APPENDIX 2

Model Development and Verification

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Model Development and Verification

The purpose of this appendix is to provide supplementary information and additional detail on the development of the hydrologic computer model used to evaluate the various alternate operating scenarios and eventually recommend an operating plan. Four aspects of the model development are covered in this appendix: (1) hydrologic record development, which is comprised of several tasks itself; (2) extent of model coverage; (3) incorporation of operational parameters; and (4) model calibration and verification.

Section 1. Hydrologic Record Development

The ultimate objective of this effort was to develop a comprehensive set of hydrologic records by converting gaged flows into inflows at the OASIS nodes. The record was developed from gaging records throughout the Susquehanna basin, and is intended to be representative of flows that can reasonably be expected to occur in the future. There are several distinct activities associated with this effort; they are briefly described below and in more detail in subsequent sections of this appendix.

The availability of gage information and the locational need for flow information in the model do not always coincide. A significant task related to development of the hydrologic record is transferring the non-impaired and extended flow records to the various model nodes and junctions, and computing the inflow, or reach gains, from the intervening drainage area between two or more model nodes.

Development of the hydrologic record is also complicated by apparent discrepancies between records from adjacent gages. It is not uncommon for the sum of two tributary gages to exceed the measured flow at the first gage downstream of their confluence on the following day. Likewise, the situation can arise where the flow at an upstream gage is greater than the flow at another gage immediately downstream on the following day. This discrepancy can be caused by travel times, evaporation, withdrawals and discharges, and losses of flow to streambank infiltration. An additional significant source of discrepancies is the uncertainty inherent in streamflow measurements; the data from USGS gages is, at its best, rated as having an error of 5 to 10 percent less than or greater than the actual flow value.

When discrepancies such as those described above arise, the routine used to generate local inflows might return negative values for the flow contribution from intervening drainage areas between nodes and gages. While perhaps counterintuitive, “negative inflows” act to preserve the integrity of the flow record and should not be seen as inherently erroneous.

A brief description of the major activities in development of the hydrologic record are given below. More detailed information is presented in subsequent sections.

Assembly of Hydrologic Records – The hydrologic record runs from 1930 to 2002. The starting date for the record was chosen in order to include the drought of the 1930s and a

few antecedent years, and because eight gages were started in 1928 and 1929. Prior to 1928, the paucity of available gaging records makes it difficult to develop a representative reconstruction of all of the gages required to produce the hydrologic records for the model. Other records used include rainfall measurements, evaporation measurements, and records of reservoir operations.

Development of Historic Water Use Time Series – It was important for two reasons to develop estimates for consumptive water use in the Susquehanna basin: first, for use in reconstructing the "unimpaired" hydrologic flow record (see below); and second, for use in the model simulations of various operating scenarios. For the first purpose, monthly average consumptive use estimates were developed for various locations in the basin spanning the entire period of record, then distributed to appropriate corresponding gage locations and added to the historic gage records to develop an "unimpaired" hydrologic record. For the second purpose, the time series monthly average consumptive uses developed for the first purpose were used to generate estimates of current consumptive use throughout the basin and, in conjunction with population projections, to generate estimates of consumptive use in the year 2025.

Computation of Unimpaired Gage Flows – The first step in building the record from available gage data was to compute a monthly record of "unimpaired" gage flows. Gages only show the actual flow in the stream; they have no information about what the flow would have been without human intervention. "Impairments" are modifications of the natural flows due to change in reservoir storage (including evaporation and precipitation on the reservoir surface) and consumptive withdrawals of water (municipal, industrial, or agricultural). If water is withdrawn above a gage and returned to the river below the gage, the impairment is the entire withdrawal. Only by first reconstructing the natural flows at gages can the data then be used to accurately generate synthetic flow data between gaging locations or to fill in data gaps in gage records.

Synthesis of Missing Gage Records and Reach Gains – Many of the gages have incomplete records; their operation either began after 1930 or ended prior to September 30, 2002. The second step in the process is to assemble a monthly record of unimpaired gage flows and "gains," the difference in unimpaired flow between a given gage and the gage(s) immediately upstream. These flows and gains were fed into a program named *fillin* (developed by William Alley and Alan Burns of the USGS[1]) to fill in the missing flows and gains for each gage with missing records. The results of the *fillin* program are referred to as "extended" flows and gains.

Computing Inflows at OASIS Nodes – The next step in the process is to compute the OASIS nodal inflows based on the flows and gains computed in step 3. The monthly values are disaggregated into daily values as a part of this step. The output from this step is the set of inflows at all the OASIS nodes for the period of record.

[1] "Mixed-Station Extension of Monthly Streamflow Records," *Journal of Hydraulic Engineering*, ASCE, Vol. 109, No. 10, October 1983

Application of Flow Routing – The transport of flow from one node to the next downstream node is, in most cases, assumed to occur completely within one full timestep of the model (one day). However, there were 15 stream reaches between model nodes where either extensive travel distance or hydrologic complexity led the modeling team to conclude that flow routing was necessary. Flow routing is the application of a formula related to the natural dispersion characteristics of a volume of flowing water; the formula describes the portion of the flow that arrives downstream in the next timestep and the remainder that arrives during the following timestep. The Muskingum routing methodology was used to develop routing coefficients for the formulas.

A. Assembly of Hydrologic Records

The data used to develop the hydrologic record are listed in Table 1.1. All of the files used in developing this record are in the folder *hydrology* located in the OASIS model directory at the Commission office.

Table 1.1. Sources of Data

Type of Data	Source
Streamflows	USGS
Susquehanna Basin Reservoir Historical Stages	SRBC, COE
Rainfall at Reservoirs	SRBC
Evaporation	SRBC
Susquehanna Basin Water Use Demands	SRBC
Baltimore System Inflows and Demands	City of Baltimore

The 61 streamflow gages in the Susquehanna basin that are used in this project are listed in Table 1.2. Additional drainage area data for reservoirs and OASIS model stream nodes are shown in Tables 1.3 and 1.4, respectively.

Table 1.2. List of USGS Stream Gages

Stream	Location		Gage Number	Start Date	End Date	Area Sq. mi.	---- OASIS Reference ---- Name	Num.
Susquehanna River	Colliersville	NY	14975	10/1/24	9/30/68	349	Colliersville	1
Susquehanna River	Unadilla	NY	15005	6/8/38	3/31/95	982	Unadilla	2
Unadilla River	Rockdale	NY	15025	11/22/29	3/31/95	520	Rockdale	3
Susquehanna River	Conklin	NY	15030	1/1/13		2,232	Conklin	63
Tioughnioga River	Cortland	NY	15090	5/20/38		292	Cortland	4
Tioughnioga River	Itaska	NY	15115	10/1/29	6/30/67	730	Itaska	5
Chenango River	Chenango Forks	NY	15125	11/11/12		1,483	ChenangoFk	6
Susquehanna River	Vestal	NY	15135	10/1/37	6/30/67	3,941	Vestal	7
Susquehanna River	Waverly	NY	15150	3/1/37	9/30/95	4,773	Waverly	8
Cowanesque River	Lawrenceville	PA	15200	10/1/51		298	Lawrenceville	12
Tioga River	Lindley	NY	15205	1/11/30	3/31/95	771	Lindley	13
Tioga River	Erwins	NY	15265	7/12/18		1,377	Erwins	14
Chemung River	Corning	NY	15299.5	10/1/74		2,005	Corning	64
Chemung River	Chemung	NY	15310	9/7/03		2,506	Chemung	65

Table 1.2. List of USGS Stream Gages (continued)

Stream	Location		Gage Number	Start Date	End Date	Area Sq. mi.	---- OASIS Reference ---- Name	Num.
Susquehanna River	Towanda	PA	15315	10/1/13		7,797	Towanda	15
Towanda Creek	Monroeton	PA	15320	2/1/14		215	Monroeton	16
Susquehanna River	Meshoppen	PA	15334	10/1/76		8,720	Meshoppen	17
Tunkhannock Creek	Tunkhannock	PA	15340	2/1/14		383	Tunkhannock	18
Lackawanna River	Old Forge	PA	15360	10/1/38		332	OldForge	19
Susquehanna River	Wilkes Barre	PA	15365	4/1/1899		9,960	Wilkes Barre	20
Susquehanna River	Danville	PA	15405	4/1/05		11,220	Danville	21
WBr Susquehanna River	Bower	PA	15410	10/1/13		315	Bower	22
Clearfield Creek	Dimeling	PA	15415	10/1/13		371	Dimeling	23
WBr Susquehanna River	Karthaus	PA	15425	3/1/40	9/30/95	1,462	Karthaus	24
Driftwood Branch	Sterling Run	PA	15430	10/1/13		272	Sterling Run	25
Sinnemahoning Creek	Sinnemahoning	PA	15435	10/1/38		685	SinnCk	26
First Fork	Stevenson	PA	15440	10/1/53		245	Stevenson	27
Kettle Creek	Cross Fork	PA	15445	10/1/40		136	CrossFk	28
WBr Susquehanna River	Renovo	PA	15455	10/1/07		2,975	Renovo	29
Spring Creek	Axeman	PA	15465	10/1/40		87.2	Axeman	30
Bald Eagle Creek	Milesburg	PA	15472	10/1/55		265	Milesburg	31
Bald Eagle Creek	Blanchard	PA	15475	5/1/54		339	Blanchard	32
Blockhouse Creek	English Center	PA	15495	10/1/40		37.7	EnglishCenter	33
Pine Creek	Waterville	PA	15497	10/1/57		944	Waterville	34
Lycoming Creek	Trout Run	PA	15500	12/1/13		173	TroutRun	35
WBr Susquehanna River	Williamsport	PA	15515	3/1/1895		5,682	Williamsport	36
Chillisquaque Creek	Washingtonville	PA	15537	5/1/79		51.3	ChillisCk	38
Susquehanna River	Sunbury	PA	15540	10/1/37		18,300	Sunbury	39
Penns Creek	Penns Creek	PA	15550	10/1/29		301	PennsCk	40
E Mahantango Creek	Dalmatia	PA	15555	10/1/29		162	EmahanCk	41
Frankstown Branch	Williamsburg	PA	15560	10/1/16		291	Williamsburg	42
Juniata River	Huntingdon	PA	15590	10/1/41		816	Jun_Hunt	43
Raystown Branch	Saxton	PA	15620	10/1/11		756	Saxton	44
Raystown Branch	Huntingdon	PA	15632	10/1/46		960	Ray_Hunt	45
Juniata River	Mapleton Depot	PA	15635	10/1/37		2,030	Mapleton	46
Aughwick Creek	Three Springs	PA	15645	6/1/38		205	3Springs	47
Juniata River	Newport	PA	15670	4/1/1899		3,354	Newport	48
Sherman Creek	Shermans Dale	PA	15680	10/1/29		200	Shermansdale	49
Clarks Creek	Carsonville	PA	15685	10/1/37	12/31/96	22.5	Carsonville	50
Letort Spring Run	Carlisle	PA	15698	6/15/76		21.6	Carlisle	51
Conodoguinet Creek	Hogestown	PA	15700	10/1/11		470	Hogestown	52
Susquehanna River	Harrisburg	PA	15705	10/1/1890		24,100	Harrisburg	53
Yellow Breeches Creek	Camp Hill	PA	15715	1/1/10		216	CampHill	54
Swatara Creek	Harper Tavern	PA	15730	1/1/19		337	HarperTavern	55
W Conewago Creek	Manchester	PA	15740	10/1/28		510	Manchester	56
Codorus Creek	Spring Grove	PA	15745	5/1/29		75.5	SpringGrove	57
Codorus Creek	York	PA	15755	8/1/40	9/30/96	222	York	58
Susquehanna River	Marietta	PA	15760	10/1/31		25,990	Marietta	59
Conestoga River	Lancaster	PA	15765	10/1/28		324	Lancaster	60
Susquehanna River	Conowingo	MD	15783.1	10/1/67		27,100	Conowingo	61
Deer Creek	Rocks	MD	15800	10/1/26		94.4	Rocks	62

A map depicting the location of the stream gages used in the development of the hydrologic record is shown on the following page.

Figure 1.1. Locations of Stream Gages Used in Development of Hydrologic Record

Table 1.3. Drainage Areas of Reservoirs

Dam	Area sq. mi.	Oasis Node	Stream
Otsego	75.3	100	Susq R
East Sidney	103	125	Ouleout Ck
Whitney Point	257	150	Otselic R
Tioga	280	185	Tioga R
Hammond	122	190	Crooked Ck
Cowanesque	298	200	Cowanesque R
Curwensville	365	290	W Br Susq R
Glendale	41.9	292	
Stevenson	243	305	First Fork Sinn
Bush	226	320	Kettle Ck
Sayers	339	345	Bald Eagle Ck
Little Pine Ck	165.4	355	Little Pine Ck
Chillisquaque		375	Chill. Ck
Shawnee	37.5	395	Raystown Br Juniata R
Raystown	959	400	Raystown Br Juniata R
Dehart	21.6	425	Clarks Ck
Letterkenny	33.8	440	Conodoguinet Ck
York Haven	24,973	475	Susq R
Pinchot	17.5	490	Conewago Ck
Marburg	24.3	505	Codorus Ck
Indian Rock	94	520	Codorus Ck
Redman	40	525	E. Br. Codorus Ck
Williams	41.6	530	E. Br. Codorus Ck
Safe Harbor	26,090	555	Susq R
Holtwood	26,786	560	Susq R
Muddy Run	9.2	565	Muddy Run
Conowingo	27,100	570	Susq R
Octoraro	139.6	585	Octoraro Ck

Table 1.4. Drainage Areas of Stream Nodes

Stream Nodes	Area (sq. mi.)	OASIS Node
Susquehanna River @ Colliersville	349	110
Susquehanna River @ Oneonta	679	115
Susquehanna River @ Unadilla	982	130
Unadilla River @ Rockdale	520	135
Susquehanna River @ Bainbridge	1,610	140
Susquehanna River @ Conklin	2,232	145
Susquehanna River @ Binghamton	2,286	165
Otselic River @ mouth	258	150
Tioughnioga River @ Whitney Point	457	155
Chenango River @ Chenango Forks	1,483	160
Susquehanna River @ Vestal	3,941	175
Susquehanna River @ Waverly	4,773	180
Susquehanna River @ Athens	4,933	245
Tioga River @ Tioga	282	185
Crooked Creek @ mouth	132	195
Tioga River @ Lindley	771	205
Tioga River @ Erwins	1,377	210
Cohocton River @ Campbell	470	215
Chemung River @ Corning	2,006	220
Chemung River @ Elmira	2,162	230
Chemung River @ Chemung	2,506	240
Susquehanna River @ Towanda	7,797	250
Susquehanna River @ Meshoppen	8,720	255
Lackawanna River @ Old Forge	332	270
Susquehanna River @ Wilkes Barre	9,960	275
Susquehanna River @ Danville	11,220	280
Clearfield Creek @ Dimeling	371	295
West Branch Susquehanna @ Karthaus	1,462	300
West Branch Susquehanna @ Keating	1,594	315
Sinnemahoning Creek @ Sinnemahoning	685	310
West Branch Susquehanna @ Renovo	2,975	325
West Branch Susquehanna @ Lock Haven	4,120	350
Bald Eagle Creek @ Milesburg	265	340
Pine Creek @ Waterville	944	360
West Branch Susquehanna @ Jersey Shore	5,167	365
West Branch Susquehanna @ Lewisburg	6,847	380
Susquehanna River @ Sunbury	11,298	385
Juniata River @ Huntingdon	960	405
Juniata River @ Mapleton Depot	2,030	410
Juniata River @ Newport	3,354	415
Susquehanna River @ Duncannon	23,131	420
Susquehanna River @ Dauphin	23,489	435
Conodoguinet Creek @ Hogestown	470	445
Susquehanna River @ Harrisburg	24,100	450
Yellow Breeches Creek @ Camp Hill	216	460
Swatara Creek @ Lebanon	337	465
Susquehanna River @ Marietta	25,990	495
Codorus Creek @ Glatfelter Diversion	75.5	510
Codorus Creek @ York	222	535
Conestoga River @ Lancaster	324	545
Deer Creek @ Rocks	94.4	600
Deer Creek @ Darlington	168	610

B. Development of Historic Water Use Time Series

All available records or estimates of consumptive water use for all locations in the basin were compiled for use in generating a time series of monthly average consumptive use on a watershed basis. Available records included the two Pennsylvania State Water Plans from the 1930s and the 1970s, municipal withdrawal records, periodic USGS water use estimates, records of power plant construction and water use, and reports of withdrawal and consumptive use made to the Commission by regulated entities. Use records were compiled by watershed; the 8-digit USGS Hydrologic Unit Code (HUC) regions were used in New York and Maryland, and the State Water Plan sub-watersheds were used in Pennsylvania.

Two aspects of the consumptive use time series were considered: (1) the "background" consumptive use, representing the distributed use by households, agricultural operations, and small commercial and industrial applications; and (2) large point source consumptive uses such as those associated with power plants and municipal diversions. Fairly accurate records for power plant and municipal use are available, but the modeling team needed to rely on available estimates for most domestic, agricultural, commercial, and industrial water demand.

These two components of consumptive water use were treated differently in the generation of the time series. The background use was assumed to change gradually from year to year, in conjunction with changes to populations. Large point sources, however, are recognized as incremental uses that begin on specific dates and increase by discrete blocks rather than gradually over time.

C. Computation of Unimpaired Gage Flows

The consumptive water use at each demand node and the flow equivalent of both the change in reservoir storage (storage at end of current month minus storage at the end of the previous month) and the net evaporation (evaporation minus rainfall) were added to the gage flows. These computations are done with monthly data. It is important to note that an impairment carries all the way downstream. For example, the change in flow due to a change in storage at Cowanesque Lake carries all the way down to the mouth of the Susquehanna. Thus, the quantity of water entering the Conowingo pond is affected by all the demands and reservoirs upstream.

The final output from this activity was a record of unimpaired flows at all the gages that are affected by demands and change in storage. The consumptive water use demand and reservoir nodes for which data are available are listed in Table 1.4. Rather than attribute localized demands to each individual node, the demands were aggregated and applied at a limited number of nodes near the mouths of major watersheds in the basin, at 15 nodes. There are also five nodes representing the demand at individual power plants. The six reservoir nodes where change in storage was computed represent the largest reservoirs in the basin and are all flood control facilities of the U.S. Army Corps of Engineers. Other modeled reservoirs, specifically water supply reservoirs, are smaller than Corps reservoirs and do not exhibit dramatic changes in storage and, thus, do not have significant effects on streamflows over long-term periods.

Table 1.5. Demand and Reservoir Nodes with Data

Demand Nodes				Reservoir Nodes	
Number	Name	Number	Name	Number	Name
170	Binghamton	182	Waverly	175	Whitney Point
225	Corning	235	Chemung	190	Tioga/Hammond
265	Wilkes Barre	285	Berwick PP	200	Cowanesque
316	Keating	366	Jersey Shore	290	Curwensville
382	Montour PP	386	Sunbury	345	Sayers
406	Huntingdon	416	Newport	400	Raystown
421	Duncannon	451	Harrisburg		
476	York Haven Local	480	Three Mile Island PP		
485	Brunner Island PP	496	Marietta Local		
550	Lancaster	575	Peach Bottom PP		

D. Synthesis of Missing Gage Records and Reach Gains

Computations for this section are done after *fillin* has been run to extend the record of flows and gains for gages with missing records. An important part of this process is "scaling." The objective of scaling is to ensure that the sum of filled-in records upstream of a gage with an actual record equals the actual recorded flow. The *fillin* program does not ensure this for two reasons. First, it utilizes only a single correlated record for each value generated, thus ignoring sums, and second, it works with log transforms, and not actual flows.

In order to ensure that the sums equal the actual flows, the individual flows making up the sum are all multiplied by common scaling factor. The value of the factor is set for each period so that the sums match.

Factor = actual flow / sum of *fillin*-generated flows and gains

When each of the generated flows is multiplied by this factor, the sum of the products will be the actual flow. The products are the values that will be used as the final-generated gains or flows.

Here is an example. From April 1995 to present, the Colliersville, Rockdale, and Unadilla gages have no record, so there is no actual gain at either Unadilla or Conklin. The two gage records and two gains were extended using *fillin.* Those extended values then needed to be adjusted so that the sum of the two flows and the two gains matched the recorded flow at Conklin. So, the Conklin actual flow is maintained by scaling with the Rockdale extended flow and the Unadilla and Conklin extended gain. The calculation is:

Colliersville flow = Conklin actual flow * Colliersville extended flow / (Colliersville extended flow + Unadilla extended gain + Rockdale extended flow + Conklin extended gain)

In this way, it is ensured that the total volume of all the flows and gains upstream from a given gage match the flow at the gage. The formulas for each node are available for review in the project files at the Commission.

E. Computing Inflows at OASIS Nodes

This section describes how the local inflows to the OASIS nodes are computed. These inflows are the water that joins the water from the upstream node as it flows to the node of interest. The inflows are disaggregated into daily flow and gain values from the monthly values. The disaggregation formula is:

daily unknown = monthly unknown * daily known / monthly known

It is important to note that the goal is not to replicate history in disaggregating the monthlies into dailies; rather, it is to build daily flows whose variation is *representative* of history.

The formulas for computing the nodal inflows and disaggregating them from monthly values to daily values are available for review in the project files at the Commission.

F. Application of Flow Routing

The Muskingum routing method relies on two coefficients: K (a measure of travel time through a reach) and X (a measure of channel storage within a reach), to compute the outflow hydrograph (stream flow versus time) from a reach, given an inflow hydrograph. The K and X values lead to the computation of three coefficients (c1, c2, and c3), which are used in the following equation to compute an outflow hydrograph.

$$O_{t+1} = c1*I_{t+1} + c2*I_t + c3*O_t$$

Where, O_{t+1} is today's outflow from the reach, O_t is yesterday's outflow from the reach, and I_t and I_{t+1} are yesterday's and today's inflow into the reach, respectively.

The method used to calculate the coefficients was the optimizer function in Microsoft Excel. Three hydrographs were entered into Excel: the upstream gage values (u/s), the computed gains, and the downstream gage values (d/s). The gains are added to the upstream hydrograph; this is then used with the downstream hydrograph to compute the c values. The objective function is to minimize the sum of the absolute values of the residuals, subject to c1+c2+c3 = 1 and each c is non-negative. A sample computation and the resultant coefficients are shown below. All of the files used in this analysis are available in the project files at the Commission.

Bainbridge to Conklin, node 140 to node 145. U/s hydrograph is Rockdale gage plus Unadilla gage plus Inflow140 plus Inflow145, gage at Conklin is d/s hydrograph.

Results: c1 = 0.108; c2 = 0.838; c3 = 0.054

Section 2. Extent of Model Coverage

Although the focus of the planning study is on the conditions in and below the Conowingo pond, the Workgroup recognized that upstream conditions play a role significant enough to merit their inclusion in the model. Specifically, operations at the Conowingo dam during low flow conditions are driven by conditions at the USGS stream gage located at Marietta, Pennsylvania, and reliable modeling capabilities at that location on the Susquehanna River are, thus, essential to successful analysis. Further, conditions at Marietta are, in turn, driven by hydrologic conditions in the 25,990 square miles of upstream drainage. Those conditions are influenced not only by upstream flow regimes, but also by upstream water demands and the operation of flood control and water supply reservoirs. See Figure 2.1 for a depiction of the extent of basin coverage by the model.

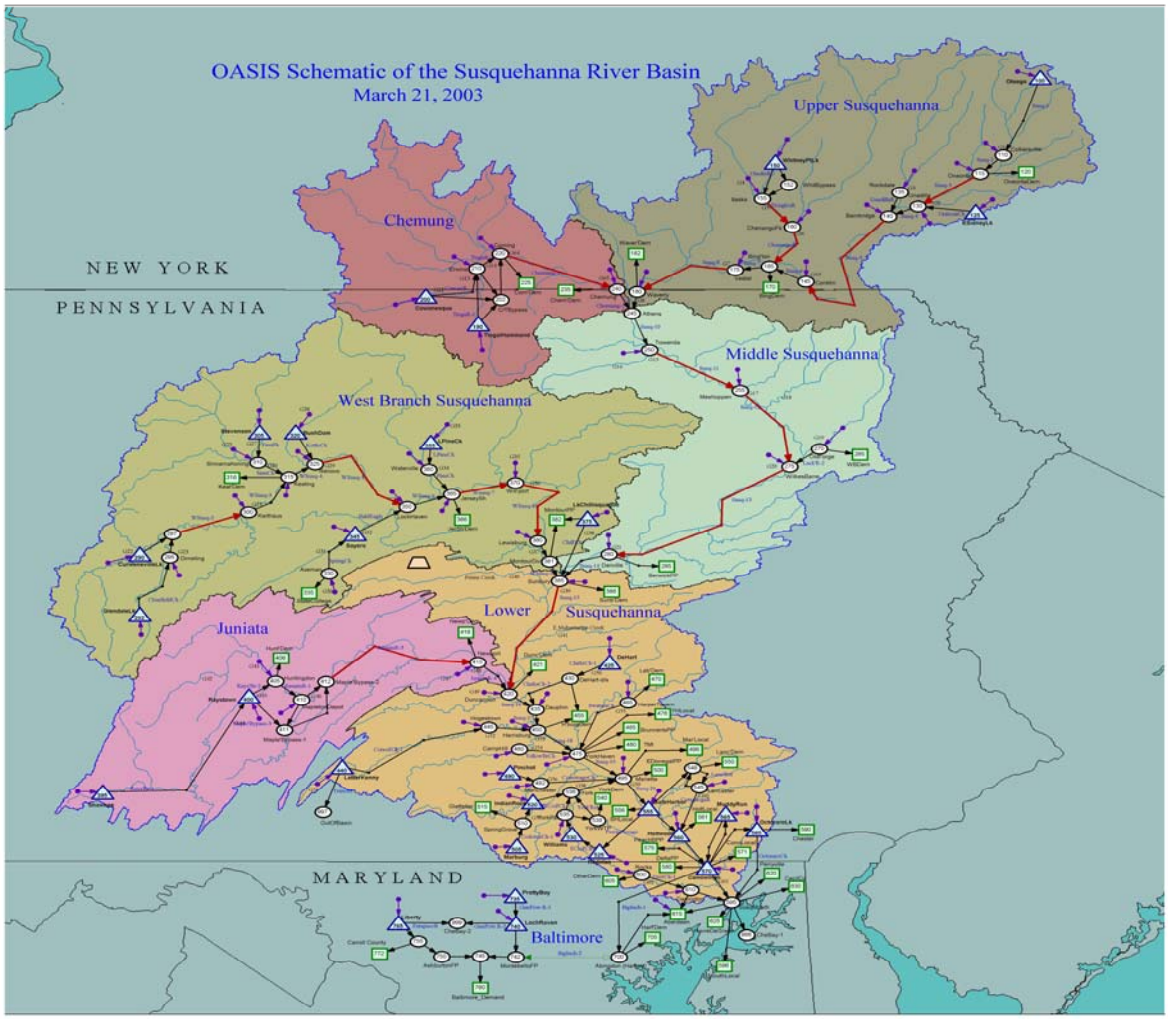


Figure 2.1. Schematic of Hydrologic Model Coverage

Section 3. Incorporation of Operational Parameters

Concerted efforts were made to understand and accurately model the sometimes complex operating rules and management protocols of the large reservoirs and hydroelectric facilities that can affect the Conowingo pond, particularly operations during low flow conditions.

A. Water Supply Reservoirs

Based on information provided by the owners and operators of the water supply reservoirs built into the OASIS model, the appropriate conservation releases (see Table 2.1) and operating rules were incorporated into model logic.

Table 3.1. Water Supply Reservoir Conservation Releases

Reservoir	Owner	Conservation Release, mgd (cfs)
Lake Redman	York Water Company	Not applicable[1]
Lake Williams	York Water Company	7.8 (12)
Octoraro Lake	Chester Water Authority	18 (27.7)
Liberty Reservoir	City of Baltimore	Not applicable[2]
Prettyboy Reservoir	City of Baltimore	7.2 (11)
Loch Raven Reservoir	City of Baltimore	Not applicable[3]

1 – Lake Redman feeds directly into Lake Williams without any intervening stream.
2 – Liberty Reservoir discharges significant quantities of water, well above a conservation release, on a continual basis to supply the Ashburtion filtration plant, the western zone of the City of Baltimore's service area, and needs in Carroll County.
3 – Loch Raven Reservoir discharges significant quantities of water, well above a conservation release, on a continual basis to supply the Montebello treatment plant, the eastern zone of the City of Baltimore's service area, and needs in Harford County.

Operating Rules: General rules for major water supply reservoirs are described below. Detailed rule documentation is available in the project file at the Commission.

Chester Water Authority: The rules supplied by Chester Water Authority for pumping from the Susquehanna River and Octoraro Reservoir are based on levels in the Octoraro Reservoir and the seasonal and annual balance between pumping sources.

City of Baltimore: Operating rules for the City's reservoirs are based on seasonal levels at the Prettyboy and Loch Raven reservoirs. Those levels also determine the extent of pumping from the Susquehanna River.

York Water Company: The timing and duration of pumping from the Susquehanna River are determined by the level of storage in Lake Redman.

B. Flood Control Reservoirs

USACE reservoirs are subject to many complex rules, particularly during flood events. The most important rules for this modeling effort are those that pertain to low flow events, specifically with respect to conservation releases. See Table 3.2. It is not uncommon for published operating rules to provide for conservation releases that exceed the amount of flow that would be present in the reach under unregulated conditions. For that reason, the conservation releases from USACE reservoirs have the potential to affect water availability in the Conowingo pond.

Table 3.2. USACE Reservoir Conservation Releases

Reservoir	Conservation Release, mgd (cfs)
Cowanesque	9.7 (15)
Tioga/Hammond	22.6 (35)
Whitney Point	6.5 (10)
East Sidney	6.5 (10)
Curwensville	32.3 (50)
Stevenson	23.3 (36)[1]
Bush	6.5 (10)
Sayers	80.8 (125)
Raystown	129 (200) mid-May through mid-November; 310 (480) remainder of year
York Indian Rock	Not applicable[2]

1 – Operations are managed by USACE, but the dam is actually owned by PADEP.
2 – York Indian Rock is a dry reservoir, except during heavy rains.

Operations of Commission Storage at Cowanesque and Curwensville: The baseline version of the model operates under the release protocols as defined in the agreement between USACE and the Commission, but alternate model runs were available for simulation, in which the criteria for timing and quantity of low flow releases were altered. Because it cannot be assumed that operating protocols will change, only the existing contracted operations were used in the final set of alternatives. The contract entails the release of Commission storage when the flow at the Wilkes Barre or Harrisburg gage drops below the Q7-10 value. Q-FERC levels at Marietta occur much more frequently than Q7-10 does, so it is possible that critical low flow problems are occurring in the Conowingo pond without any releases being made from Commission storage.

C. Hydroelectric Facilities

Operations at the major hydroelectric facilities on the lower Susquehanna River were modeled in accordance with the requirements contained in the separate FERC operating licenses, specifically with respect to meeting minimum release requirements and pond elevation requirements. See Table 3.3.

Table 3.3. FERC Operating Requirements

Facility	Owner	Pond Elevation Limits (NGVD)	Minimum Release, mgd (cfs)
Safe Harbor	PPL, BGE	224.2 – 227.2	Not applicable[2]
Holtwood	PPL	163.5 – 171; minimum of 167.5 for recreation	Not applicable[2]
Muddy Run	Exelon	480-520	Not applicable[2]
Conowingo	Exelon	101.5 – 108.5[(1)]; minimum of 106.5 for recreation	Minimum of flow at Marietta gage or seasonal thresholds (see Section III.B. of the main report)

1 – Elevations are in reference to the Conowingo datum.
2 – These facilities do not have minimum release requirements in their FERC licenses, and at times will release no water to downstream reaches.

Operating Capacities and Protocols:

Safe Harbor and Holtwood: These facilities were modeled as run-of-river operations, although they are subject to peaking operations, particularly during low flows. However, the quantity of inflow to the facilities is generally the same quantity of water discharged over a 24-hour period, so the peaking cycle occurs within the timestep of the daily model. These two dams are, therefore, modeled to remain at full pond levels and, thus, discharge only the excess inflow water after evaporation and demand needs are satisfied.

Muddy Run: When sufficient water is available in Conowingo pond, Muddy Run Pumped Storage Facility is operated in accordance with the schedule shown in Table 3.4. When lesser quantities of water are available in Conowingo pond for pumping up to Muddy Run, the operations require that all available water be pumped. All water is also discharged in accordance with the schedule, even if circumstances are such that insufficient water is likely to be available for refilling Muddy Run on subsequent days.

Conowingo: Top priority at Conowingo is given to satisfying withdrawals for public water supply and power plant cooling needs, followed by meeting minimum release requirements. Maintenance of recreation levels and making water available for Muddy Run operations are given lesser priority, in that order.

Table 3.4. Muddy Run Pumped Storage Facility Operating Schedule

Day of Week	Pumping Rate and Duration	Discharge Rate and Duration
Sunday	24,800 cfs for 8.33 hours overnight	No discharge
Monday	24,800 cfs for 10.2 hours overnight	32,000 cfs for 9 hours during the day
Tuesday	24,800 cfs for 10.2 hours overnight	32,000 cfs for 9 hours during the day
Wednesday	24,800 cfs for 10.2 hours overnight	32,000 cfs for 9 hours during the day
Thursday	24,800 cfs for 10.2 hours overnight	32,000 cfs for 9 hours during the day
Friday	No pumping	32,000 cfs for 9 hours during the day
Saturday	24,800 cfs for 9 hours overnight	No discharge

Section 4. Model Calibration and Verification

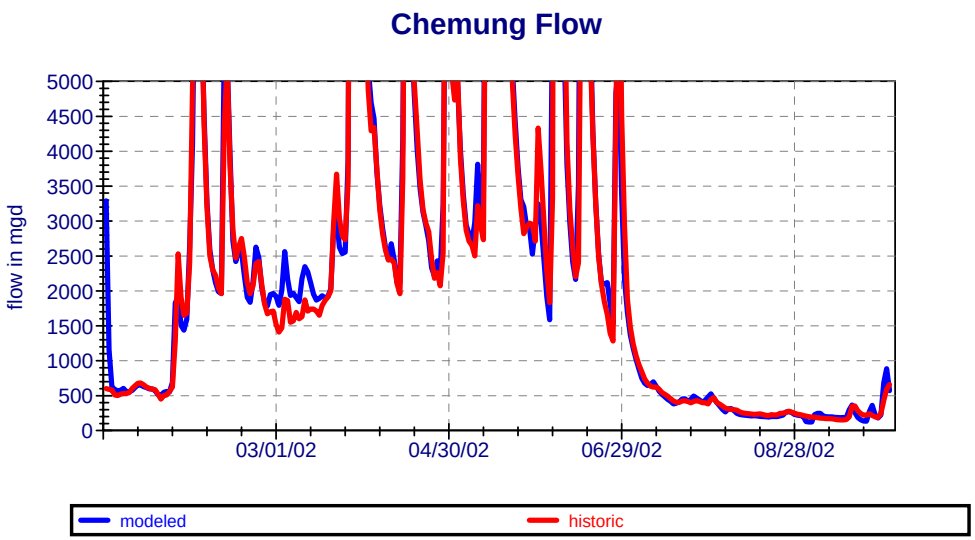
It was not the intent of the programmers to develop a hydrologic record that matches the published record precisely on a daily basis. By virtue of the methodology used to develop the hydrologic time-series, the generated record and the published record will match each other on a monthly-average basis, within a few percent. The resulting hydrologic time-series, while not exactly reproducing the measured data, give a very reasonable representation of a range of flow conditions that could be expected to occur in the Susquehanna River Basin.

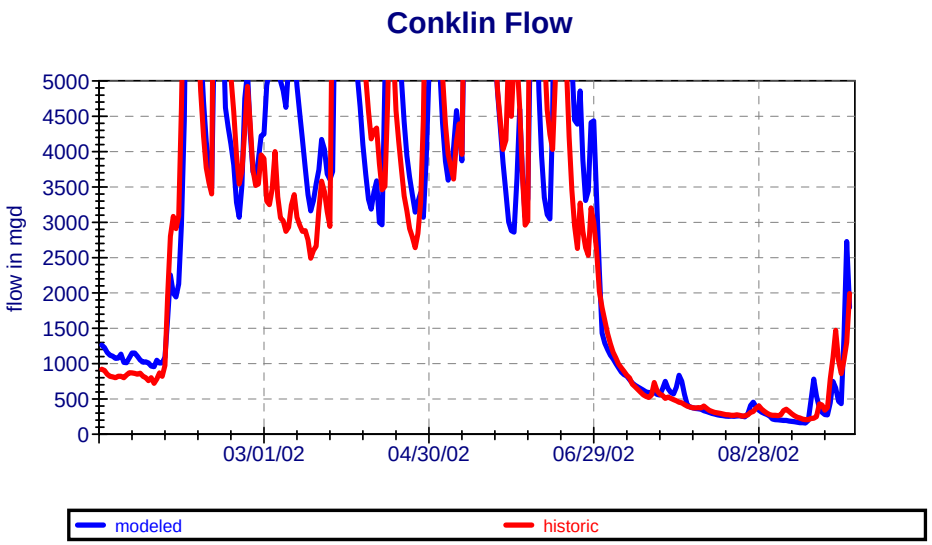
Because the timing of the model development coincided with the drought of 2002, hydrologic conditions during the drought were used to verify that the model was producing reasonable results. Operational rules and parameters in place during the summer of 2002 were simulated in the model and run with the hydrology generated for the year. Model results were compared to observed conditions in various areas of interest, grouped into the categories Hydrology and Operations. The comparative plots used for the verification by the Workgroup are displayed below.

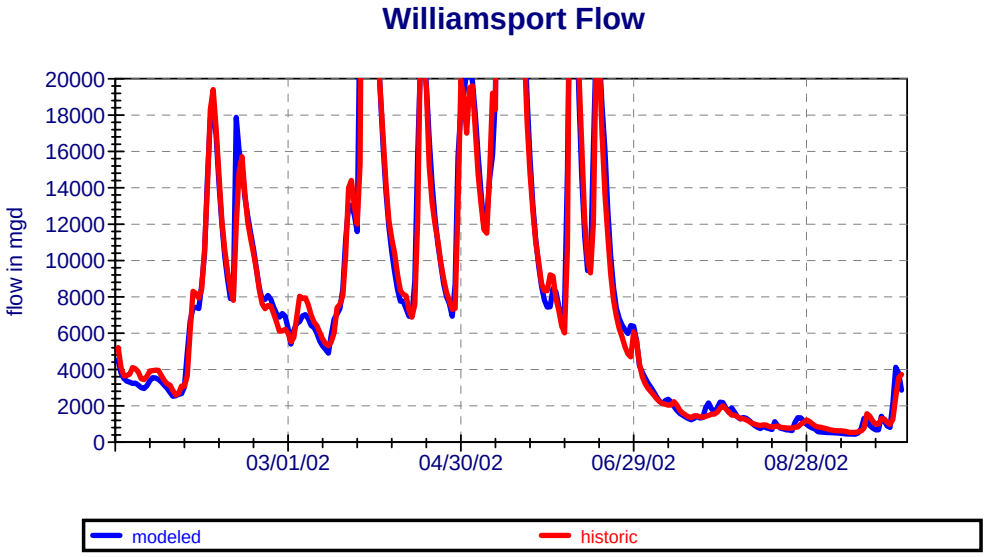
A. Hydrology

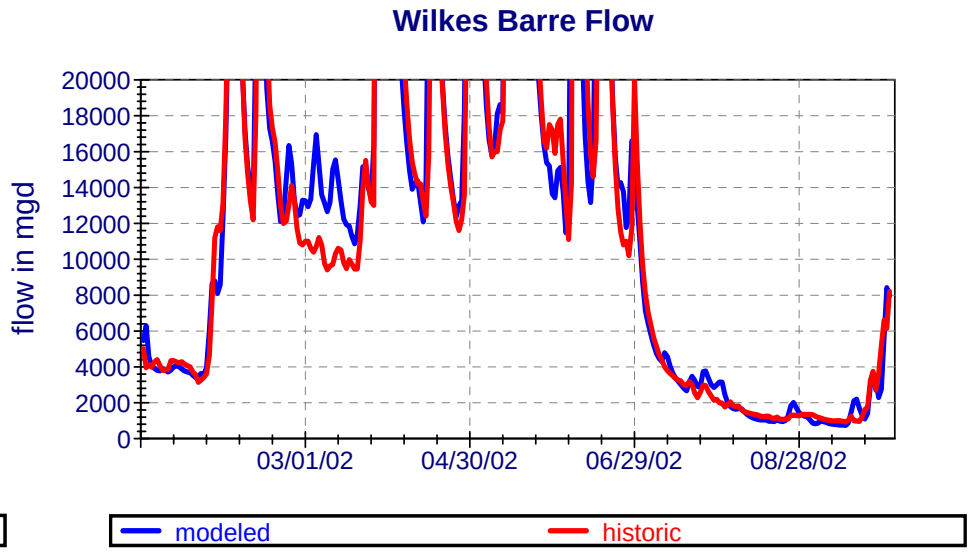
Plots of historic and modeled river flow were prepared for 10 locations throughout the basin and are presented below. Each of the six major subbasins was represented by at least one location: Chemung River at Chemung, Susquehanna River at Conklin, Susquehanna River at Wilkes Barre, Susquehanna River at Danville, West Branch Susquehanna River at Williamsport, Susquehanna River at Sunbury, Juniata River at Newport, Susquehanna River at Harrisburg, Susquehanna River at Marietta, and Susquehanna River below Conowingo Dam (representing releases from the dam).

Plots of time series of flow at the 10 locations are shown below. Because the 2002 drought had recently occurred and was familiar to Workgroup members, it was used to display the comparison between historic and modeled flows. At each of the 10 locations, the modeled flows matched the historic flows very well. An analysis of flow replication over the period of record in the model showed that the flow at every model node matched records within a few percentage points on a monthly average basis, well within the accuracy of the streamflow gage measurements.

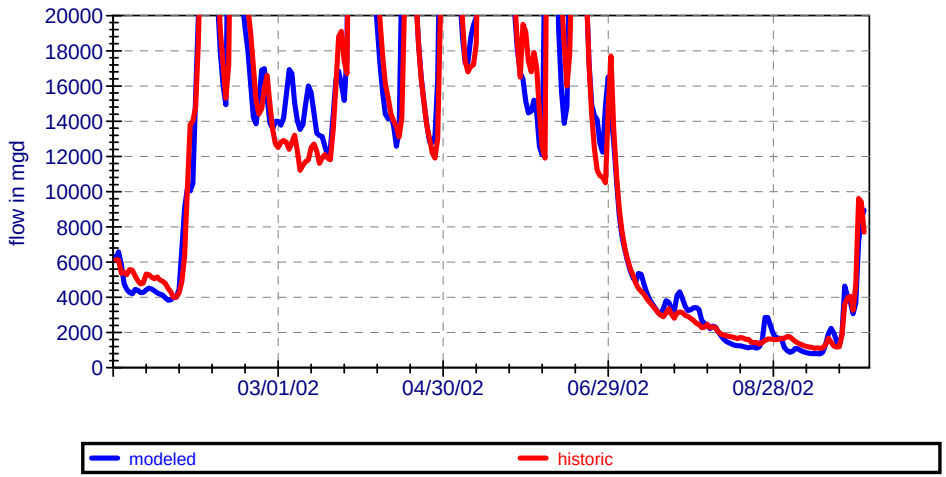

Chemung Flow
flow in mgd
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
03/01/02
04/30/02
06/29/02
08/28/02
modeled
historic


Conklin Flow
flow in mgd
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
03/01/02
04/30/02
06/29/02
08/28/02
modeled
historic

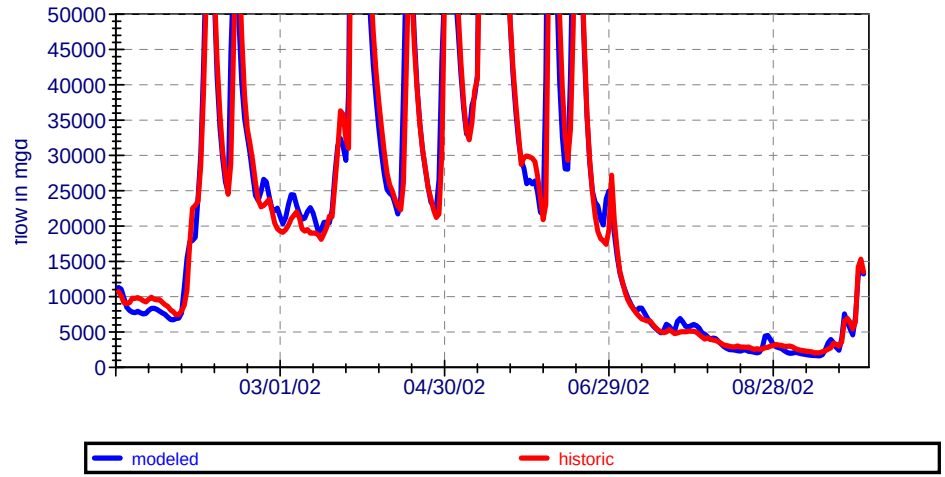

Williamsport Flow
flow in mgd
20000
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
03/01/02
04/30/02
06/29/02
08/28/02
modeled
historic


Wilkes Barre Flow
flow in mgd
20000
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
03/01/02
04/30/02
06/29/02
08/28/02
modeled
historic

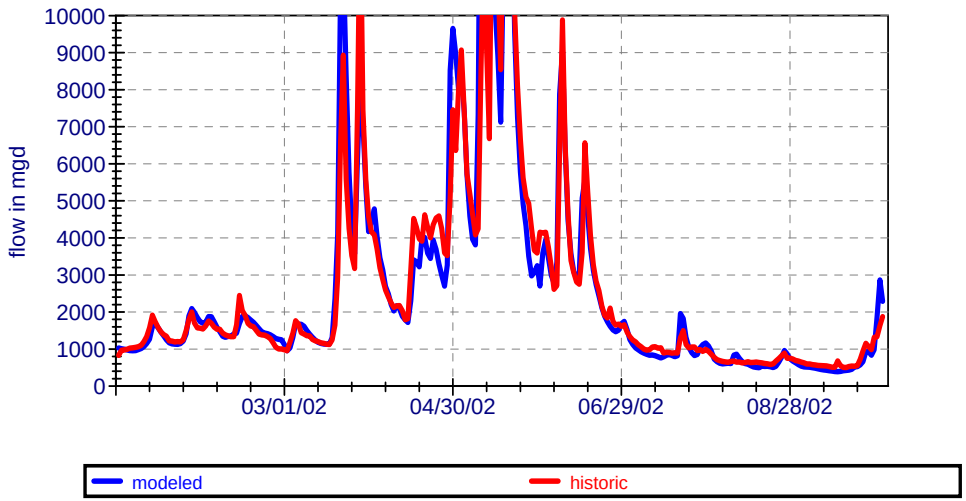
Danville Flow



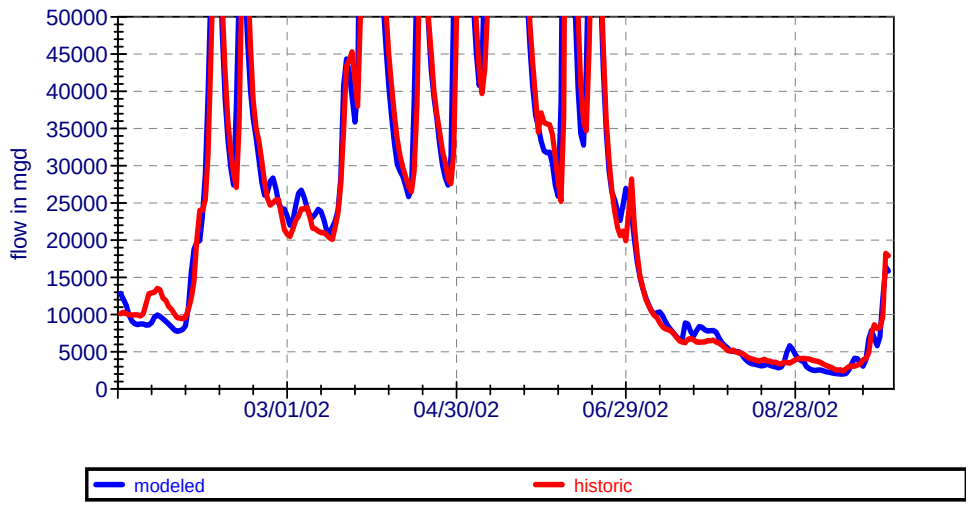
Sunbury Flow

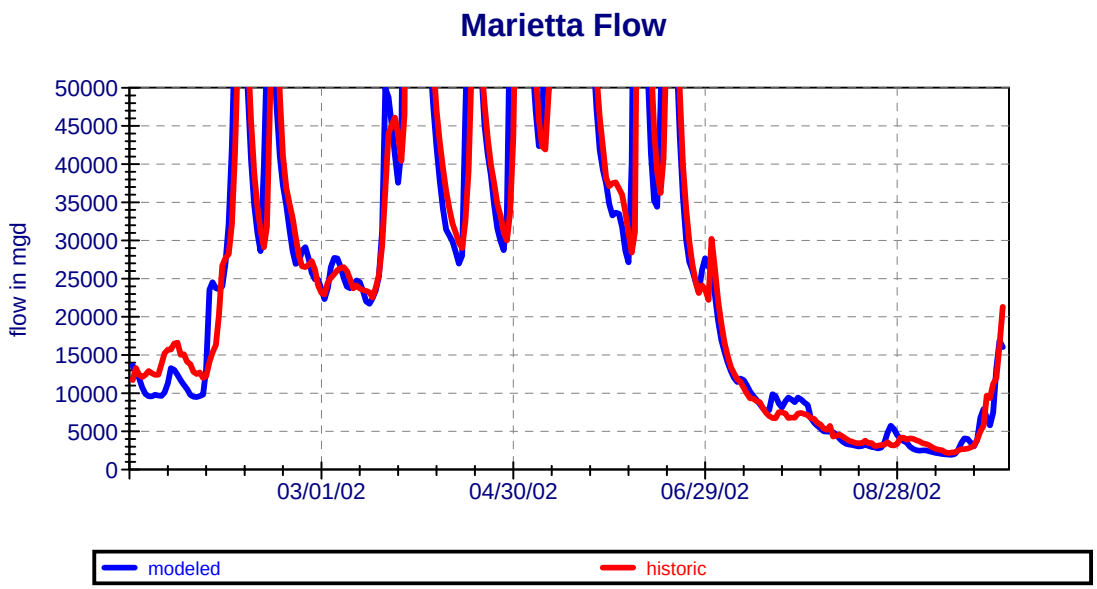


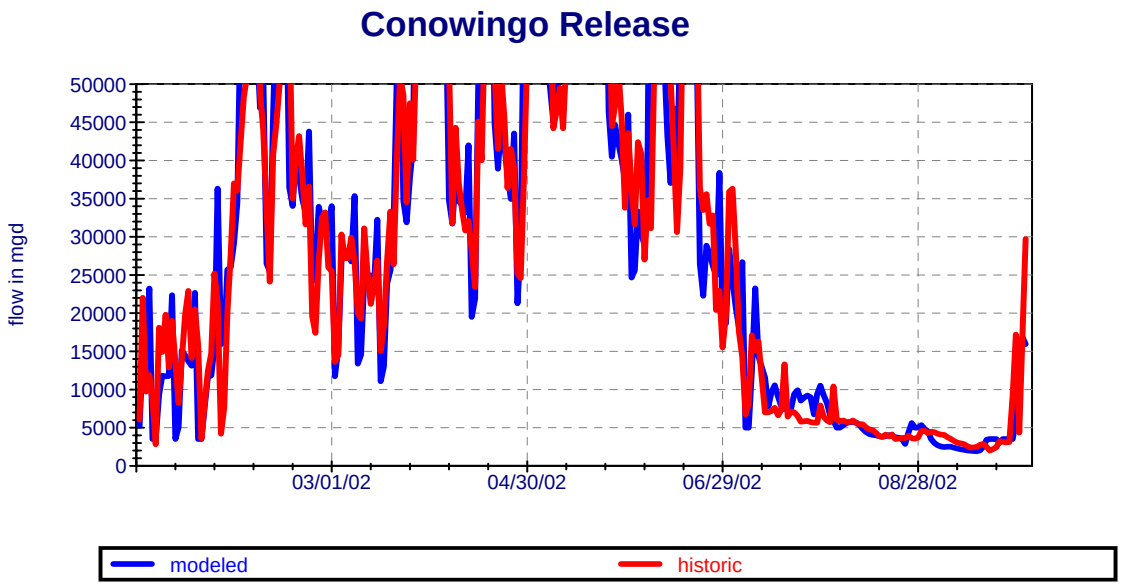
Newport Flow



Harrisburg Flow



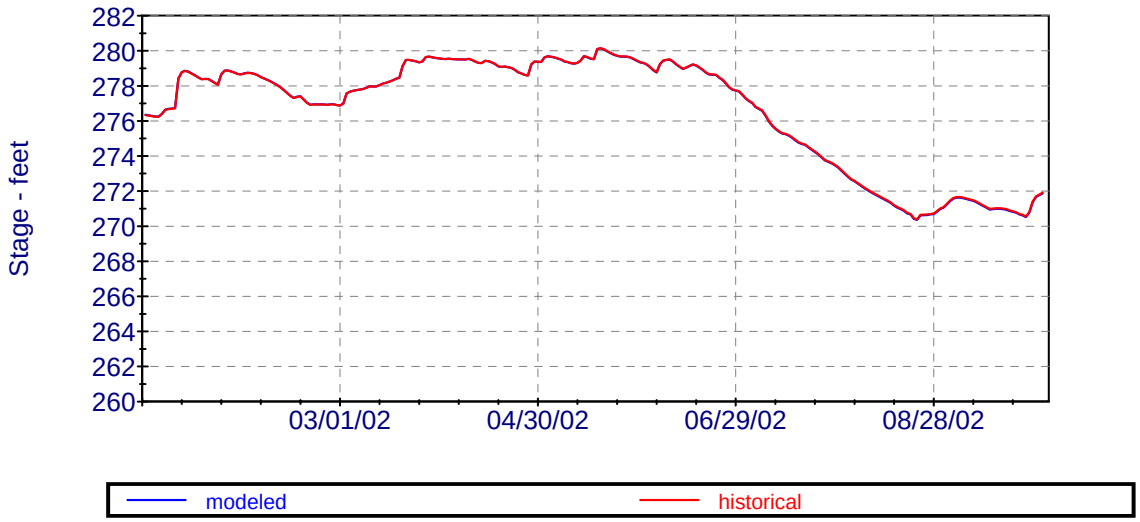




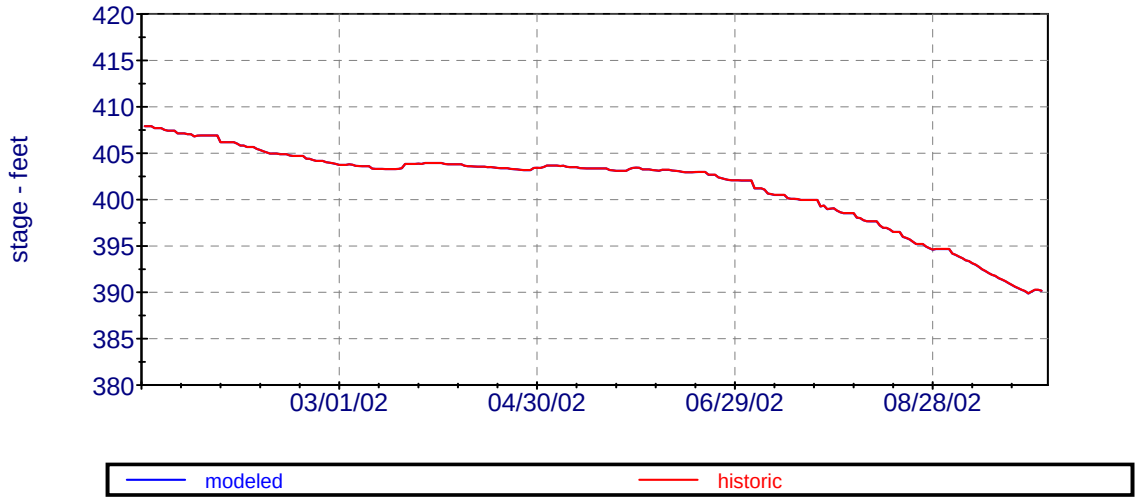
B. Reservoir Operations

Plots of modeled and observed stages at water supply reservoirs (Chester Water Authority's Octoraro Reservoir and City of Baltimore's Liberty, Loch Raven and Prettyboy Reservoirs) and the Conowingo pond were prepared and are shown below. The results are similar enough that the trace of the modeled results cannot be seen underneath the observed historical results. The similarity between the modeled stages and the observed stages served to confirm that the physical and operational parameters of the reservoirs were modeled accurately, including flow characteristics such as inflow and releases, as well as the relation between volume and elevation.

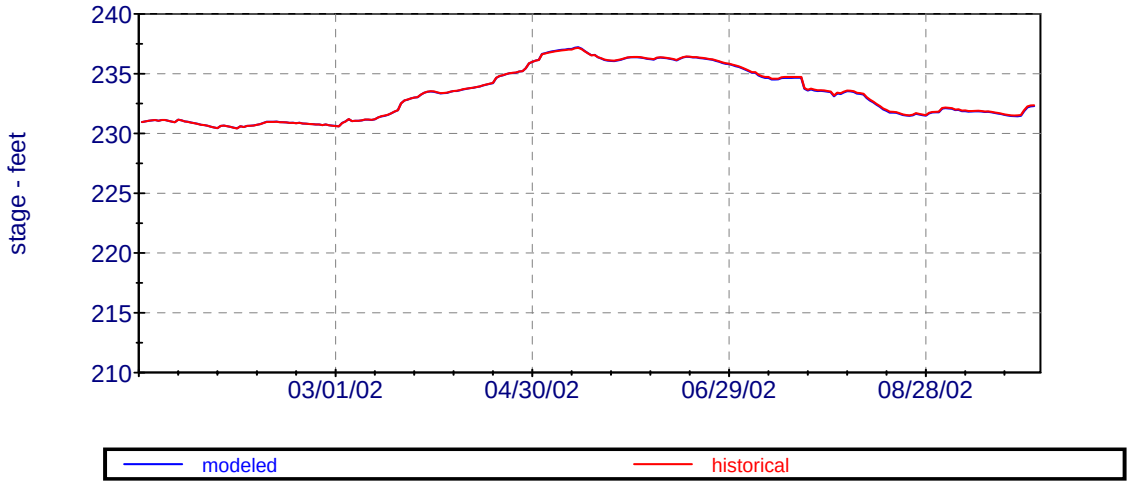
Octoraro Stage

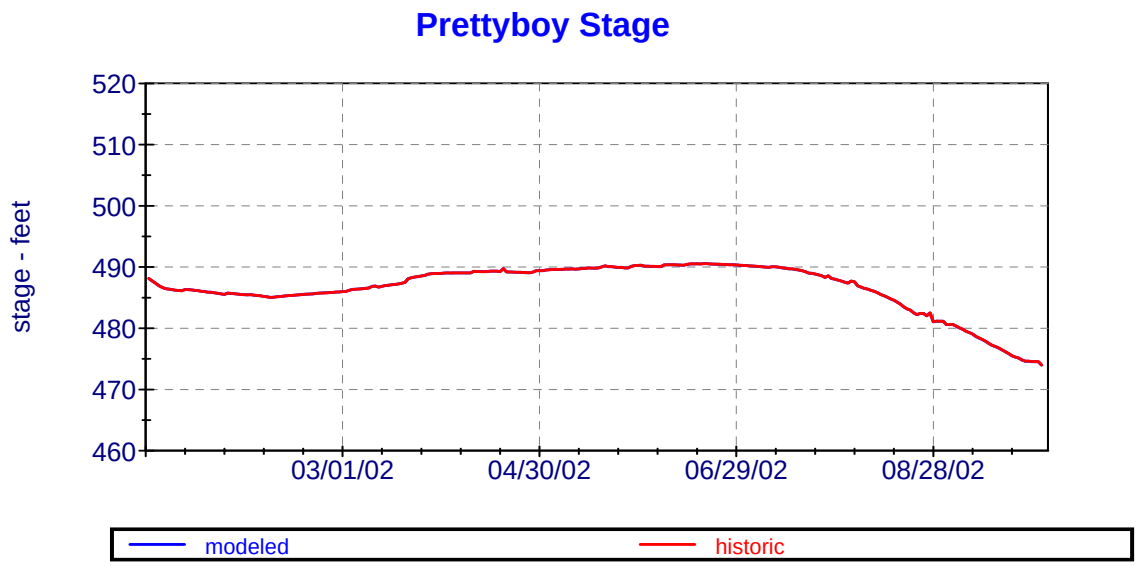


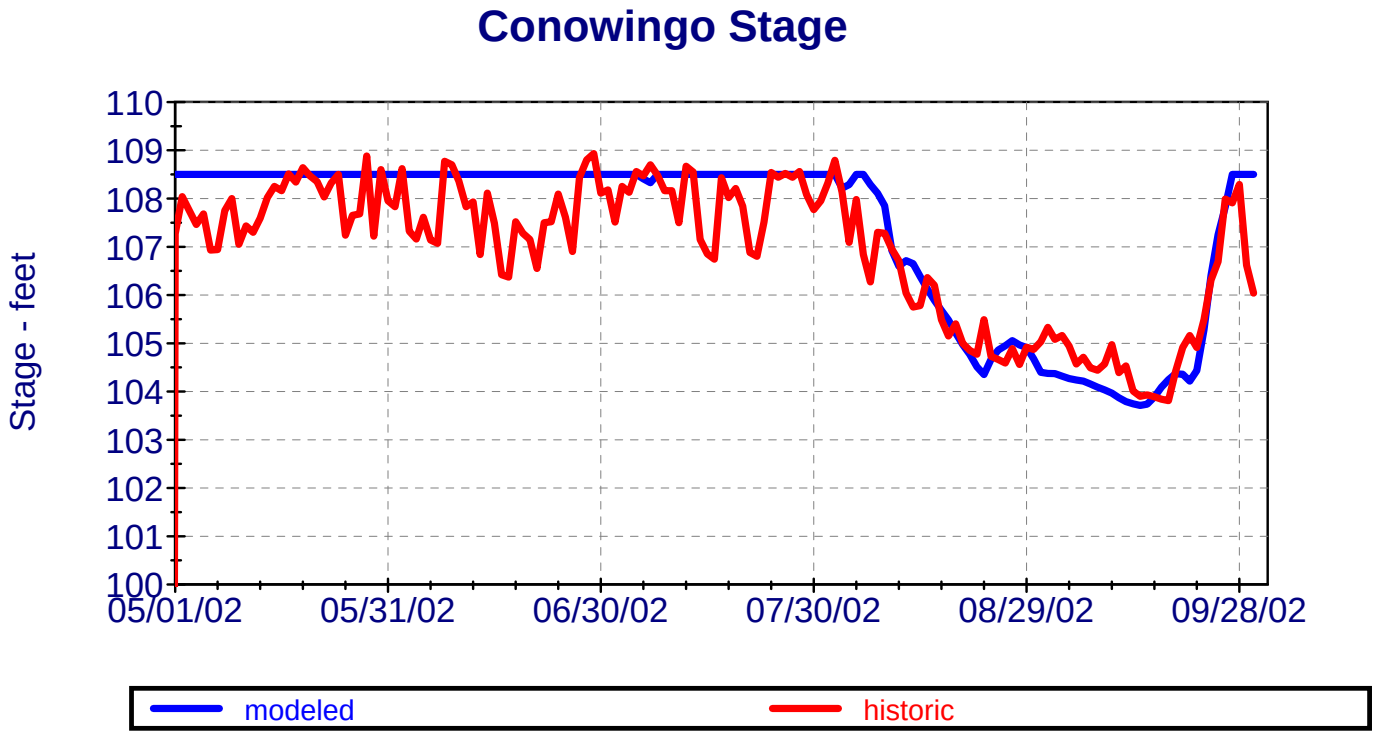
Liberty Stage



Loch Raven Stage




Prettyboy Stage
stage - feet
520
510
500
490
480
470
460
03/01/02
04/30/02
06/29/02
08/28/02
modeled
historic


Conowingo Stage
Stage - feet
110
109
108
107
106
105
104
103
102
101
100
05/01/02
05/31/02
06/30/02
07/30/02
08/29/02
09/28/02
modeled
historic