch system reservoirs. Release decisions were made by 10 am each day. This schedule allowed time for COE staff to implement the changes and also allowed ICPRB CO-OP staff time to compile data and obtain concurrence on release decisions from the CO-OP Operations Committee.

The flow at Little Falls was monitored throughout the day to guard against sharp, unexpected changes. If necessary, operations were adjusted to reflect changing river conditions. Most commonly, changes to Aqueduct load shifting or Little Seneca release rates could be made at any time during the day. In late afternoon or early evening, a prediction of flow at Little Falls for the following day was made in order to determine appropriate Aqueduct withdrawals from Great Falls and Little Falls for the following day. The Great Falls and Little Falls flow targets were then communicated to Aqueduct personnel and adjustments to the withdrawal rates were made at the intake facilities by midnight. The recommended Great Falls and Little Falls withdrawal rates were calculated using a 30 mgd safety factor.

While a critical component of water management activities, the daily flow predictions utilized in the procedures described above were subject to significant uncertainty. This and other operational issues are discussed in the following section.

4 Operational issues

Several important issues affecting water supply management emerged during summer 2002. One issue concerned the accuracy of existing tools for estimating the probability of reservoir releases later in the summer. Additional issues also arose which more directly impacted efficient water supply management. These involved time of travel in the river, flow volatility, an apparent water loss in the river between Point of Rocks and Little Falls, as well as gaging issues and difficulty in resolving conflicting information. Each of these issues is discussed in more detail below, including recommendations for addressing these issues and improving future water supply management.

4.1 Early prediction of future reservoir releases

In the late spring and early summer, ICPRB CO-OP estimates the probability of reservoir releases in the following summer/fall release season. These estimates are calculated by comparing recent Potomac flows to historical flows. However, because of a relatively wet April and May in 2002, streamflow in early June was at a normal level. Low groundwater levels were masked by the recent runoff producing rain events, and the model predicted approximately normal probabilities of reservoir releases for the subsequent release season.

Recommendation:
Preliminary work has indicated that precipitation in the 12 month period June 1 to May 31 may indeed provide improved prediction of summer reservoir releases. A better predictor of reservoir releases might be developed by incorporating information on groundwater levels and longer term records of precipitation and streamflow than are used in the current model. Continued study of the use of precipitation and other possible predictors, such as groundwater levels, may provide improvements to the current method for producing early warnings of potential summertime reservoir releases.

4.2 Little Falls rating curve at low flow

The completion of a new fish passageway at Little Falls in January 2000 altered the stage-discharge relationship for low flow events at Little Falls. However, before summer 2002, flows did not reach sufficiently low levels to allow measurement of stage and discharge at low flow levels. Consequently, the USGS stage-discharge rating curve did not cover low flows in early summer 2002. The USGS was able to take measurements during low flow periods on July 9 and August 20. These additional measurements allowed the update of the rating curve to account for the fish ladder effects on low flows. The updated rating curve was applied to the real time data for the entire low flow season, resolving the issue.

4.3 Uncertainty in Point of Rocks gage

The streamflow gage on the Potomac River at Point of Rocks, MD is subject to the effects of submerged aquatic vegetation. When there is significant growth of aquatic grasses, the flow velocity decreases and the river stage increases to accommodate the same volumetric flow rate. Thus, the stage-discharge rating curve at Point of Rocks changes as submerged aquatic vegetation grows and later dies off. As grass is growing, the gage tends to over-register flow because of the grasses' tendency to raise stage.

The USGS regularly measures flow at Point of Rocks during the summer to track changes in the growth of aquatic grasses, and applies an adjustment to the stage-discharge rating curve to obtain a better estimate of the flow. However, even with these adjustments, the uncertainty in gage flow increases when grass is present. Consequently, the reliability of the Point of Rocks gage may be suspect during periods of heavy aquatic vegetation growth. In such periods, it can be difficult to distinguish between grass effects and real changes in flow. The problem was compounded in summer 2002 because of an apparent water loss between Point of Rocks and Little Falls, discussed in Section 4.5.

Operational recommendations:
Estimates of flow at Point of Rocks based on upstream gages should be compared to the reported gage flow regularly as a means of assessing the accuracy of the Point of Rocks gage. The installation of temporary stage measurement devices in the stretch of the river upstream of the mouth of Seneca Creek is also recommended to better anticipate low flow conditions.

4.4 Time of travel

The time required for a release from Little Seneca Reservoir to reach the metropolitan area water intakes was not well documented prior to 2002, as only one small previous release had been made in 1999 for water supply purposes. Test releases in the 1980's, discussed below, documented the travel time of larger releases from Seneca Reservoir to the Potomac River. However, the travel time of a release from the mouth of Seneca Creek to Little Falls was not addressed. Uncertainty in this time of travel makes it difficult to time releases from Little Seneca Reservoir so that they can be used most efficiently. It was difficult to see the arrival of Little Seneca releases at the Little Falls gage in part because Seneca releases were often small when compared to flow in the river. However, even the larger releases tended to be swallowed by other fluctuations in flow due to Little Falls pumping, storm runoff, Jennings Randolph releases, or other causes. Possibly, waves resulting from the Seneca releases were severely dampened upon entering Seneca pool.

Although we do not have information on the total travel time from Little Seneca Reservoir to Little Falls, we have been able to observe the travel time of waves for portions of this distance.

On September 9, 2002, a Little Seneca release was begun at the rate of 125 mgd at 9 – 10 am. The beginning of the release was observed at Seneca Creek at Dawsonville at about 5 pm, 7-8 hours later. The stage at the FCWA intake, across the river from the mouth of Seneca Creek, began to rise at about 10 pm, a total of 12-13 hours after the release began. The intake is actually located slightly upstream of the mouth of Seneca Creek but is located within the same pool of water backed up by Feeder Dam #2, a rubble dam developed for the C&O Canal. The observation that a Seneca release affected stage at the FCWA intake indicates that a Seneca release raises the stage within the pool, which then increases the rate at which water flows over the dam. The degree to which this slows down and dampens the flood wave is unknown. However, a distinct increase in flow due to the reservoir release was not observed further downstream.

The travel times of test releases from Little Seneca were measured in 1986 and 1989. Flow in Seneca Creek at Dawsonville measured about 65 mgd on April 24, 1989. A 310 mgd release on April 25, 1989 took 5-6 hours to reach the mouth of the creek. Another test in 1986 at lower flows in the creek took longer to reach the Potomac River. An estimate of 10 hours was provided for the travel time of Little Seneca releases during lower flow periods (memo from Steve Gerwin to John Corless, WSSC, 1989 as reproduced in ICPRB report 99-3).

Versar collected stage data in the Potomac River during summer 2002 as part of a data collection program for reevaluation of the environmental flow recommendation. As seen in Figure 4-1, this data shows that the travel time between Old Angler's Inn and Little Falls is about 6-7 hours. Old Angler's Inn is about 7-8 miles upstream of Little Falls, and 2-3 miles downstream of Great Falls. The total travel time from Great Falls to Little Falls is probably about 9-10 hours.

The observed travel time of waves from Little Seneca Reservoir to the FCWA intake is about 12-13 hours during low flow, and the estimated travel time from Great Falls to Little Falls is about 9-10 hours. The travel time in the 8 mile stretch between FCWA's intake and Great Falls has not been documented. Further, it is unknown how much of an effect Seneca pool has on slowing down and dampening the wave. However, as this stretch of the river generally has a smaller slope and is slower moving than the stretch of comparable distance between Old Angler's Inn and Little Falls, the travel time must be at least as long as the travel time from Old Angler's Inn to Little Falls. Based on this assumption, the travel time between FCWA's intake and Great Falls is probably at least 6-7 hours. Using this estimate, the total travel time of a Little Seneca Reservoir release to Little Falls is 12-13 hours, plus 6-7 hours, plus 9-10 hours for a total of at least 27-30 hours.

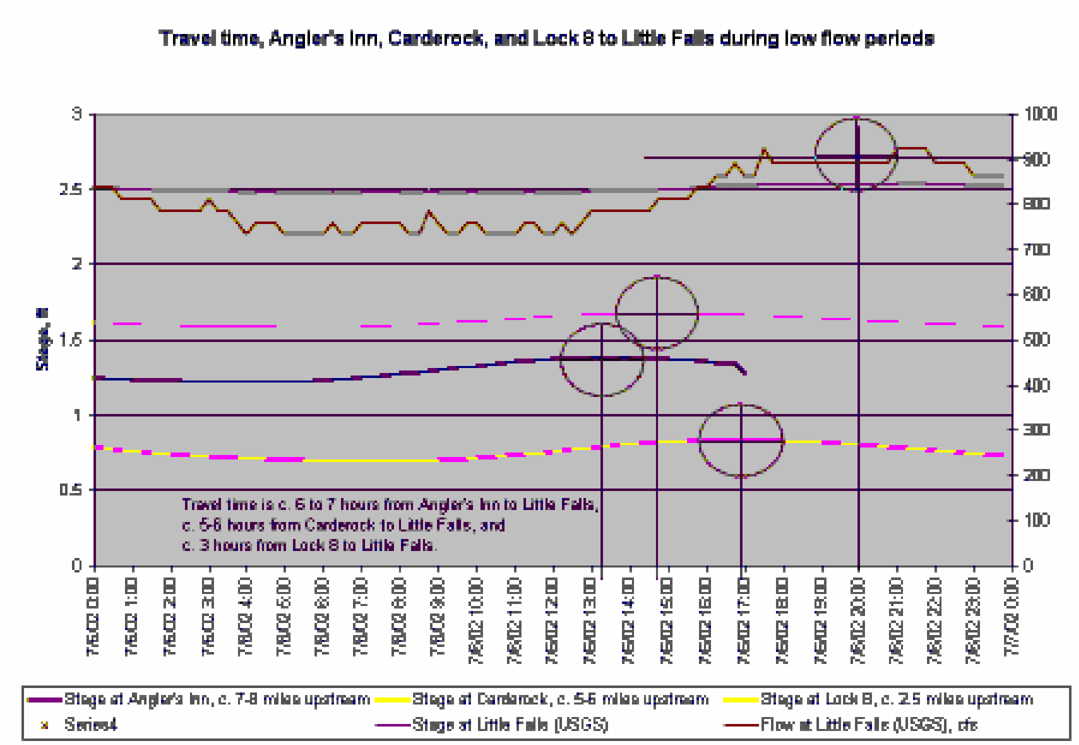

Figure 4-1 Stage measured by Versar at locations between Great Falls and Little Falls, along with USGS measured stage and flow at Little Falls.

<u>Operational Recommendation</u>:
Additional gaging in the river between Seneca pool and Little Falls may yield better information on the travel time of Seneca releases. Locations which are not directly affected by Aqueduct operations may be especially useful in detecting releases. It would also be beneficial to monitor Potomac River stage upstream of the mouth of Seneca Creek so that Seneca releases can be timed to fill in troughs in river flow and can be suspended as soon as river flow rises. In summer 2002, it was impossible to anticipate changes in river flow conditions with the precision necessary to most efficiently utilize Little Seneca Reservoir.

Test releases are recommended the next time flows are low in the late fall and reservoirs are full. Ideally, temporary gages could be in place to help monitor the river at strategic locations.

4.5 Water Loss between Point of Rocks and Little Falls

The Washington metropolitan area's Potomac water supply intakes are located between Potomac River gaging points at Point of Rocks and Little Falls. In early July, it was noted that there was an apparent water loss between these two gaging stations. The estimate of Little Falls flow was calculated using flows from the Point of Rocks gage, with adjustments for withdrawals and intervening inflows between Point of Rocks and Little Falls. This estimate of Little Falls flow was as much as 150 mgd higher than the recorded flow at the Little Falls gage. This discrepancy implied that water was being lost between the Point of Rocks and Little Falls gaging stations.

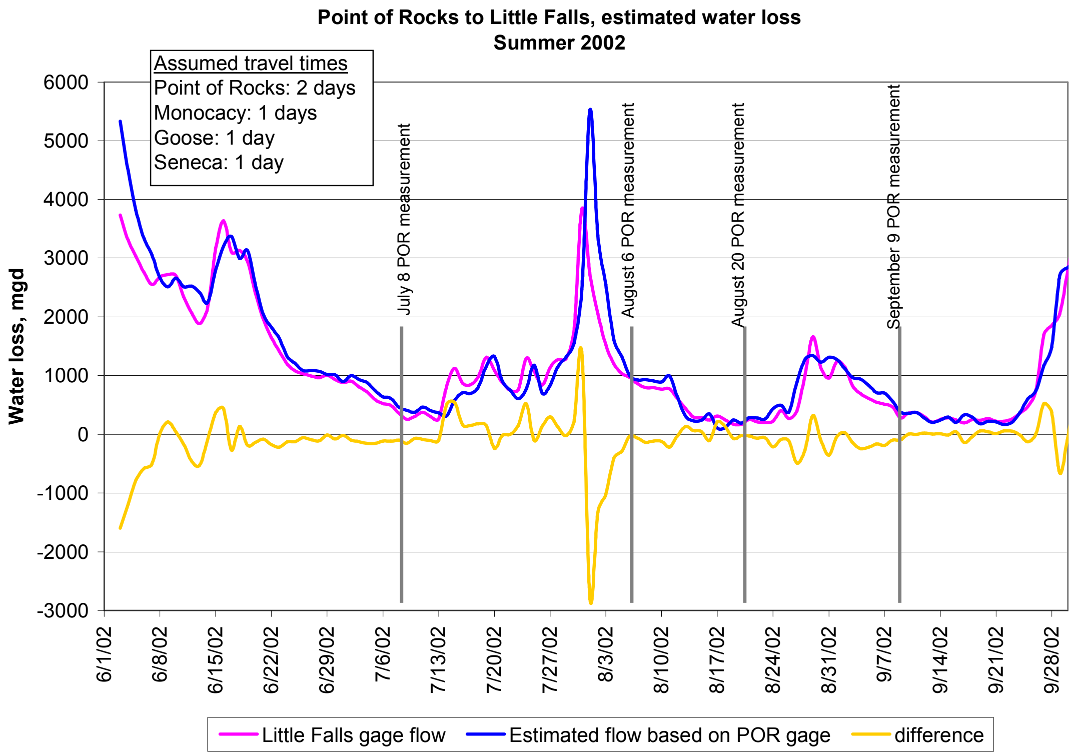

Figure 4-2 Estimated water loss between Point of Rocks and Little Falls, June 1, 2000 – September 30, 2000. Data source: USGS provisional data, FCWA, WSSC, Aqueduct

The water balance calculations require an estimate of the travel time between different points along the river. In general, shorter travel times generated the smallest estimates of water loss, whereas longer travel times generated the largest estimates of water loss.

Figure 4-2 shows the magnitude of the loss in the period June 1 – September 30 using the most likely estimate of travel time between Point of Rocks and Little Falls at low flows. In the figure, a negative difference between the estimated and observed Little Falls flows indicates an apparent water loss. As can be seen, the peaks in the observed Little Falls hydrograph do not always match the peaks in the hydrograph estimated by lagging Point of Rocks and other upstream flows. In some cases, inaccuracies in travel time produce clear overestimates or underestimates of the Little Falls flow. For example, from July 31 – August 1, the rapid shift from a calculated difference of +1500 mgd to -3000 mgd is clearly a result of errors in the estimation of travel time. However, it is difficult to correct for all of these errors because the travel time depends on the flow rate. While a travel time of 1 day or less may be appropriate for large peaks such as was observed on July 31, it is not appropriate for steadier flow conditions at flow rates of 1000 mgd or less.

The effects of travel time can be illustrated by focusing on the period June 25, 2002 to July 12, 2002, a period in which flows were consistently less than 1200 mgd and diminishing slowly. If we assume that all upstream gage flows and the effects of withdrawals instantaneously reach the Little Falls gage, i.e., that the travel time is zero, then the average water loss for this period is 7 mgd. While this provides a lower bound on the possible magnitude of water loss, in reality, we know that there is some travel time between the upstream gage locations and Little Falls. To obtain an upper bound on the possible magnitude of water loss, we assumed that the travel time from Point of Rocks is 3 days, the upper limit of our estimates of reasonable travel time. Using this estimate of travel time, the water loss for the period averages 156 mgd. Table 4-1 shows the estimated water loss for the period given various estimates of travel time. Figure 4-2 compares the estimated and observed flow at Little Falls with an assumed travel time of 2 days from Point of Rocks to Little Falls. The small peaks and troughs match nicely in the latter part of the hydrograph shown, and it was felt that 2 days was the best estimate of travel time from Point of Rocks to Little Falls at flows less than about 1200 mgd. Travel time in part of this stretch of river is discussed further in the section on the time of travel of Little Seneca releases. Over the period June 25 – July 12, the average water loss was 99 mgd for a travel time from Point of Rocks of 2 days.

Table 4-1 Average water loss from June 25, 2002 – July 12, 2002 for different assumptions about travel time to Little Falls from upstream gages. Our best estimate of the actual travel time is highlighted.

Assumed travel times to Little Falls	Average water loss, June 25, 2002 – July 12, 2002 Point of Rocks to Little Falls
Point of Rocks: 3 days Monocacy: 2 days Goose: 1 day Seneca: 1 day	156 mgd
Point of Rocks: 2 days Monocacy: 1 day Goose: 1 day Seneca: 1 day	99 mgd
Point of Rocks: 1 day Monocacy: 1 day Goose: 1 day Seneca: 1 day	55 mgd
Point of Rocks: 0 days Monocacy: 0 days Goose: 0 days Seneca: 0 days	7 mgd

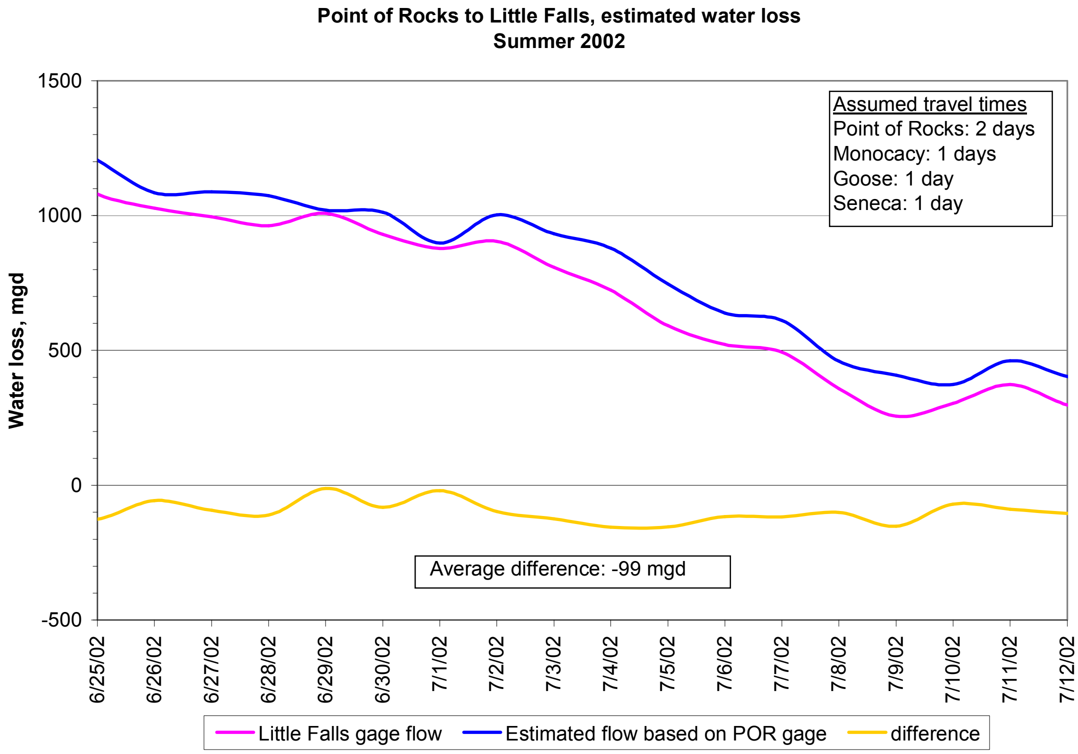

Figure 4-3 Little Falls flow as observed at the USGS gage and as estimated based on the Point of Rocks (POR) USGS gage for June 25, 2002 – July 12, 2002. The difference is the estimated water loss for the assumed travel times shown. Over the entire period, there was an apparent water loss of 99 mgd

A number of possible explanations were advanced to account for the water loss. They included:

- Gage error
- Unknown withdrawals
- Evaporation from river surface
- Infiltration of river water into adjacent alluvial aquifer
- Infiltration of river water due to geologic fractures or other conditions.

Each of these possible explanations are discussed briefly below.

4.5.1 Gage error

Section 4.2 noted that problems were encountered with the Little Falls rating curve during summer 2002, due to the installation of a fish ladder and the lack of available data to calibrate at low flow. During low flow periods in 2002, the USGS was able to measure flow at Little Falls and update the rating curve to account for fish ladder effects at low flows. The updated rating curve was applied to the real time data for the entire low flow season and thus Little Falls data is believed to be accurate to normal gage precision.

As noted in Section 4.3, the Point of Rocks gage has the tendency to over-register flow when submerged aquatic vegetation is growing in the channel. Consequently, the USGS regularly measures flow at Point of Rocks during the summer and adjusts the rating curve to account for grass growth.

According to Bob James, Section Chief of the Surface Water Analysis section at the Maryland-Delaware-District of Columbia District USGS Office, measurements of flow are generally accurate to within about 5% of the actual flow value. However, when submerged aquatic vegetation is prevalent, the uncertainty rises to about 10%. The time period from June 25 – July 12 can be used to illustrate the possible effects of gage error. Flows from June 25 – July 12 at Point of Rocks ranged from 800-1500 mgd, while the estimated water loss averaged 99 mgd for this period. Flow was measured at Point of Rocks on July 8, 2002, near the end of this time period. At this time, there was no recorded effect by aquatic vegetation and the uncertainty in Point of Rocks gage flow can be estimated at about 5%. If the Point of Rocks gage were overestimating by 5% and the Little Falls gage was exactly correct, gage error at Point of Rocks would explain 40- 75 mgd of the apparent water loss, depending on the actual flow on a particular day. Flow at Little Falls during this time period ranged from 250-1100 mgd. A 5% underestimation at that gage would explain an additional 13-55 mgd of the apparent water loss, again depending on the specific flow conditions. In total, gage error could explain as much as 50 – 130 mgd of the difference between the observed and estimated flow at Little Falls on some days during the June 25 – July 12 time period. The difference between observed and estimated flows ranged from -10 mgd to -160 mgd for that period. Thus, at the outer limit, it is possible that on some days, gage error accounts for the apparent water loss in its entirety. However, the actual magnitude of any gage error is unknown and could be considerably smaller, or even work in the opposite direction.

One means of further evaluating gage error is to conduct a similar water balance analysis on the stretch of river upstream of Point of Rocks. The Shepherdstown gage is located about 24 miles upstream of Point of Rocks. Antietam Creek and the Shenandoah River are the main tributaries entering the Potomac River between Shepherdstown and Point of Rocks. Had gage error at Point of Rocks been responsible for the apparent water loss from Point of Rocks to Little Falls, we would expect to see an apparent water gain from Shepherdstown to Point of Rocks. Instead, as shown in Figure 4-4, there was also a consistent water loss in this stretch of the river through much of the June 25 to July 12 period. While this does not rule out the possibility that gage error at Little Falls, Shepherdstown, and the Potomac tributaries coincidentally created an apparent water loss along the entire stretch of river, it does lend significantly more confidence to the estimated water loss calculations.

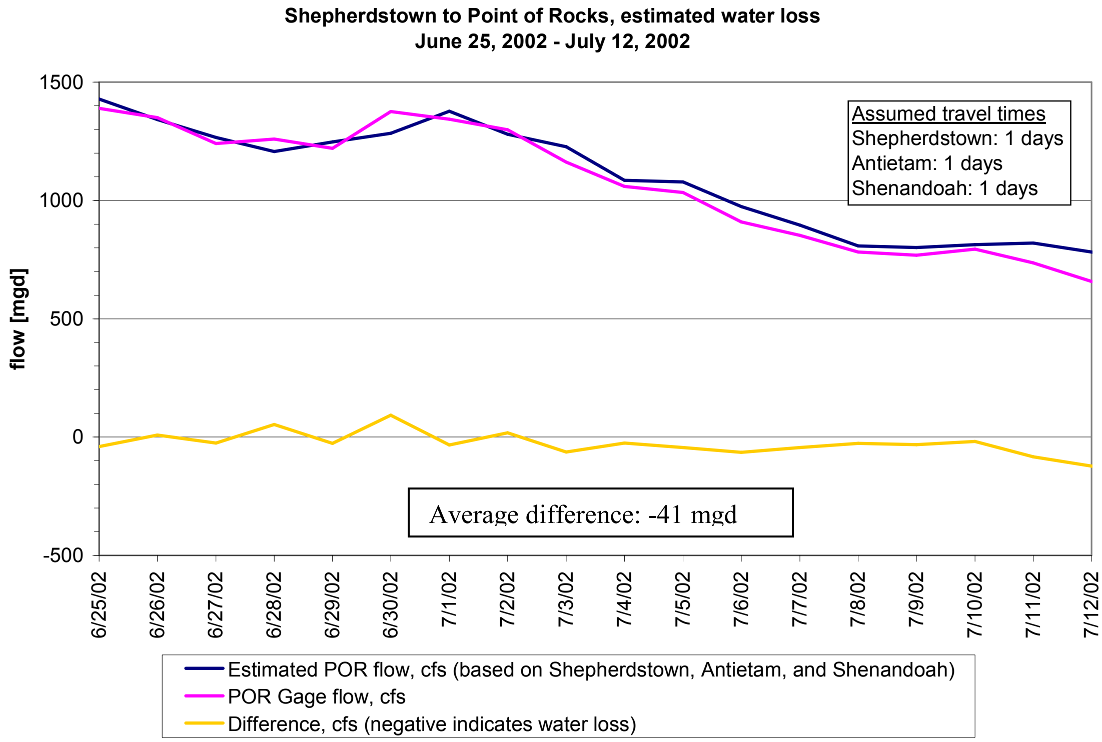

Figure 4-4 Point of Rocks (POR) gage flow compared to flow estimated using gage flow on the Potomac at Shepherdstown and on Antietam Creek and the Shenandoah River. For the period June 25, 2002 – July 12, 2002, the average water loss was 41mgd.

At other times during the summer, after aquatic vegetation growth began to affect the Point of Rocks gage, gage error may have played a more important role and it is more difficult to make quantitative estimates of water loss with confidence. Depending on the cause of the water loss, higher or lower rates of water loss may have been experienced after the June 25 – July 12 period discussed earlier.

The potential effects of gage error during other time periods are important to note because of the implications for our ability to rely on the Point of Rocks gage, regardless of the magnitude of any water loss due to other causes. Figure 4-5 shows observed and estimated flow at Point of Rocks for the period June 1 – September 30. The estimated flow is based on gage flow at Shepherdstown and gaged tributary inflow from the Shenandoah River and Antietam Creek. Also included on the plot are the dates on which the USGS made measurements of flow at Point of Rocks. It is interesting to note that between August 20 and September 9, the Point of Rocks gage appeared to be reading high with respect to the Shepherdstown gage. However, after the September 9 measurement, the Point of Rocks gage appeared to be reading low until the rise in flow following rainfall in late September. The timing of this abrupt shift from an apparent gaining stretch to an apparent losing stretch just after a flow measurement was taken suggests that some gage error was in play during this time period. Further, during the period in which the river from Shepherdstown to Point of Rocks was "gaining", calculations suggest that the river from Point of Rocks to Little Falls was "losing" (see

Figure 4-2) This further supports the hypothesis that gage error at Point of Rocks had significant impacts during this period.

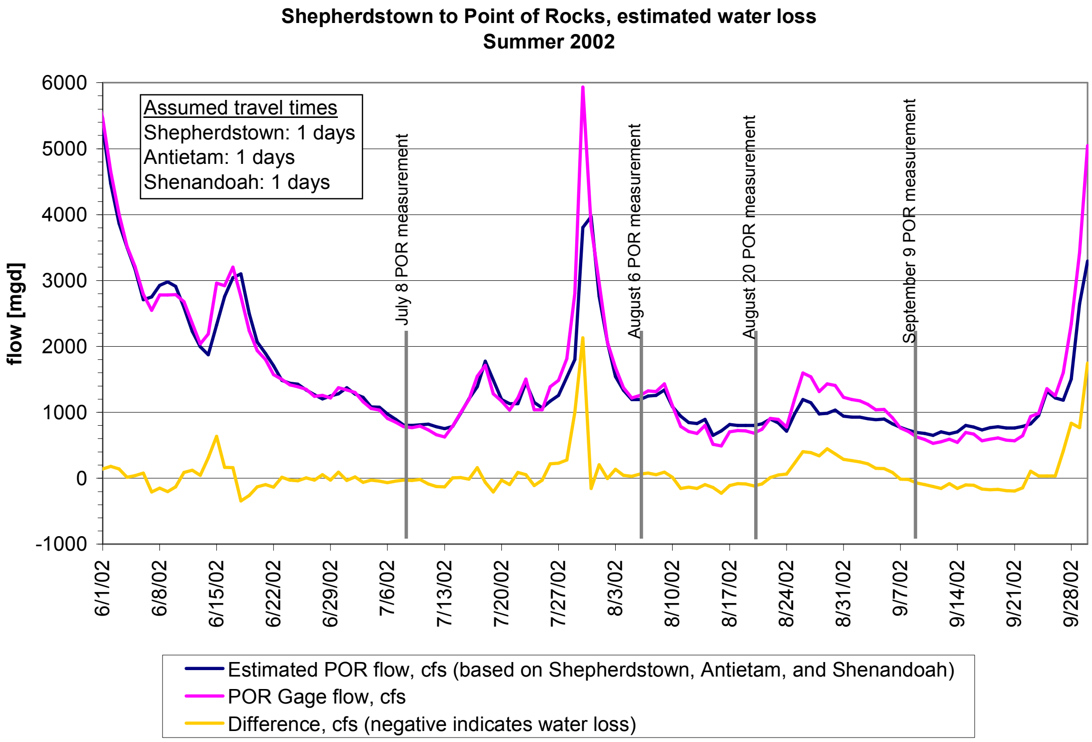

Figure 4-5 Estimated water loss on the Potomac River between Shepherdstown and Point of Rocks (POR). Flow measurements were taken by the USGS at Point of Rocks on the days indicated.

4.5.2 Unknown withdrawals

It is possible that the cumulative effect of many small withdrawals by riparian water users is significant. To better evaluate this possibility, we obtained information on permitted withdrawals from the Potomac River and some nearby groundwater withdrawals. The USGS compiles information collected from the Maryland Department of the Environment and the Virginia Department of Environmental quality. Records include both annual and monthly withdrawal amounts. To estimate peak summertime withdrawals, the maximum monthly value reported in the previous several years from each user between Point of Rocks and Little Falls was tabulated. The total withdrawal from agricultural users, golf courses, and other commercial irrigators may be mostly consumptive and is on the order of 3 mgd.

Municipal consumptive use was estimated. Rockville withdraws a summertime maximum of about 7 mgd, all of which is considered a consumptive use because Rockville's wastewater enters the Potomac interceptor and is discharged downstream of Little Falls. USGS reports that Leesburg withdraws about 4 mgd during the summer from tributaries that flow to the Potomac, about 20% more than their wintertime withdrawals. The excess summertime withdrawal is assumed to be outdoor water use which is not returned to the Potomac, for a consumptive use of 0.8 mgd. Frederick County Division of Utilities and

Solid Waste Management has provided information to ICPRB on metered water withdrawals and metered wastewater return flows for both the City of Frederick and Frederick County DPW (Frederick County Division of Utilities and Solid Waste Management, 2003). This information was examined to quantify Frederick's municipal consumptive water use during summer periods. During dry summer months, Frederick's average consumptive use was estimated to be 3.6 mgd, with an estimated 26.7% consumptive use as a percentage of total withdrawals. Note that some fraction of this withdrawal is from groundwater sources. In total, consumptive municipal withdrawals account for about 11 mgd in dry summer months.

The Dickerson power plant reports a summertime consumptive use of about 10 mgd.

In total, about 24 mgd of consumptive use is estimated from permitted withdrawals during the summer. However, the relationship between the amount of water permitted for withdrawal and that actually withdrawn may not be accurate, as the degree of enforcement and permit compliance is unknown.

Permitted groundwater withdrawals adjacent to the river are minimal. Within about 1 mile of the river, less than 0.2 mgd of withdrawals are found in Maryland and Virginia. However, Virginia does not require reporting of withdrawals less than 10,000 gallons/day or agricultural uses less than 1 million gallons per month in the study region. Maryland does not regulate agricultural withdrawals less than 10,000 gallons per day. Consequently, groundwater withdrawals adjacent to the river may be somewhat higher than shown by the state permits.

It is possible that there are additional, undocumented withdrawals of water along the Potomac. However, while the consumptive use of water may explain part of the water loss, it is not believed to be sufficiently large to fully explain the phenomena.

4.5.3 Evaporation from river surface

Based on a rough estimate of the surface area of the Potomac River between Point of Rocks and Little Falls, direct evaporation from the river surface was estimated to be no greater than 30-40 mgd (Jonathan Dillow, USGS, administrative letter to ICPRB, December 13, 2002). Evaporation rates were estimated based on pan evaporation rates from the U.S. Department of Agriculture evaporation pan at Beltsville, MD in August 2002.

4.5.4 Infiltration into alluvial aquifer

A field study with USGS was undertaken in 2002 to determine whether or not river water was infiltrating the banks and recharging the adjacent alluvial aquifer. Infiltration into the alluvial aquifer would require a lowered groundwater table adjacent to the river. It was hypothesized that evapotranspiration from trees and other vegetation adjacent to the river could be lowering the water table and driving the process.

Nine drivepoint wells were installed along the Maryland shore and on an island in the Potomac River. Wells were located near the mouth of Seneca Creek, Sycamore landing road, Edwards Ferry, and the mouth of the Monocacy River. In addition, four wells were located on Sycamore Island, just upstream of Little Falls. These wells showed that during much of summer 2002 the river level was higher than the groundwater level measured in the alluvial aquifer within 10-20 feet of the river. This indicated that water was moving from the river into the groundwater system. However, at Edwards Ferry, a second well was installed approximately 100 ft from the river's edge. The groundwater level in this well was higher than the river level, indicating flow towards the river. This finding suggests that there was a narrow band of depressed groundwater levels adjacent to the river. In addition, slug tests at the two Edwards Ferry wells indicated that the hydraulic conductivity of the soil was low. If this hydraulic conductivity measurement and the average gradient measured at all sites were representative of the entire Potomac shoreline, the average daily loss to infiltration would amount to little more than 1 mgd. However, hydraulic conductivity is highly variable, and the range of uncertainty in this estimate was estimated at six orders of magnitude (+3/-3). The level of uncertainty can be reduced by obtaining additional estimates of the hydraulic conductivity in the study area.

It is also important to note that a diurnal pattern in water level was observed at two well locations. The diurnal pattern was consistent with the hypothesis that evapotranspiration was driving the process. During the daytime, when evapotranspiration is at its highest, groundwater levels were at their lowest. During the nighttime, when evapotranspiration is minimal, groundwater levels increased. The hypothesis is further supported by data from the second Edwards Ferry well, located 100 ft from the river's shore. At this location, where groundwater flow was towards the river, there was no diurnal pattern to groundwater levels.

4.5.5 Infiltration into geologic fractures

Another possible explanation for the water loss is infiltration into geologic fractures or other highly conductive areas. It is possible that the water loss is concentrated in these geologically favorable areas. However, this possibility was not studied in detail. A possible method to identify specific losing reaches is to take flow measurements at multiple locations along the river between Point of Rocks and Little Falls to identify reaches through which there is a sudden drop in flow.

4.5.6 Operational Recommendations:

While progress was made towards understanding the water loss phenomena, additional work is necessary to more fully understand and plan operations for water loss between gaging sites. Evaporation and consumptive use may together account for 50-60 mgd of the water loss between Point of Rocks and Little Falls. Preliminary data suggests that losses from infiltration into the alluvial aquifer are only on the order of 2 mgd, but the number is highly uncertain. The cause of the remaining 60-70 mgd of water loss bears further study, possibly including:

- Estimation of transpiration potential using GIS and land use mapping

- Simultaneous streamflow measurements at multiple locations along the Potomac study area during low flows to identify specific losing reaches
- Continued monitoring of groundwater levels in installed wells
- Additional slug tests at existing wells to better estimate the hydraulic conductivity of the alluvial aquifer
- Additional study of consumptive losses along river including field verification of existing consumptive water users

4.6 Flow volatility

During low flow events in 2002, the Potomac River at Little Falls exhibited great volatility, with flows dropping by as much as 200 mgd over a period of 12 hours during low flow periods. Such sudden and unexpected drops in river flow have the potential to create serious problems in the Aqueduct's ability to meet water supply demands.

4.6.1 Water supply withdrawals

In part, some of this volatility may have been caused by operations at FCWA and WSSC, where withdrawal rates sometimes varied depending on the time of day. At FCWA, a strong diurnal pattern to withdrawals was evident, with more water pumped in the afternoon and evening hours, and less during the nighttime. Withdrawals at FCWA fluctuated by as much as 80 mgd from peak to off-peak hours early in the drought. At WSSC, there was not a strong diurnal pattern to variations in withdrawals, but withdrawals also sometimes moved sharply up or down by up to 40 mgd. After this problem was identified, FCWA and WSSC kept withdrawal rates as constant as was operationally feasible.

On some days, Aqueduct operations were also kept as constant as possible, but implementation of this strategy was inconsistent. During summer 2002, it was known that some of the flow volatility at Little Falls was caused by Aqueduct's pumping at Little Falls. The hydrograph responds quickly to pumping at Little Falls, dropping sharply when pumps are turned on and rising when pumps are turned off. Analysis later revealed the degree to which flow volatility can be caused by operational changes at Little Falls. On September 9-10, 2002, flow fluctuated wildly at Little Falls, rising or falling by over 200 cfs in a matter of hours (Figure 4-6). As shown in Figure 4-7, however, the timing of these fluctuations corresponded exactly to changes in pumping rates at Little Falls. These fluctuations in stage were not observed at Old Angler's Inn or Carderock, upstream of Little Falls.

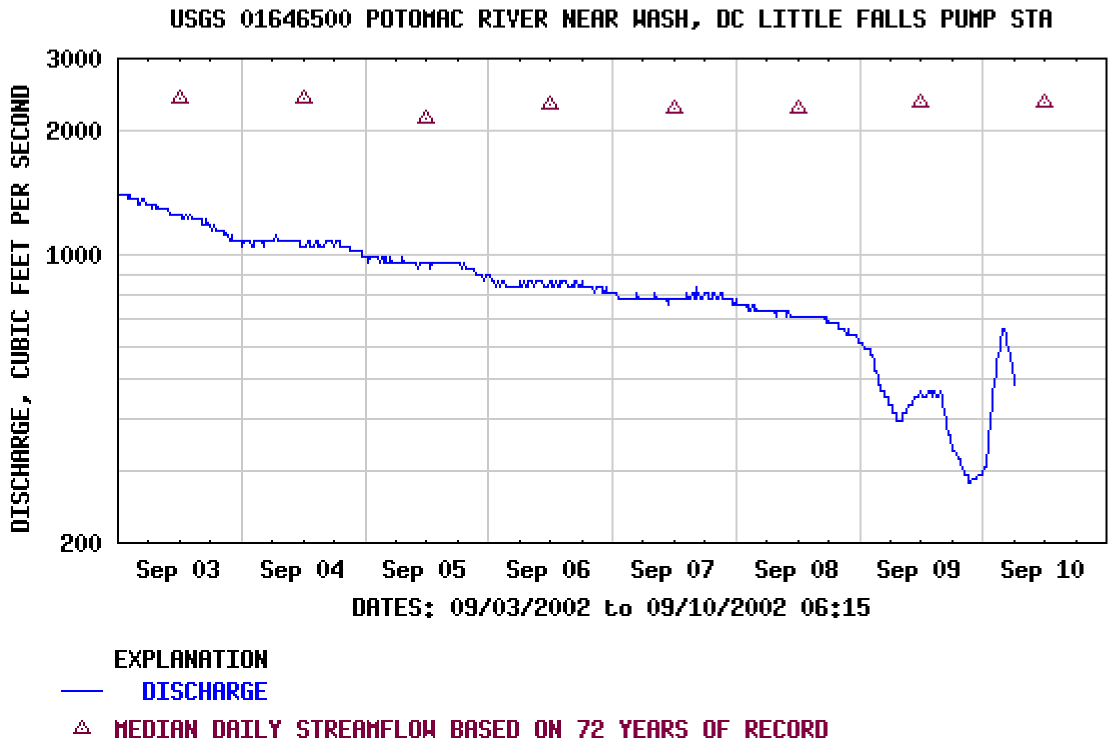

Figure 4-6 USGS gage flow at Little Falls. Wide fluctuations are seen on September 9 -10, 2002.

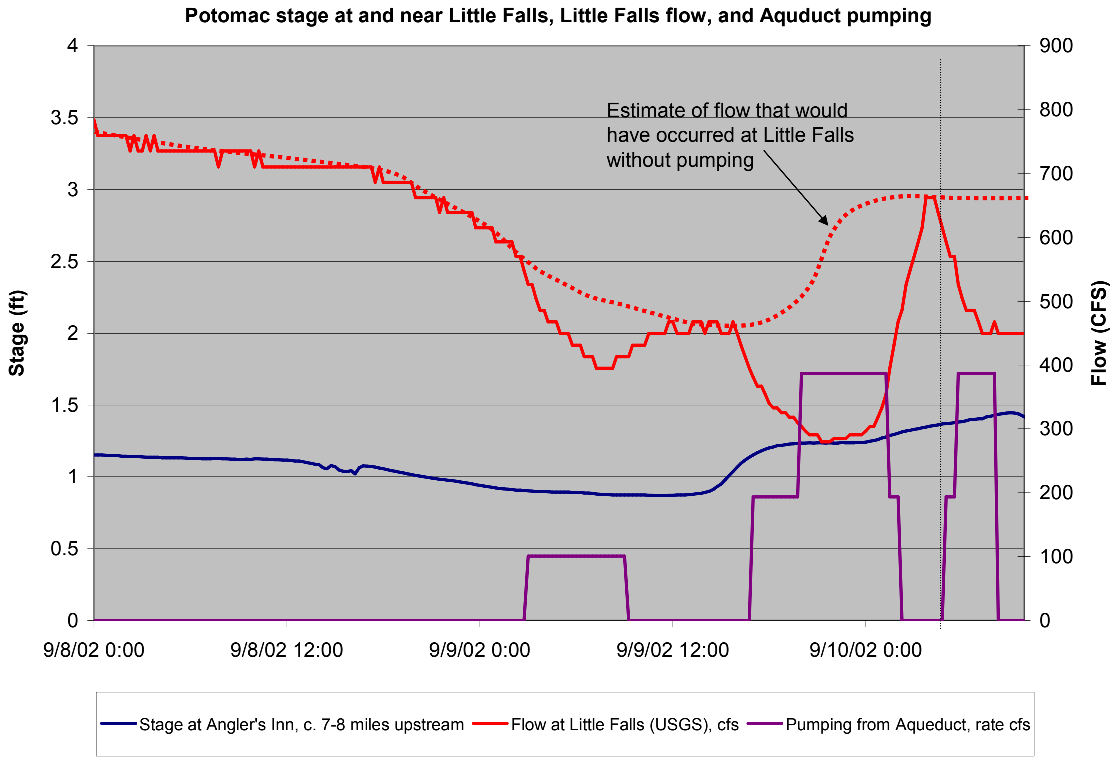

Figure 4-7 Analysis of flow and stage records for September 9-10, 2002 revealed the large influence of Little Falls pumping on flow across the dam. While the stage at Anglers Inn and Carderock were smooth, fluctuations in flow at Little Falls corresponded to changes in pumping rates at the Aqueduct facility.

However, on at least one occasion, the flow at Little Falls dropped suddenly, and thus far, inexplicably. As shown in Figure 4-8, the flow at Little Falls (shown in red), dropped suddenly on September 11, 2002 beginning about 8 am. Stage recorded at Old Angler's Inn did not show any corresponding drop in flow and there was no pumping at Little Falls. The Great Falls conduit was opened to 3.5 feet from the fully closed position the night before and was fully open throughout the day. While this could have resulted in a drop in flow at Little Falls, a similar drop was not evident in the stage measured at Old Angler's Inn, located between Great Falls and Little Falls.

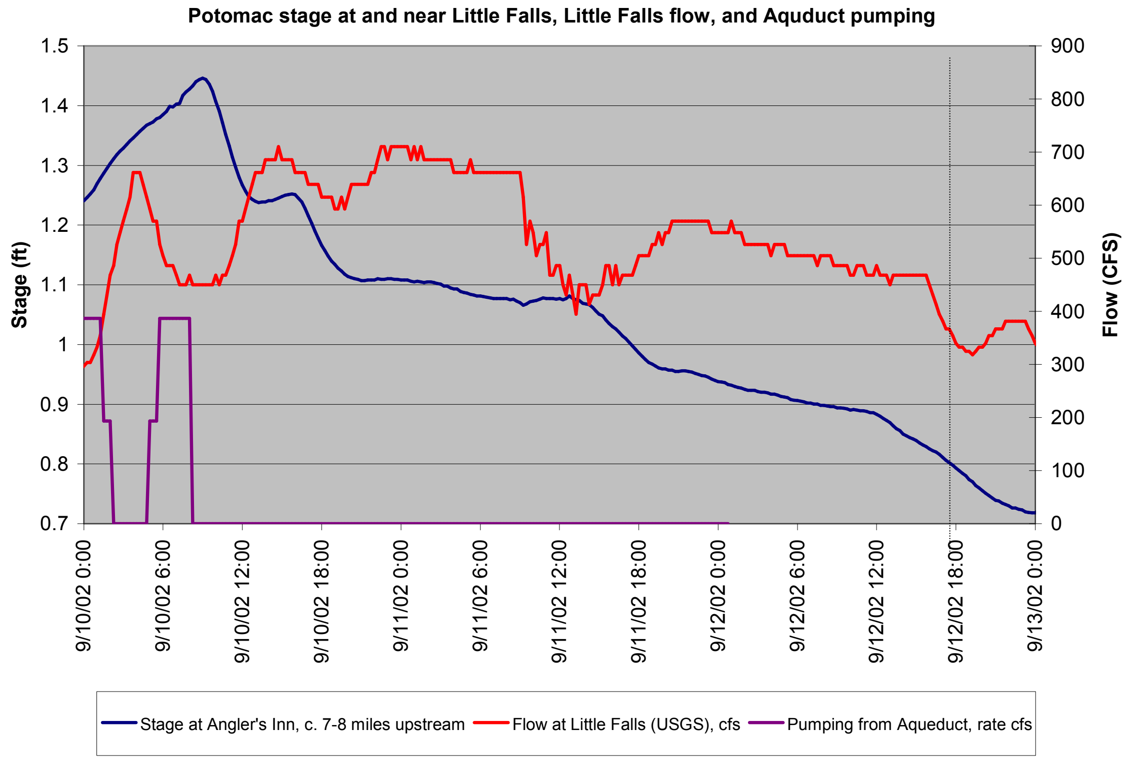

Figure 4-8 The flow at Little Falls (shown in red) dropped inexplicably on September 11, 2002. There was no pumping at Little Falls on this day, and the stage and Anglers Inn does not show a corresponding drop.

<u>Operational Recommendations</u>:
Additional gaging in the river may give better warning of sudden changes in flow. The installation of real time monitoring equipment for stage at FCWA's Potomac River intake and at Aqueduct's Great Falls intake can provide information at permanent locations. ICPRB recommends that technology is put in place to allow the stage signals at FCWA and at Great Falls to be viewed in real-time for use during droughts. Although stage information at FCWA's intake was provided daily during the drought of 2002, the information was of critical importance and real-time data would have better informed water management decisions.

In addition, temporary gages can be installed in the low flow season. In particular, a gage upstream of the mouth of Seneca Creek can help us to anticipate fluctuations in flow and adjust Little Seneca releases accordingly. Additional stage measurements upstream of Great Falls will give a better indication of what is headed downstream, before any of the effects of Aqueduct operations are realized. Gaging between Great Falls and Little Falls can aid in the understanding of the effects of Great Falls operations on downstream flow and can also give a final check on flows heading into Little Falls.

The continued implementation of steady withdrawals at WSSC and FCWA during low flow periods is also recommended. This action eliminates uncertainty as to whether fluctuations in flow are caused by WSSC or FCWA operations. In addition, more consistent implementation of steady withdrawals by the Aqueduct at Great Falls and Little Falls is recommended.

4.6.2 Power plant operations

The operation of run of river power plants is also believed to be a source of wide fluctuations in flow. Plants are located on both the main stem Potomac River upstream of Point of Rocks and on the Shenandoah River upstream of Millville. Figure 4-9a shows Potomac River flow at Hancock, upstream of run of river power plants at Dam #4 and Dam #5 on the Potomac. Here a smooth recession is seen. However, at Shepherdstown (Figure 4-9b), located downstream of the power plant, that recession has been disrupted and rapid fluctuations in flow can be seen. Further downstream, the effects become more muted, but are still observable at Point of Rocks (Figure 4-9c) and Little Falls (Figure 4-9d).

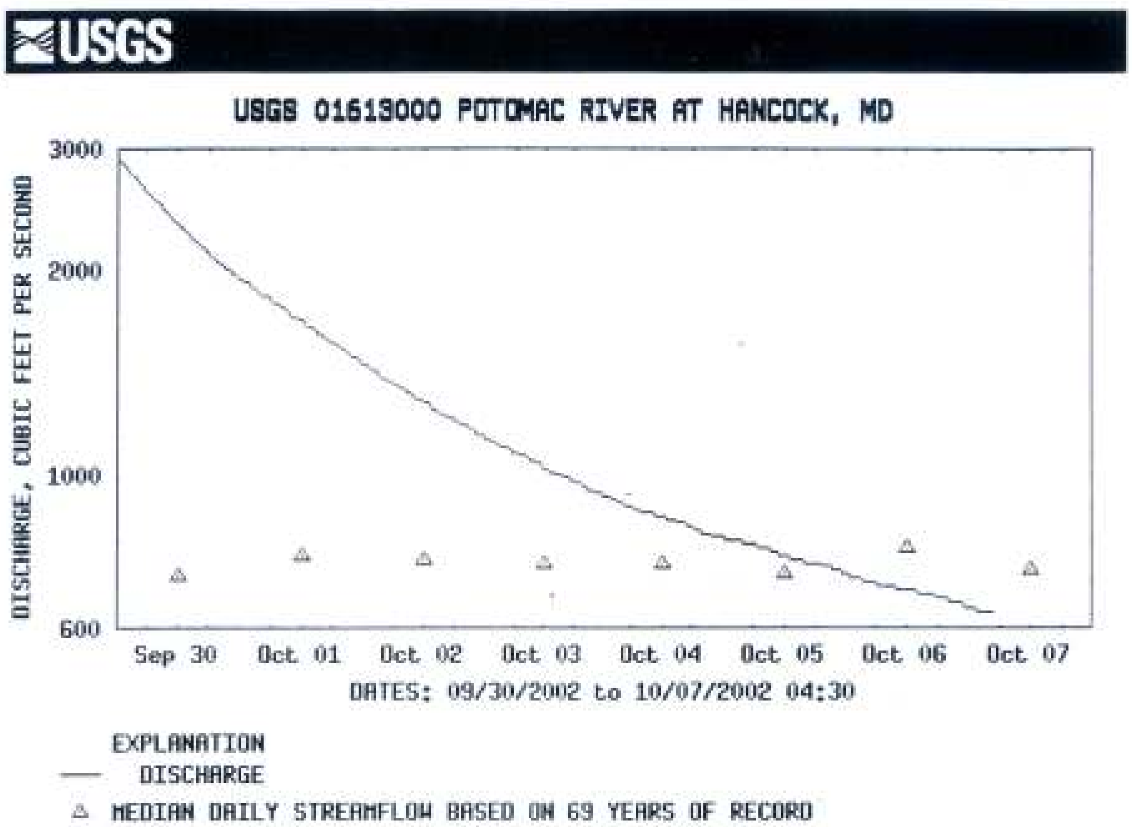

Figure 4-9a Potomac River flow at Hancock, MD showing a smooth recession.

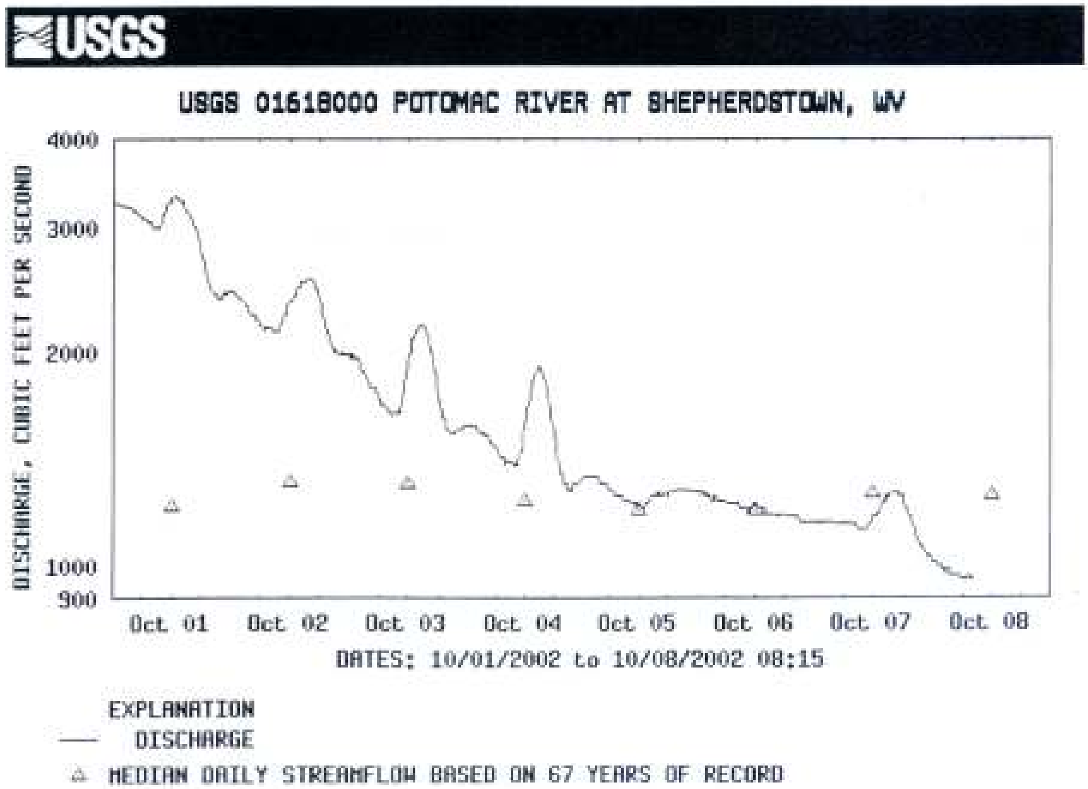

Figure 4-9b Potomac River flow at Shepherdstown, WV. Shepherdstown is downstream of Dam # and rapid variation in flow can be seen.

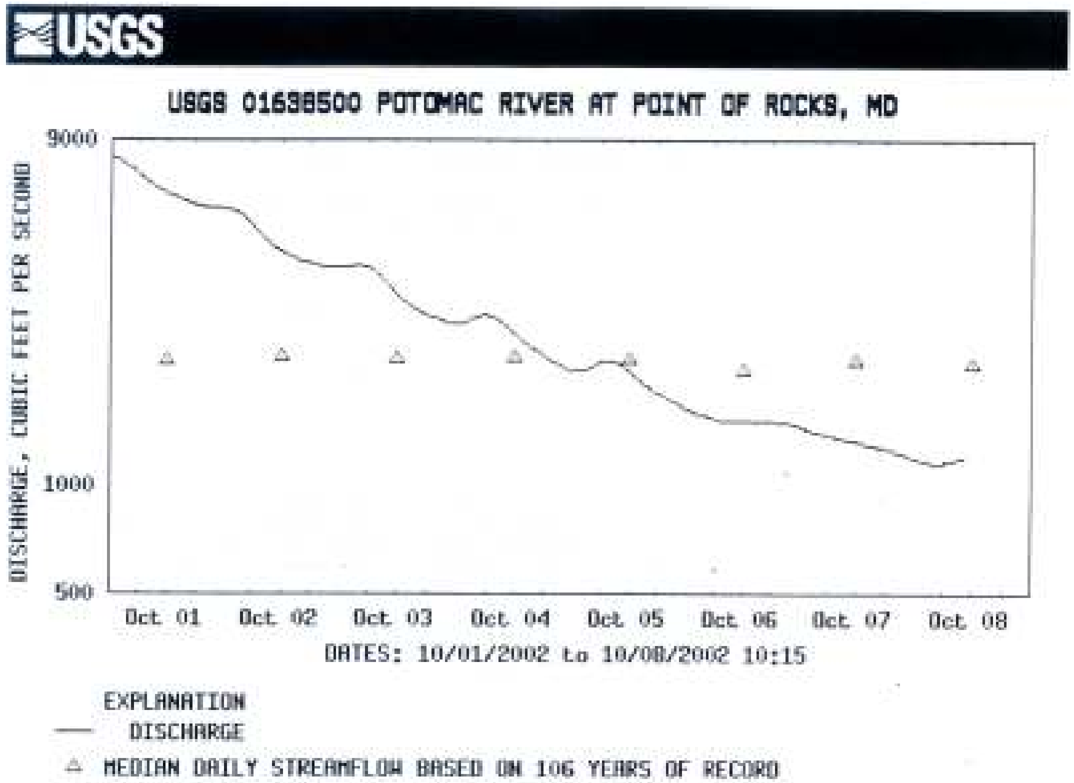

Figure 4-9c Potomac River flow at Point of Rocks, MD is further downstream and while the flow variation is less pronounced, it is still present.

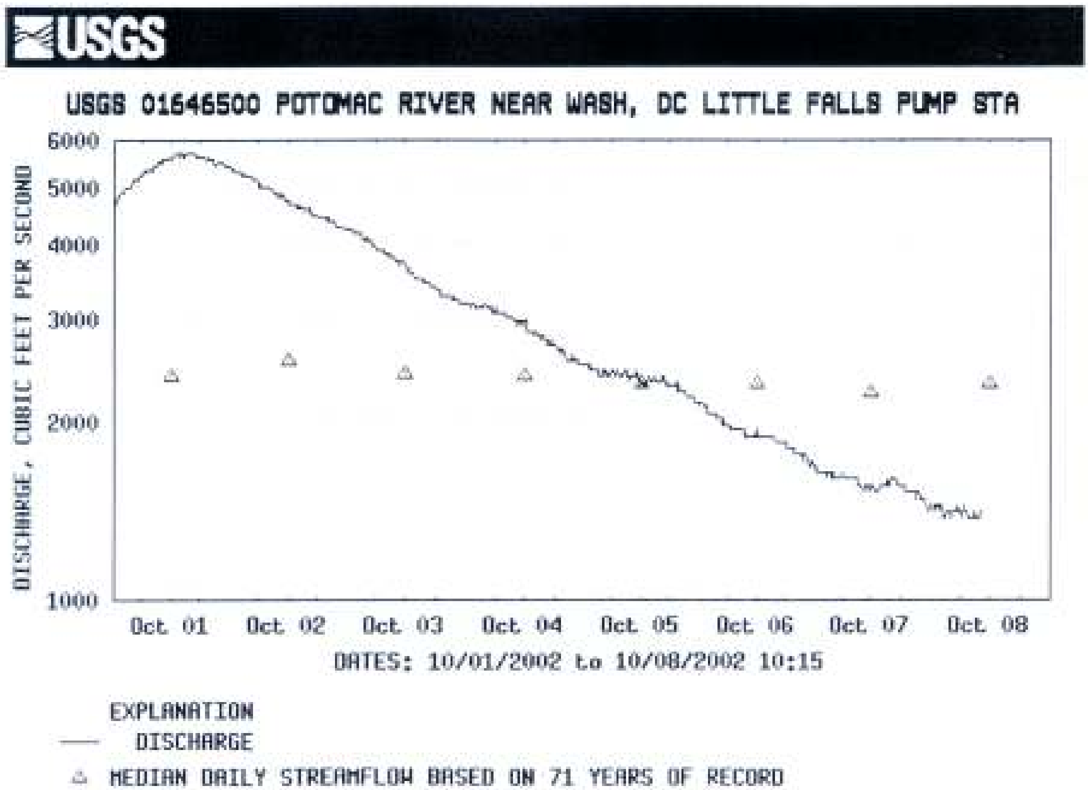

Figure 4-9d Potomac River flow at Little Falls, MD. The rapid variation in flow has been significantly dampened but can still be seen as far downstream as Little Falls.

<u>Recommendation</u>:
Further investigation of power plant operations is recommended.

4.7 Effects of storm events

Following rainfall events in summer 2002, it was often difficult to assess whether or not runoff could be expected to boost river flows long enough to suspend water supply releases from Jennings Randolph Reservoir. The effects of a small rain event may not be enough to keep river flows above levels requiring augmentation in nine days. On the other hand, a large rain event may provide sufficient runoff to keep flows elevated for weeks. At the extremes, it may be easy to distinguish between a "small" event and a "large" event. However, in the murky middle ground, it is difficult to determine exactly what effect rain will have on future streamflow. The effects of a rain event on flow at Little Falls depend on the intensity, duration, and location of the rainfall in the basin as well as on soil moisture conditions preceding the rain event.

<u>Operational Recommendations</u>
With the currently developed tools for the Potomac River Basin, we are unable to calculate the volume of runoff from a storm event nor the timing of its arrival at any of the water supply intakes. Such knowledge would aid in the efficiency of our operations

and could be accomplished through development of a calibrated rainfall-runoff model for the basin with a basic flow routing component. Existing modeling work at the Middle Atlantic River Forecast Center (MARFC) is geared towards flood events, and does not appear to be sufficient for our needs. In addition, river forecasts from MARFC are currently available only 48-hours into the future.

Development of a basin-wide rainfall runoff model might take as much as 2-person years of effort, and would need to be updated regularly during a drought. However, it may be worth exploring the development of such a model to improve operational efficiency.

4.8 Washington Aqueduct Division load shifting:

Drought management activities on the Potomac River are targeted to meet an environmental flow recommendation of 300 mgd between Great Falls and Little Falls. Under normal operations, the Aqueduct withdraws water primarily by diverting water into a gravity fed conduit at Great Falls. Under low flow conditions, some or all of the Great Falls withdrawals are suspended by instead withdrawing water from a pumping facility at Little Falls, about 10 miles downstream. By load shifting from Great Falls to Little Falls only when necessary, significant pumping costs for the Little Falls facility can be avoided while still meeting environmental flow recommendations.

In 2002, load shifting decisions for the next day were made in the late afternoon to early evening so that they could be implemented beginning at midnight. This necessitated estimation of flow on the next day, a task rife with uncertainty because of the operational issues discussed in the previous sections.

Flow at Great Falls is not measured directly with a gage. Instead, the flow must be estimated by adding Little Falls withdrawals to the river flow measured at the Little Falls gaging station. This estimate is subject to uncertainty because of the travel time of water in the river between Great Falls and Little Falls and of water in the conduit between Great Falls and the treatment plant. As a result of the lag between operational changes at Great Falls and their effects at Little Falls, different 24-hour periods are used to calculate flow downstream of Great Falls and to determine operational targets. However, the calculated estimate of flow downstream of Great Falls fell slightly below 300 mgd on the days shown in Table 4-2 below.

Table 4-2 Estimated flow on the Potomac River downstream of Great Falls, estimated based on Little Falls flow and withdrawal rates.

Date	Estimated flow downstream of Great Falls [mgd]	Gage flow at Little Falls [mgd]	Great Falls withdrawal [mgd]	Little Falls withdrawal [mgd]
8/18/02	275	246	169	29
8/22/02	283	213	149	70
9/17/02	277	197	106	80

The uncertainty created by each of the operational issues described in previous sections, as well as uncertainty in setting gate openings at Great Falls to obtain desired withdrawal amounts contributed to these low flow days. The same gate setting may yield different withdrawal amounts depending on the river stage. An incorrect setting can not be quickly adjusted because the actual withdrawal from Great Falls is not measured, but estimated based on total daily Aqueduct production and measured Little Falls pumping.

Table 4-3 shows estimated withdrawal amounts at Great Falls at various gate settings for several days in 2002. Few days are available because Great Falls gates were seldom kept constant throughout a 24-hour period. Frequent changes were made with frequent changes in river conditions (or our predictions of future river conditions). While the table gives some indication of the withdrawals which can be expected for different gate settings during low flow events, additional data is needed to more fully describe the relationship between gate settings and withdrawal amounts.

Table 4-3 Estimated withdrawal at Great Falls for various gate settings. The estimated flow upstream of Great Falls was between 400 – 500 mgd on each day.

	Gate Setting, ft	Great Falls withdrawal, mgd
9/15/02	1.25 - 1.50 *	110
9/16/02	1.25 - 1.50 *	130
8/16/02	1.00	106
9/20/02	1.00	103
9/21/02	1.00	106
9/22/02	1.00	121
9/23/02	1.00	107
9/13/02	0.75	90
9/14/02	0.75	73
7/13/02	0.50	32

* New conduit gate was set at 1.25 feet, old conduit gate was set at 1.50 feet.

<u>Operational Recommendations</u>:
This problem can be addressed in part by reducing the uncertainty in flow prediction with the recommendations already discussed above for each of the other operational issues. In particular, the measurement of river stage at Great Falls is expected to be beneficial. Working with the USGS, it may be possible to develop an approximate stage-discharge relationship at Great Falls.

In 2002, an operational safety factor of 30 mgd was attempted when making load shifting decisions. Until the uncertainties in flow prediction and gate settings are more fully addressed, it may be prudent to utilize a larger safety factor in load shifting decisions. At a minimum, a safety factor of 55 mgd may be indicated, the maximum amount by which estimated flow downstream of Great Falls fell short of the flow recommendation plus safety factor of 330 mgd. However, a higher safety factor results in higher pumping costs for the Aqueduct. With improvements in operations and with better information through new real time stream gages, a safety factor closer to 30 mgd may be adequate. In future droughts, some discussion is warranted among the Operations Committee to determine an appropriate safety factor for meeting this flow recommendation.

To ensure that no miscommunication occurs, phone conversations should be followed up with an email reiterating the two withdrawal targets.

Throughout summer 2002, both the Little Falls and Great Falls withdrawal targets were given to Aqueduct staff. In the early part of the summer, the Little Falls number was given as the firm target, with the idea that Little Falls pumping rate could be controlled more precisely. However, this meant that any changes in Aqueduct demand would be met by changing Great Falls withdrawal rates, perhaps undesirably. Thus, the Great Falls withdrawal target was later used as the firm target, with any changes in demand being made up at Little Falls. This procedure is recommended for the future, as this fixes the flow in the reach downstream of Great Falls with the recommended minimum flow. In addition, if demands decrease, the Aqueduct can decrease pumping and save on pumping costs.

4.9 Predicting Little Falls Flow: contradictory and uncertain information

As a result of each of the operational issues discussed above, management decisions were sometimes made in the face of contradictory information and large uncertainties. Over the course of the summer, methods for making flow predictions for reservoir release decisions were developed which differed from some of the methods used in 1999 and outlined in the Operations Manual. These changes were necessary to take into consideration the variety of operational issues discussed in previous sections.

ICPRB CO-OP used a large safety factor during 2002 operations. A flow target of 200 mgd at Little Falls was used when making release decisions from Little Seneca Reservoir. Jennings Randolph was managed less conservatively, with a 100 mgd flow target at Little Falls because of the long travel time. Conditions often changed in the intervening period, and any shortfalls could be met with Little Seneca releases.

4.9.1 Predicting short-term flow at Little Falls

Various methods were used to predict flow at Little Falls early in the drought, and these methods were refined over the summer. Early on, the various methods used sometimes resulted in very different predictions of flow. For example, Figure 4-10 shows two methods used for prediction of flow at Little Falls on August 13, 2002 - a graphical method and a quantitative method. The inset box in the figure outlines the quantitative method based on routing area-adjusted tributary flow added to upstream Potomac flow. The resulting calculation showed a flow of 856 mgd at Little falls (adjusted) in 3 days time. (Adjusted flow at Little Falls is equal to the gage flow plus upstream withdrawals by the CO-OP utilities.) A graphical method used to predict flow based on recent rates of recession and represented by the dotted line in Figure 4-10, provided a flow prediction of 600 to 800 mgd in 3 days time. (The adjusted flow at Little Falls three days later, on August 16, was 796 mgd.)

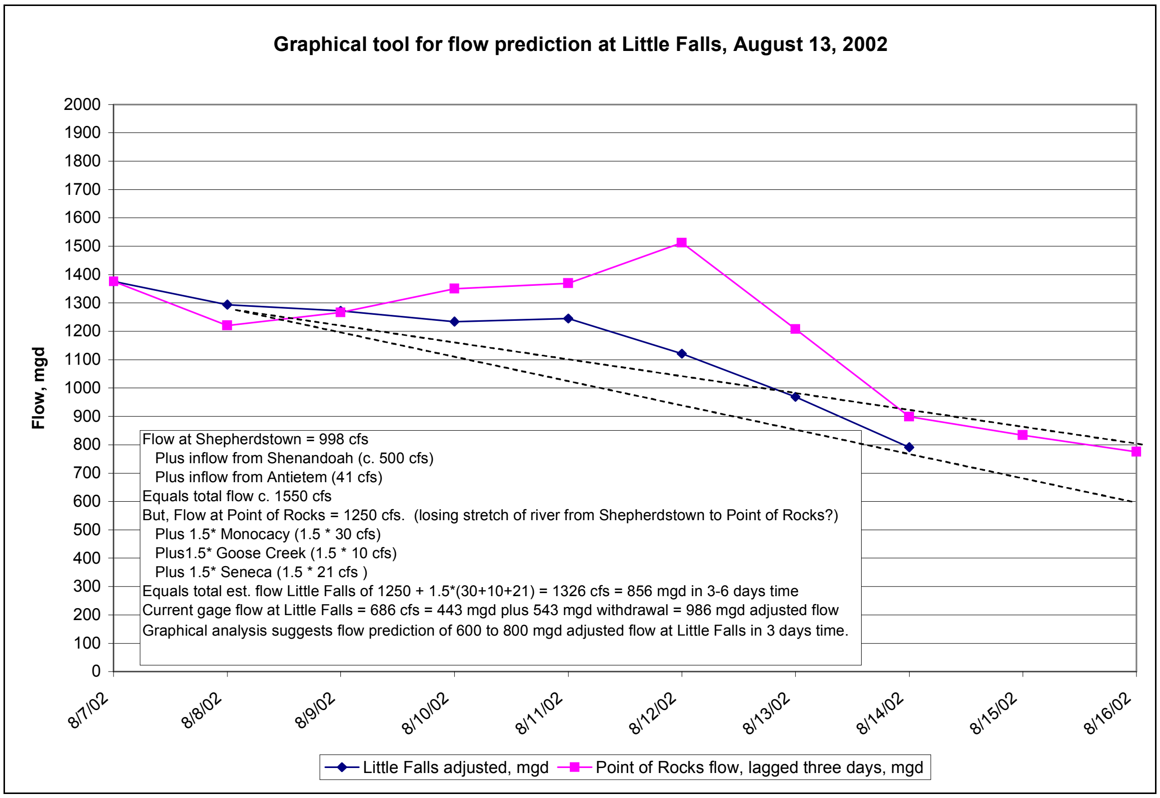

Figure 4-10 Flow prediction at Little Falls on August 13, 2003.

The flows calculated quantitatively did not account for apparent water loss between gages, which seemed to occur between Shepherdstown and Point of Rocks, and again from Point of Rocks down to Little Falls. Thus, the calculation of flows using upstream tributaries tended to overestimate downstream flows. For example, from the inset box in Figure 4-10, the calculated flow at Point of Rocks was developed based on adding the flow at Shepherdstown (998 cfs) to the flows from the Shenandoah (c. 500 cfs) and Antietem (41 cfs) to arrive at an estimate of Point of Rocks flow of c. 1,550 cfs. The gage flow at Point of Rocks was only 1,250 cfs, demonstrating the uncertainty as to actually knowing what flow was occurring in the river. The experience from 2002 verified to ICPRB personnel that the best method for forecasting flow at Little Falls in the next one to three days was to start with current gage flow at Little Falls, adjusted using graphical or spreadsheet methods based on recent trends in flow at Point of Rocks. Stage data for FCWA, provided later in the drought, was also helpful in informing potential trends in flow.

Figure 4-11 illustrates the graphical flow prediction process for September 13, 2002, showing the estimate of flow at Little Falls with a recession rate applied as determined by Point of Rocks gage lagged by 2 to 3 days. Graphical methods were useful for developing estimates of the uncertainty in forecasts of future flow. Graphical methods were often supplemented with spreadsheet analysis to explicitly forecast flows. For example, numerical estimates of the drop in flow at Point of Rocks were routed and subtracted from Little Falls flow in an Excel spreadsheet, with adjustments for changes in water supply withdrawal rates and for changes in Little Seneca release rates. The graphical method was useful for visualizing overall trends, which could then be used to modify the spreadsheet calculation of forecast flow. The graphical method also was useful for assessing trends from other gages such as the FCWA stage data.

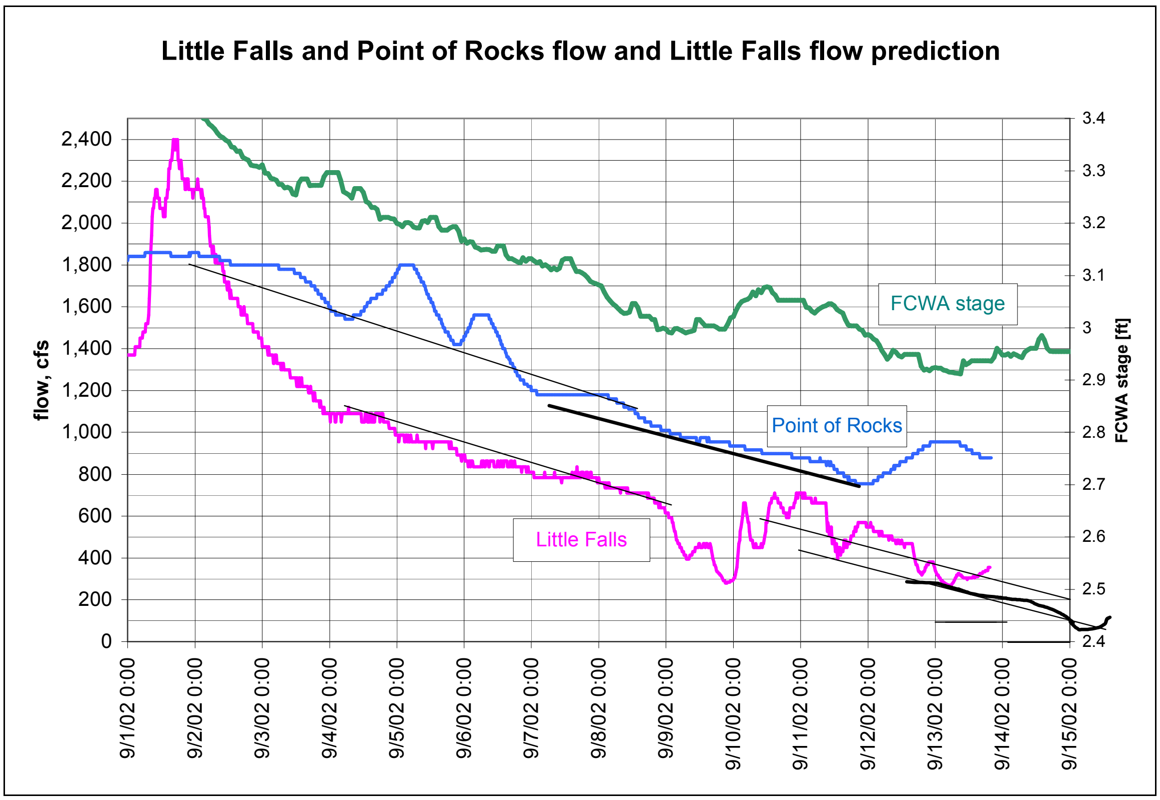

Figure 4-11 Flow prediction at Little Falls on September 13, 2003.

Figure 4-12 shows the daily average flow at Point of Rocks plotted against the daily average flow at Little Falls, with a lag of 2 days. The uncertainty in Little Falls flows predicted using Point of Rocks flows can be seen to be quite large. As shown in Figure

4-13, the daily average stage measured at FCWA is a better indicator of the daily average flow at Little Falls on the same day. However, the scatter around the best fit line remains considerable for some flow levels. The travel time between the FCWA intake and Little Falls at low flows is likely to be at least 15 hours (see Section 4.4), so a comparison of daily average stage at FCWA and daily average flow at Little Falls for the same day is imprecise.

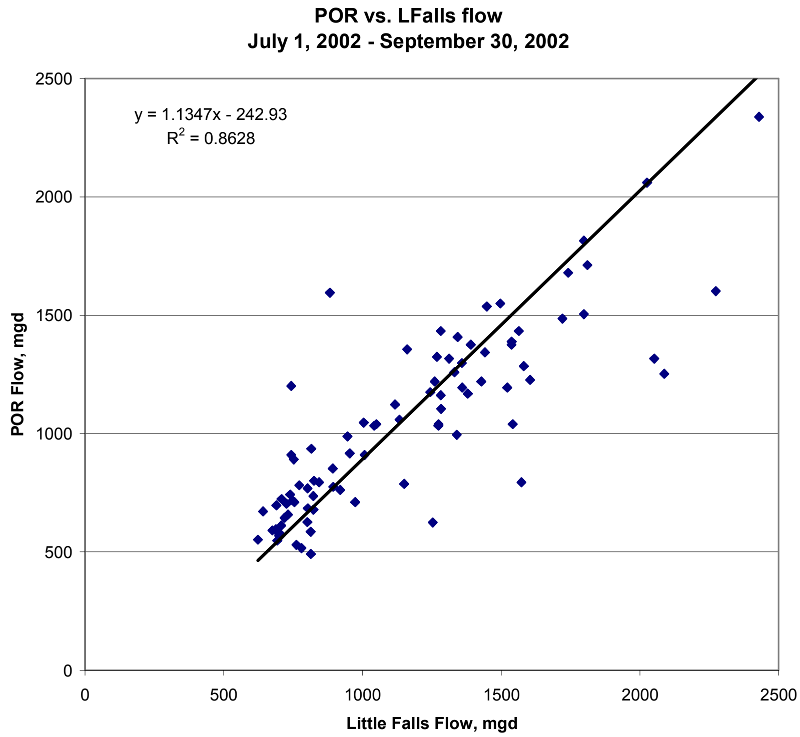

Figure 4-12 Daily provisional average flow at Point of Rocks (POR), lagged by 2 days, is plotted against daily provisional average flow at Little Falls for summer 2002.

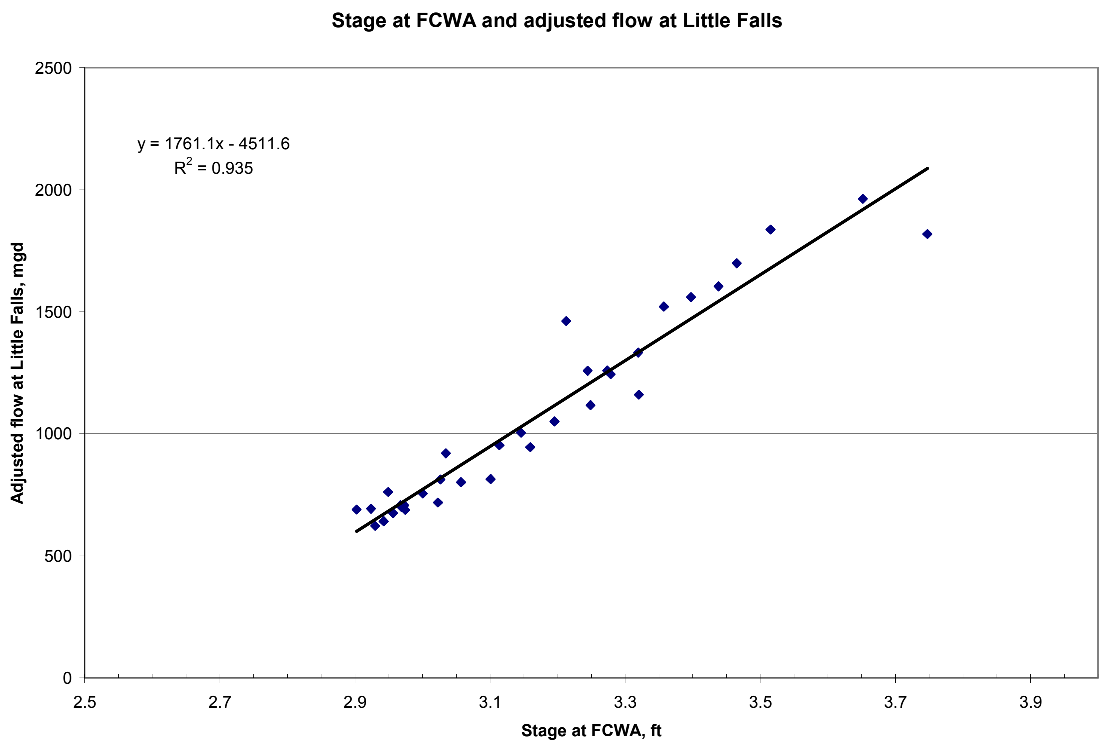

Figure 4-13 Potomac River stage measured at FCWA's intake is plotted against the adjusted daily average flow at Little Falls for the same day.

4.9.2 Predicting long-term flow at Little Falls

The method used to predict long-term flow at Little Falls (in 9-days time) is based on assessing flow trends throughout the watershed, and estimating the cumulative impact of those flow trends at individual tributaries at the most downstream flow control point at Little Falls.

The main method used to forecast tributary flow was to use recession equations, based on historical data. These equations were developed for each tributary through an examination of the drought events in the historical record and were used to predict tributary flow in the current drought using a best fit equation. In the drought of 2002, the equations used to predict tributary streamflow were superceded at times with forecasts based on ICPRB professional judgment at each tributary. Professional judgment, rather than best-fit regression equations, was found to provide better estimates of tributary flows as staff could apply knowledge about current conditions such as soil moisture, forecasts of temperature and rainfall, recent rain events, and information about recent rates of recession at each tributary.

Prior to the drought of 2002, tributary flow predictions were added to Potomac flow working in an upstream to downstream direction, in order to develop a forecast of flow at the most downstream location. The method involves starting with a flow value from a gage on the Potomac near the headwaters, and adding the predicted (recessed) flows from tributary gages (lagged at appropriate intervals) in order to develop an estimate of Little Falls flow downstream. This method was practiced in Potomac Reservoir and River Simulation Model runs and in drought exercise operations prior to 2002. However, the application of this method in 2002 operations resulted in predictions of flow at Little Falls that were higher than those actually realized, possibly due to water loss between upstream and downstream gages. Working from upstream to downstream would tend to over-predict Little Falls flow during droughts, because it does not explicitly take into account the water loss due to consumptive use.

Later in the drought, a method was developed to work around the water loss issue, namely to use the current Little Falls gage flow as a starting point. Water loss due to consumptive use was already reflected in the gage value shown at the Little Falls station, and forecasts of future flow would thus also already reflect upstream consumptive use. The current Little Falls flow was adjusted by the anticipated changes in tributary flow rather than using gage flow from upstream in the headwaters as the starting point and adding recessed and routed tributary flows. Note that even though using the Little Falls gage flow as a starting point was more reliable, this method does implicitly assume a constant water loss rate. Predictions of Little Falls flow may be improved if a better explicit understanding of consumptive use allows for predictions of variability in the water loss rate.

5 Summary of operational recommendations

A number of operational issues were identified during the 2002 drought. The following actions are recommended in order to better manage the metropolitan area water system during future low flow conditions.

- **Continue to study alternative predictors (combination of precipitation, streamflow, groundwater) of summer reservoir releases.**
- **Continue withdrawing at steady rates from all Potomac intakes, to minimize flow volatility.**
- **Maintain more constant withdrawal from Little Falls pumping station - otherwise risk (1) lowering river level below top of pump intake, (2) lowering instantaneous river flow to zero.**
- **Continue to explore water loss due to consumptive water users and infiltration.**
- **Install equipment at FCWA's intake and at Aqueduct's Great Falls intake to provide real time stage measurements. In addition, install three telemetered gages in the Potomac: one upstream of the mouth of Seneca Creek , another upstream of Great Falls but downstream of Seneca Creek, and a third downstream of Great Falls. These actions will assist in dealing with flow volatility, understanding travel time, and may also be beneficial to understanding the water loss problem.**
- **Conduct test releases from Little Seneca Reservoir during appropriate autumn months to observe travel times.**

- **Study the impact of power plant operations on flow volatility.**
- **In future drought operations, the safety factors used for meeting both the Little Falls and Great Falls environmental flow recommendations should be re-evaluated.**
- **Maintain improved communications by following up telephone conversations setting release rates and withdrawal targets with an email.**
- **Develop a rainfall runoff model tailored to low flow events to better predict flow in 9-days time.**

6 Conclusions

Drought conditions in summer 2002 required augmentation of flow in the Potomac River from upstream reservoirs for only the second season since the reservoirs were constructed in the early 1980's. Coordination between the three major water suppliers and the Interstate Commission on the Potomac River Basin (ICPRB) went smoothly, and sufficient water was available in the river at all times to meet water supply needs and to maintain the environmental flow recommendation at Little Falls.

However, several issues emerged early in the summer and created difficult challenges for managing the Potomac River to meet operational goals. The operational recommendations provided here will serve to address many of those issues. Further work will need to be done in terms of developing better estimates of water loss, but the major problems of flow variability and travel time can be addressed through development of temporary gages and other recommendations. Technology continues to evolve, and it is hoped that with these improvements such benefits as real-time monitoring and automatic alarm mechanisms can be utilized to further improve operations.

The lessons learned from the drought of 2002 were extraordinarily helpful in developing improvements in operations. It is hoped that this summary report will be helpful to future CO-OP and utility personnel by recording these lessons so that they do not need to be re-learned. The recommendations listed here will undoubtedly be further refined in the next drought, however this report can serve as a tool for drought preparation and drought exercises.