Attachment A-1: Additional Information for Susquehanna River at Marietta, PA (01576000), and Conowingo, MD (01578310), and Conowingo Reservoir

Attachment A-1

Additional Information for Susquehanna River at Marietta, Pennsylvania (01576000), Conowingo, Maryland (01578310), and Conowingo Reservoir

The following information is provided to help the Lower Susquehanna River Assessment Project in their efforts to study sediment loads from behind a series of three hydroelectric dams and associated reservoirs, located on the Susquehanna River draining into the northern Chesapeake Bay. Information provided includes recurrence intervals for two U.S. Geological Survey (USGS) streamgages, river and scour sediment transport, and evaluation of streamflow and sediment transport in the reservoirs. The Susquehanna River at Marietta, Pennsylvania and Conowingo, Maryland streamgages are considered to represent the flow and sediment input to and output from the reservoir system. Due to the lack of sediment information from the upper two reservoirs, the flow and sediment results are considered the cumulative effect of all three reservoirs. Information provided in this attachment may be useful to managers when considering a range of management options dealing with flow and sediment dynamics in the Lower Susquehanna River reservoir system.

Recurrence Intervals, Total and Scour Sediment Loads

Expected flows for many recurrence intervals (RI) are presented in table A1. A recurrence interval is a statistical estimate of the likelihood of a given streamflow to occur based on historic data. The annual exceedence probability is the chance of a given flow event to occur in the current year. Figure A1 illustrates the difference between RI and flow at the two USGS Susquehanna River gages representing inflow and outflow from the reservoir system—the Susquehanna River at Marietta, Pennsylvania (01576000) and the Susquehanna River at Conowingo, Maryland (01578310), respectively for 1968-2012. RI’s were computed using methods as described in Flynn and others (2006). Flows corresponding to various RI’s were computed for this study using methods as described in Flynn and others (2006). Station skew for frequency distribution was used at both stations and historic peak flows prior to 1968 were not used in the analysis. No low outliers were detected. Useful information about short-term streamflow includes the bankfull discharge (RI of about 1.5 years) and the mean peak discharge for the period of record (RI of 2.33 years).

Table A1. USGS estimated recurrence intervals, annual exceedence probabilities, and expected-streamflow estimates for two Susquehanna River streamgages. [cfs, cubic feet per second]

Station 01576000 Susquehanna River at Marietta, Pennsylvania (1968-2012)			Station 01578310 Susquehanna River at Conowingo, Maryland (1968-2012)		
Recurrence Interval (years)	Annual Exceedence Probability	Expected Streamflow Estimate (cfs)	Recurrence Interval (years)	Annual Exceedence Probability	Expected Streamflow Estimate (cfs)
1	0.995	113,100	1	0.995	130,800
1.01	0.99	120,800	1.01	0.99	137,800
1.05	0.95	144,300	1.05	0.95	163,500
1.11	0.9	161,700	1.11	0.9	182,200
1.25	0.8	188,400	1.25	0.8	211,600
1.5	0.667	221,026	1.5	0.6667	247,989
2	0.5	265,400	2	0.5	298,200
2.33	0.4292	287,067	2.33	0.4292	322,790
5	0.2	401,700	5	0.2	436,200
10	0.1	514,200	10	0.1	589,900
25	0.04	684,900	25	0.04	797,500
50	0.02	835,300	50	0.02	984,100
100	0.01	1,008,800	100	0.01	1,202,000
200	0.005	1,206,000	200	0.005	1,455,000
500	0.002	1,514,000	500	0.002	1,857,000

Figure A1 indicates a general coincidence in streamflow between the two Susquehanna River sites up until about the 1.5-year RI (bankfull discharge), then an increasing divergence in RIs as discharge increases. This is most likely due to differences in drainage area between the two sites and flow regulation and storage of three hydroelectric facilities between the streamgages.

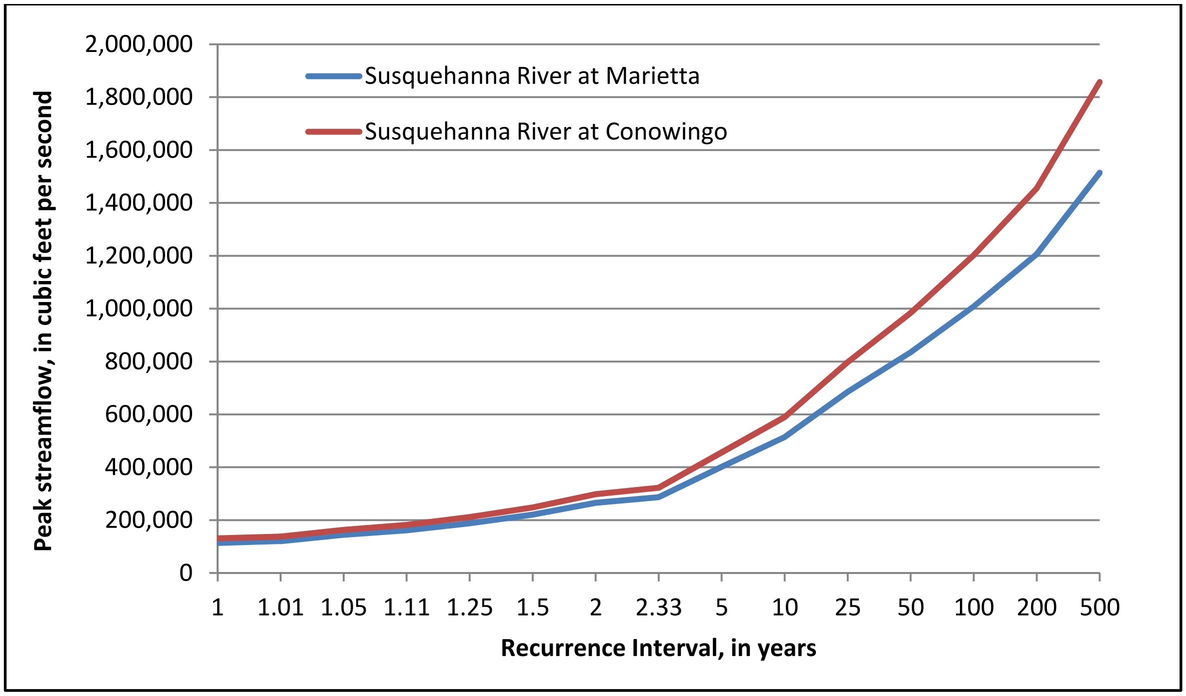


Figure A1. Recurrence Intervals for the Susquehanna River at Marietta, Pennsylvania and Susquehanna River at Conowingo, Maryland streamgages.

The USGS has been estimating sediment loads at the Susquehanna River at Marietta, Pennsylvania and Susquehanna River at Conowingo, Maryland locations since 1987. The annual loads are used to develop a simple in/out model to help predict the mass balance of sediment transport through the reservoir system. The annual loads are used to help calibrate a scour-prediction equation and estimate the sediment deposition and remaining capacity in Conowingo Reservoir.

Since 1972, there have been 11 storms with daily-mean streamflows greater than 400,000 cfs (5-year RI), the flow when an average mass wasting begins for the sediment in the reservoirs. Most likely some of the finer silt and sand particles begin to move before 400,000 cfs. Cohesive sediments such as clays and fine silts may begin to move off the reservoir bottom at flows around 200,000 cfs while the heavier sand and gravels may not move until flows are upwards of 600,000 cfs. Much of the scoured and transported reservoir sediment is re-deposited in the reservoir system. Durations of streamflow at the Susquehanna River at Conowingo, Maryland streamgage are shown in fig. A2. Note the general pattern of rapid increase then on the rising limb to the peak and a more general decrease in flow on the falling limb. This is a typical high flow response in many rivers and indicates that at higher flows the dams do not have the capability to store much water above normal pool elevations and are normally called "run-of-the-river" reservoirs. The number of days above 400,000 cfs ranged from 1 to 5 days; the average was about 3 days. The 1972 event (Tropical Storm Agnes) was the largest flood in the Susquehanna River Basin since 1896, when recording of flow began at Harrisburg, Pennsylvania. The second largest recorded flood event using daily-mean streamflow (discharge) data in the Susquehanna River basin since 1972 was in 2011 (Tropical Storm Lee, figure A2). Note that more than one event is plotted for 1984 and 2011.

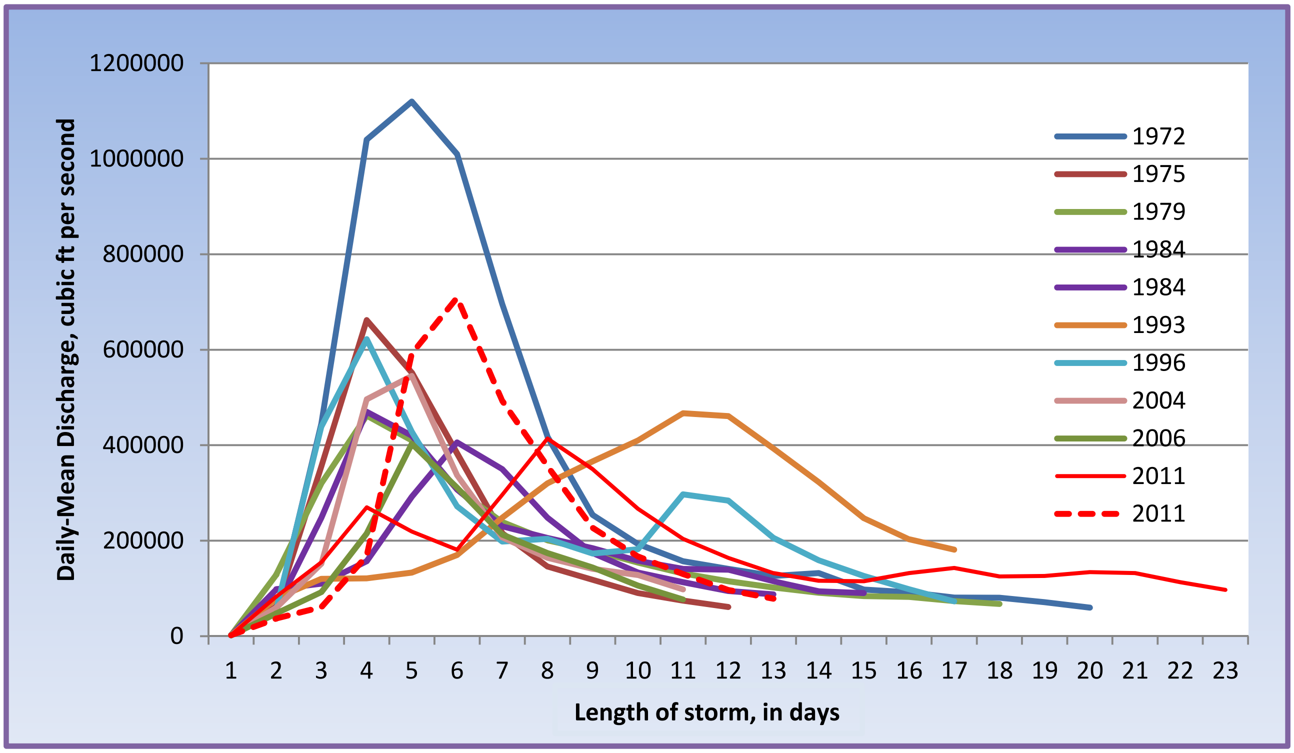


Figure A2. Streamflow (discharge) hydrographs for 11 storms above 400,000 cubic feet per second daily-mean discharge since 1972 at the Susquehanna River at Conowingo, Maryland. X axis units are days.

Streamflow can also be examined on a seasonal basis to help determine the volume and timing of discharge events over a given time period. To increase the number of discharge events, daily-mean discharges greater than 300,000 cfs at Susquehanna River at Conowingo were tabulated and shown in figure A3. Although the highest number of daily-mean discharge events greater than 300,000 cfs was in the March-May (spring) time period, the greatest daily-mean discharges per storm event occurred in June-August (summer) and September-November (fall). The summer season was most likely biased high due the daily-mean discharge of 3 of the 8 events each over 1,000,000 cfs during Tropical Storm Agnes. The higher discharges tend be in the fall season, coinciding with the Hurricane season.

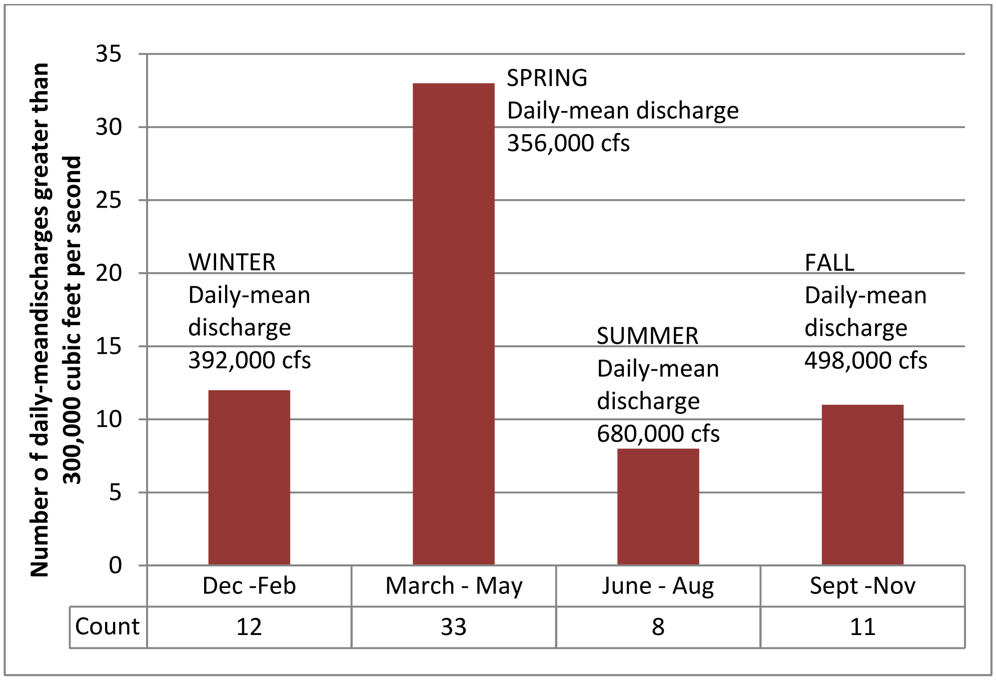


Figure A3. Number of daily-mean discharges greater than 300,000 cubic feet per second (cfs) and daily-mean discharge by season at Susquehanna River at Conowingo, Maryland (1967-2013).

The USGS developed a regression equation to predict the sediment scour load for daily-mean discharge at Lower Susquehanna River Reservoirs (figure A4). The equation is based primarily on daily mean discharge and estimated loads from six storm events during 1993-2011 (table A2) from the tow monitoring sites (Susquehanna River at Marietta and Conowingo), on bathymetry (bed-elevation change) data in the reservoirs using the Reed and Hoffman (1996), Langland and Hainly (1997), Langland (2009), URS Corporation and Gomez and Sullivan (Conowingo Reservoir only, 2012) studies, and on a comparison of estimates of sediment inflow and outflow from the reservoirs. Additional information for Tropical Storm Agnes (1972) and Tropical Storm Eloise (1975) (Gross and others, 1978) were used to help calibrate the curve. The regression equation was then used to predict scour loads for an additional three storms prior to 1972 with little to no sediment or bathymetry data for daily-mean discharge greater than 400,000 cubic feet per second (cfs) (table A2) and estimated trapping efficiency.

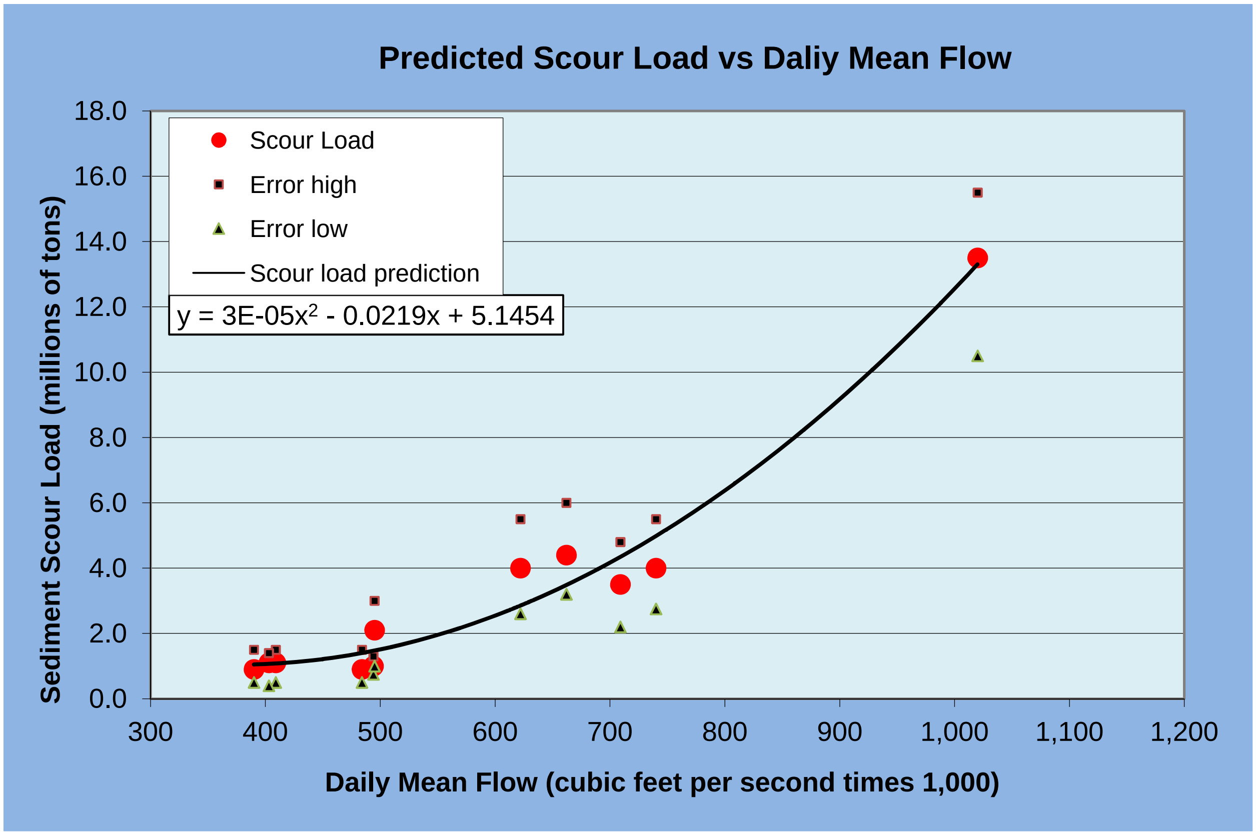


Figure A4. USGS scour equation used to predict scour from discharges generally exceeding 400,000 cubic feet per second in the Lower Susquehanna River reservoir system.

The curve and subsequent scour prediction provides a useful and quick reference for potential scour from the reservoir system to the upper Chesapeake Bay at or soon after flooding events when information may be needed quickly to ascertain potential environmental effects. While not exact as a scour predicting tool, the equation is updated with each flood event resulting in a new, slightly different equation. Complications in the predictions include errors in the methods used to estimate the daily and monthly loads, the amount of sediment entering the reservoir system, and the amount of flow and time above a certain scour threshold, generally 400,000 cfs. In addition, the length of time since a previous scour event which may increase or decrease the amount of scoured sediment, and the changing scour/deposition dynamics resulting from increased velocities as Conowingo Reservoir nears storage capacity, may lower the scour threshold and contribute to scour prediction error.

Table A2. Predicted sediment scour loads from the reservoirs for storms with an average daily-mean discharge at Conowingo, Maryland, greater than 400,000 cubic feet per second (cfs).

Date	Daily-mean Discharge (cfs)	Sediment Scour Load Event (million tons)
Mar-1936[1]	870,000	2.5
May-1946[1]	528,000	0.9
Mar-1964[1]	571,000	1.0
Jun-1972	1,020,000	13.5
Sep-1975	662,000	4.4
Apr-1993	409,000	1.1
Jan-1996	622,000	4.0
Sep-2004	495,000	2.1
Apr-2005	390,000	0.9
Jun-2006	403,000	1.1
Sep-2011	709,000	3.5

[1] Estimated using daily-mean discharge from the Susquehanna River at Harrisburg, Pennsylvania streamgage. The average ratio of streamflow between the daily-mean streamflow data for Susquehanna River at Harrisburg and Marietta streamflow gages was 92 percent using data from 1987 to 2012 with a linear regression r^2 of 0.99.

Using the data from table A1 and converting the annual exceedence probability to percent, changes in bottom surface based on the bathymetry studies, the annual sediment load estimates from Marietta and Conowingo (above and below the reservoirs), plus estimates of scour were combined to produce a range in total sediment transported through the reservoir system and a portioning to source (watershed or scour) for various flows (table A3). The ranges in scour and estimates of total loads transported out the reservoir system allow for differences in season, total volume of potential scour flow, and errors in the estimates. As previously discussed, the flow when mass scour is estimated to begin is approximately 400,000 cfs. Results from the U.S. Army Corps of Engineers 2-D model and a recent USGS report by Hirsch (2012) suggest the threshold has decreased with time. Because figure A4 suggests scour would occur down to 300,000 cfs, table A3 has an estimated scour down to 300,000 cfs. The uncertainty associated in scour estimates below 400,000 cfs is greater than for scour estimates greater than 400,000 cfs.

The percent scour to watershed load based on frequency of flow events ranges from 20 to (average 30 percent) for streamflows of 400,000 to 800,000 cfs. A flow of 800,000 cfs has a recurrence interval of 25 years. As indicated in table A3, streamflows greater than 800,000 cfs generate the greatest amounts of scour and an increasingly higher proportion of total sediment load.

Table A3. Predictions for recurrence intervals, chance of flow event per year, and ranges in scour and total sediment loads in tons and percent for various daily-mean streamflows for Conowingo Reservoir.

Streamflow (cubic feet per second)	Recurrence Interval (years)	Percent chance of flow event per year	Predicted sediment scour (million tons)[1]	Predicted total sediment load (million tons)[2]	Percent scour to total load
1,000,000	60	1.7	10.5 - 15.5	27.1 - 31.1	39 - 49
900,000	40	2.5	6.6 - 11	21.8 - 26.2	30 - 42
800,000	25	4	4.5 -7.5	17.2 - 20.2	26 - 37
700,000	17	5 .9	3.5 - 6	13.1 - 15.6	27 - 38
600,000	10	10	1.8 - 4	7.9 - 10.1	22 - 40
500,000	5.7	17.5	1 - 3	4.9 - 6.9	20 - 42
400,000	4.8	21	0.5- 1.5	2.4 - 3.4	21 - 44
300,000	2.1	52	0 – 0.5	0.5 – 1.5	0 - 33

[1] predicted scour from USGS scour equation, bathymetry results, and literature estimates
[2] predicted total load based on transport regression equation, bathymetry results, and literature estimates.

Volume Change and Total Sediment Deposition.

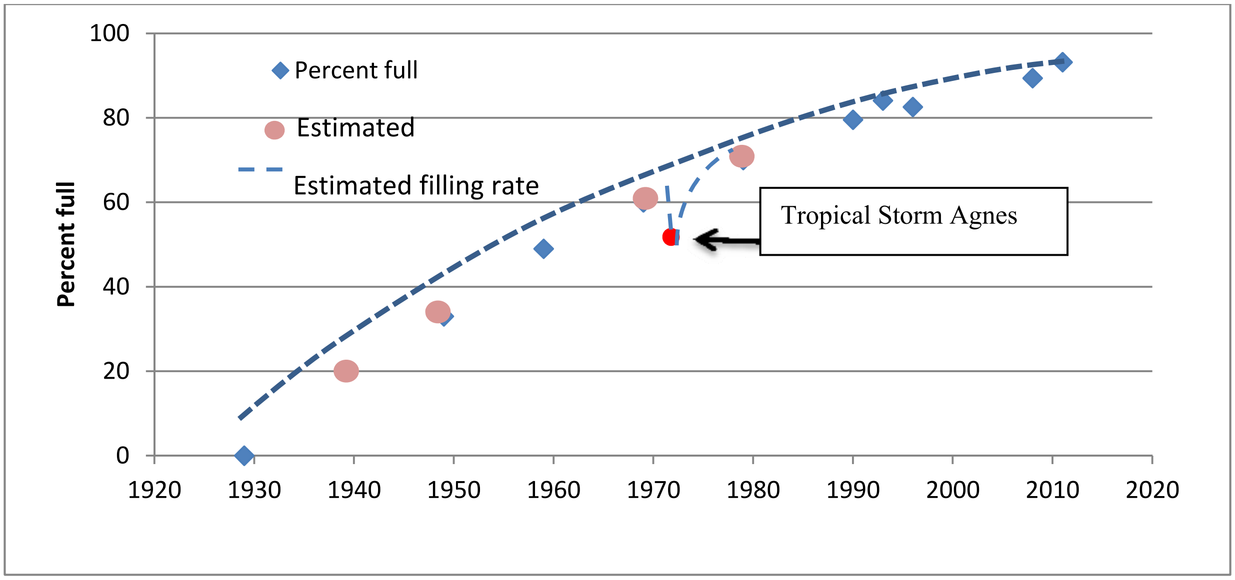
Based on previous studies (Whaley, 1960; Hainly and others, 1995; Reed and others, 1996; Langland and Hainly, 1997; Langland, 2008) URS Corporation and Gomez and Sullivan (2012) capacity and volume change are estimated for six time intervals when bathymetry results were available (table A4 and figure A4). From construction in 1929 to the first survey in 1959 (30 years), the Conowingo Reservoir lost about half of the sediment storage capacity (96 of 194 million tons). Capacity to store sediment was reduced by 30 percent by the next survey 31 years later in 1990 (155 of 194 million tons), indicating a reduction in incoming sediment, a loss of trapping efficiency, or both. The largest flood event occurred during the 1959-1990 time period when in June 1972 Tropical Storm Agnes removed approximately 13.5 million tons of sediment from Conowingo (figure A4). Table A4 indicates that in 2011, the Conowingo Reservoir was about 93 percent filled and that 13 million tons remained to reach an estimated sediment storage capacity of approximately 194 million tons.

Table A4. Storage capacity and volume change in Conowingo Reservoir from bathymetric surveys since construction.

Year	Reservoir capacity (acre feet)	Sediment Deposition (acre feet)	Total Deposition (tons)	Net gain/loss between bathymetries (tons)	percent full
1929	280,000	0	0	--	0
1959	215,000	65,000	96,000,000	96,000,000	49
1990	175,000	105,000	155,000,000	60,000,000	80
1993	169,000	111,000	164,000,000	9,000,000	84
1996	171,000	109,000	161,000,000	-3,000,000	83
2008	162,000	118,000	174,000,000	13,000,000	89
2011	157,000	123,000	181,000,000	7,000,000	92
Equilibrium	146,000*	134,000	198,000,000	17,000,000	100

*Note the equilibrium capacity previously has been reported at 142,000 acre feet. The volume was adjusted after the 2011 bathymetry survey when more detailed information near the dam became available.

Figure A5 shows that the rate of filling continues to follow a non-linear pattern since construction in 1929. Note the estimated impact of Tropical Storm Agnes which removed approximately 13.5 million tons from the reservoir system, which most likely was refilled by the end of the decade. The rate of filling has also slowed, due to a reduction in incoming sediments from the watershed and changes in reservoir scour and deposition dynamics. As the reservoir fills with sediment, the velocity increases, perhaps increasing the bed shear (can result in more scour) and decreasing the amount of residence time for sediments to settle out of the water column thereby reducing deposition. Approximately 7 percent remains of the original 146,000 acre feet of sediment storage capacity (Langland, 2008 with minor adjustment after the 2011 bathymetry). As the capacity is reduced, sediment concentrations and loads may increase to the upper Chesapeake Bay due to an increase in velocity through the reservoirs. Hirsch (2012) indicates that increases in sediment concentrations and loads are occurring and suggests the increases are occurring at lower streamflows.



*Estimated values are from a combination of methods and assuming gradual reduction in long-term trapping efficiency from 75 to 55 percent.

Figure A5. Trend in sediment storage capacity change (percent full) in the Conowingo Reservoir since construction.

Susquehanna River Sediment Transport

Using current and historical streamflow and sediment data from the Susquehanna River at Harrisburg, Pennsylvania until 1985 and streamflow from the Susquehanna River at Marietta, Pennsylvania, sediment loads were estimated from 1930 to 2009 (by decade) at Marietta and considered as input to the reservoirs (figure A6). Loads were greater in the early to mid-1900s, averaging 8.7 million tons per year due to large land disturbance activities including coal extraction and agriculture. In the 1950s, agricultural conservation measures were enacted and sediment loads began to decrease through the 1970s and 1980s as more land reverted back to forest from farm abandonment, a decrease in land disturbance from coal production, and new best-management actions to control sediment were available (table A5). Loads continued to decline to an average of 3.5 million tons per year over the last 20 years. If not for the large decreases in sediment from the watershed, the Conowingo Reservoir may have reached sediment storage capacity resulting in increased loads to the Chesapeake Bay decades ago. Figure A6 highlights the effects of climate when during the 1960's every year was below the normal annual mean streamflow as compared to the 1970's, the wettest decade on record since 1900, marked by two Tropical Storm events (Agnus and Eloise). Tropical Storm Agnus produced the highest streamflows at many locations in the

Susquehanna River basin including Conowingo Dam. The difference in the loads to Reservoirs and to Chesapeake Bay in figure A6 is indicative of decreasing inputs of sediment and potential loss of trapping efficiency over time. Since the 1990's, the decadal mean flow has increased while the decadal sediment loads have continued to decrease, an indication the best-management practices in the Susquehanna watershed may be helping to control sediment from reaching the streams.

In summary, since construction of Conowingo Dam, 1928 to 2012, approximately 470 million tons of sediment was transported by the Susquehanna River Watershed into the reservoir system, approximately 290 million tons were trapped and approximately 190 million tons of sediment was transported to Chesapeake Bay, suggesting a trapping efficiency over the 84 year time span of approximately 60 percent. Using the average estimated scour to total load ratio of 30 percent (table A3), approximately 55 million tons was estimated to be from scour in the reservoirs. Twenty of the storms for which scour is estimated represents approximately 51 million tons or 93 percent of the total scour.

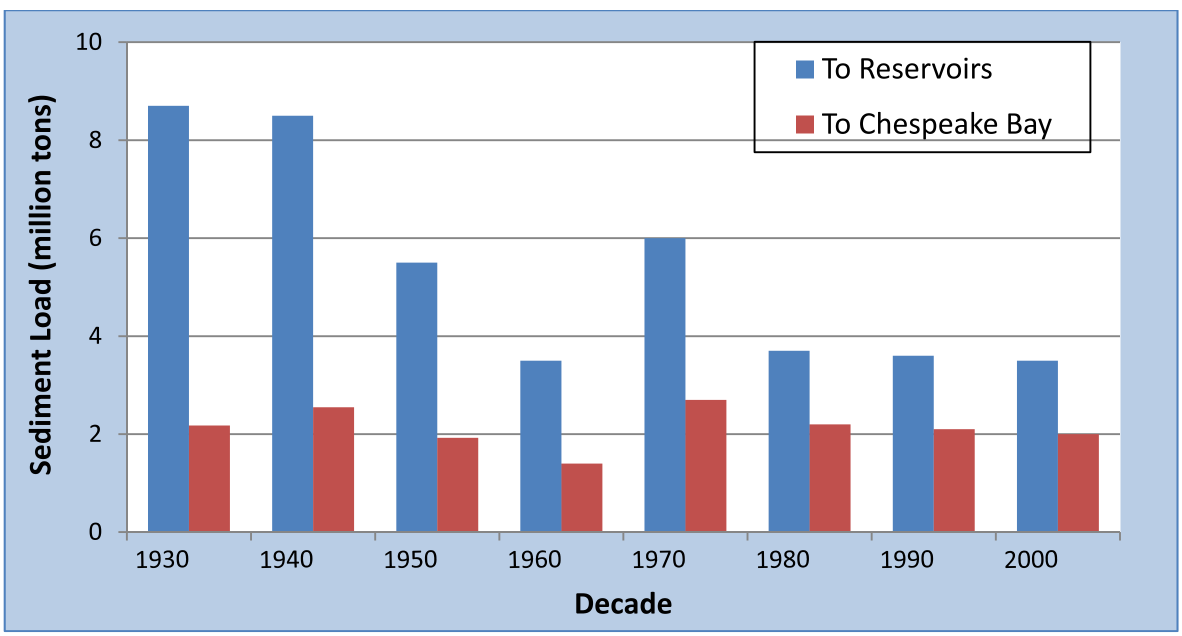


Figure A6. Total estimated sediment transported from the Susquehanna River into the reservoirs and total estimated sediment transport to the Chesapeake Bay.

Table A5. Average annual sediment loads transported into and out of the Lower Susquehanna River reservoir system and estimated trapping efficiency for multiple time periods.

Time Period	Average Annual Sediment Load to reservoirs (million tons/year)	Reservoir Trapping (percent)	Average Annual Sediment Load Trapped (tons)	Average Annual Sediment Load to Bay (million tons/year)
1928-1940	8.7	70-75	6.3	2.4
1941-1950	8.5	65-70	5.8	2.7
1951-1970	4.5	55-60	2.8	1.7
1971-1990[1]	4.9	50-55	2.6	2.3
1991-2012[2]	3.5	45-55	1.3	2.2

[1] Includes Tropical Storms Agnes and Eloise

[2] Includes Tropical Storm Lee

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