Published March 4, 2016

Journal of Environmental Quality

SPECIAL SECTION

THE CONOWINGO RESERVOIR

Conowingo Reservoir Sedimentation and Chesapeake Bay: State of the Science

Carl F. Cerco*

Abstract

The Conowingo Reservoir is situated on the Susquehanna River, immediately upstream of Chesapeake Bay, the largest estuary in the United States. Sedimentation in the reservoir provides an unintended benefit to the bay by preventing sediments, organic matter, and nutrients from entering the bay. The sediment storage capacity of the reservoir is nearly exhausted, however, and the resulting increase in loading of sediments and associated materials is a potential threat to Chesapeake Bay water quality. In response to this threat, the Lower Susquehanna River Watershed Assessment was conducted. The assessment indicates the reservoir is in a state of "dynamic equilibrium" in which sediment loads from the upstream watershed to the reservoir are balanced by sediments leaving the reservoir. Increased sediment loads are not a threat to bay water quality. Increased loads of associated organic matter and nutrients are, however, detrimental. Bottom-water dissolved oxygen declines of 0.1 to 0.2 g m^{-3} are projected as a result of organic matter oxidation and enhanced eutrophication. The decline is small relative to normal variations but results in violations of standards enforced in a recently enacted total maximum daily load. Enhanced reductions in nutrient loads from the watershed are recommended to offset the decline in water quality caused by diminished retention in the reservoir. The assessment exposed several knowledge gaps that require additional investigation, including the potential for increased loading at flows below the threshold for reservoir scour and the nature and reactivity of organic matter and nutrients scoured from the reservoir bottom.

Core Ideas

- Reservoir sedimentation prevents sediments from entering Chesapeake Bay.
- Reservoir sediment storage capacity is nearly exhausted.
- Added sediment loads are not a threat to bay water quality.
- Associated organic matter and nutrients are detrimental to bay water quality.

J. Environ. Qual. 45:882–886 (2016)
doi:10.2134/jeq2015.05.0230

Received 19 May 2015.
Accepted 2 Nov. 2015.
*Corresponding author (carl.f.cerco@usace.army.mil).

SEDIMENTATION in reservoirs is an issue of universal concern (Fan and Morris, 1992a; Labadz et al., 1995; Gunatilake and Gopalakrishnan, 1999; Palmieri et al., 2001; Podolak and Doyle, 2015). Reservoirs begin to fill with sediment from the moment they are constructed. Sediment deposition leads to loss of reservoir functions, including storage, navigation, and power generation (Bieri et al., 2012). Measures to alleviate sediment accumulation include dredging (Brusven et al., 1995; Yang et al., 2003), bypassing (Fan and Morris, 1992b; Hotchkiss and Huang, 1995), and even constructing additional reservoirs as upstream sediment traps (Chaudhuri, 2006). But suppose sediment accumulation is considered to be a reservoir function. What are the environmental consequences when this function is lost?

Chesapeake Bay is the largest estuary in the United States. It is one of many coastal seas worldwide (Diaz and Rosenberg, 2008) that exhibit bottom-water hypoxia or "dead zones" due to cultural eutrophication. Chesapeake Bay is the subject of extensive restoration efforts culminating in the recent determination of a "total maximum daily load" (TMDL) of nutrients and solids (USEPA, 2010). Reducing pollutant loads down to the TMDL is intended to eliminate water quality impairments, expressed in terms of insufficient dissolved oxygen (DO), excessive algal blooms, and poor water clarity.

The Susquehanna is the largest river in the Chesapeake Bay watershed and drains portions of New York, Pennsylvania, and Maryland. The river empties into the northernmost extent of Chesapeake Bay and provides more than half of the freshwater flow to the estuarine system. A series of dams and reservoirs (Fig. 1) at the lower terminus of the river regulates flow and influences dissolved and suspended material loads into the bay. The most upstream reservoir, Lake Clarke, forms behind Safe Harbor Dam. Holtwood Dam forms Lake Aldred, which sits below Lake Clarke. The Conowingo Reservoir, the largest of the three, forms behind Conowingo Dam, which is situated approximately 6 km above the Chesapeake Bay head of tide.

Considerable sedimentation has occurred in the reservoirs since the dams were constructed circa 1910–1930. Lakes Clarke and Aldred have filled to the extent that they are in

Environmental Laboratory, US Army Engineer Research and Development Center, 3909 Halls Ferry Rd., Vicksburg, MS 39180. Assigned to Technical Editor Peter Kleinman.

Abbreviations: DO, dissolved oxygen; LSRWA, Lower Susquehanna River Watershed Assessment; TMDL, total maximum daily load.

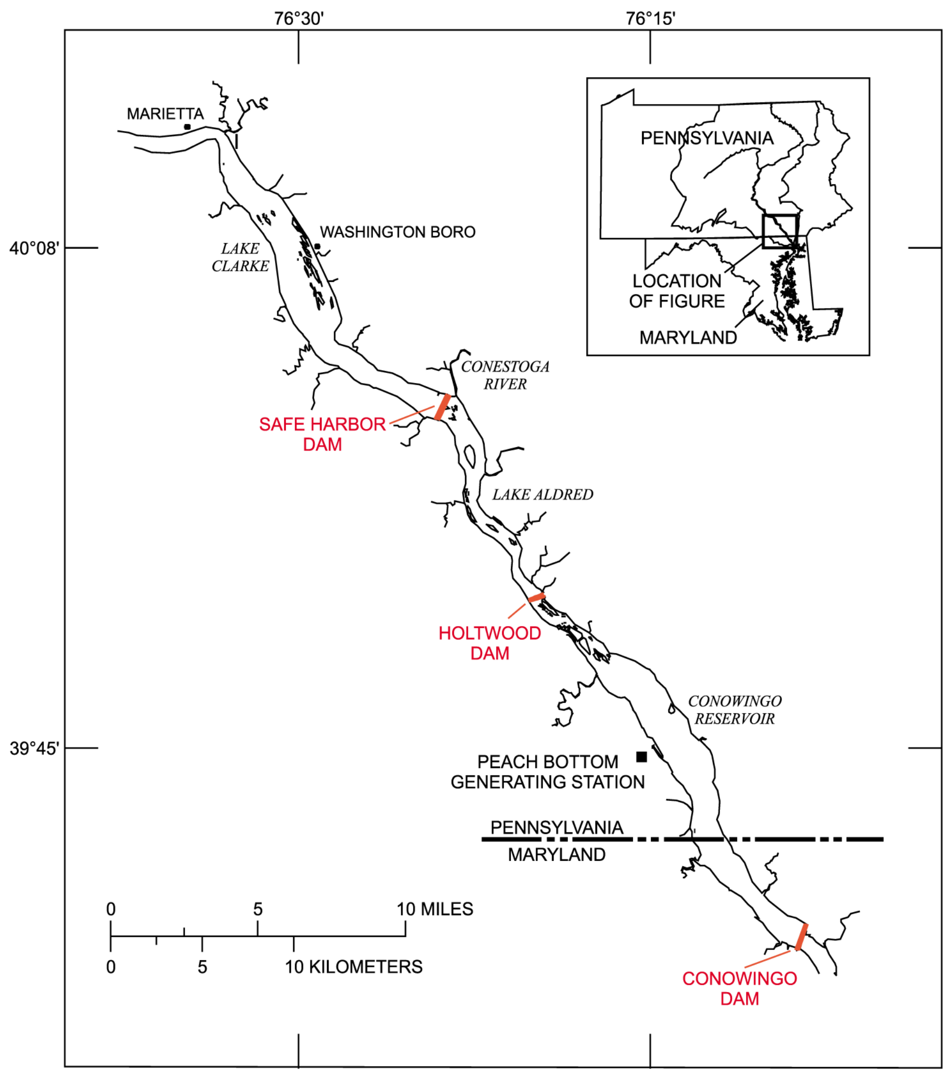

Fig. 1. Lower Susquehanna River reservoir and dam system (Langland and Cronin, 2003).

equilibrium with sediment loads coming down the river. The quantity of suspended solids entering each reservoir is essentially balanced by the quantity leaving. Conowingo Reservoir was reported to have lost 60 to 70% of its storage capacity by 1997 and was projected to reach capacity in approximately 17 yr (Langland and Hainly, 1997). The Langland and Hainly (1997) report projected substantial increases in loadings of sediment and sediment-associated phosphorus to Chesapeake Bay resulting from loss of reservoir storage capacity. Recent statistical analyses indicate the projections of Langland and Hainly (1997) are occurring. Hirsch (2012) reported the flow-normalized fluxes of phosphorus and suspended sediment at the Conowingo outfall increased by 55 and 97%, respectively, between 1996 and 2011. Zhang et al. (2013) also reported increasing trends in suspended sediment and particulate nitrogen and phosphorus at the Conowingo outfall. The increases contrasted with diminishing nutrient and solids loads to the Conowingo Reservoir, due to management actions in the watershed. They attributed the contrasting trends in loads at the reservoir inlet and outfall to diminishing sediment storage capacity within the reservoir.

Loss of sediment storage in Conowingo Reservoir threatens environmental consequences for the Chesapeake Bay, especially the portion immediately below the dam. Sediments that pass over the dam and enter the bay, instead of settling to the reservoir bottom, may increase light attenuation, with adverse consequences for submerged aquatic vegetation. Nutrients associated with the sediments may contribute to ongoing eutrophication. Loss of storage may counter or negate load reductions planned under the TMDL, which assumes continued deposition in Conowingo Reservoir at the rate that prevailed during the hydrologic period used in determination of the TMDL (1991–2000).

The threat to the Chesapeake Bay restoration effort resulted in organization of the Lower Susquehanna River Watershed Assessment (LSRWA). Objectives of the assessment included evaluation of sediment loads to the reservoir system, consideration of strategies for sediment management, and assessment of sediment management strategies on Chesapeake Bay. The assessment involved data collection, analysis of existing data, and utilization of quantitative methods ranging from desktop calculations to elaborate fate and transport models executed on high-performance computers. The assessment is now complete (USACE, 2015). The present document and succeeding papers summarize the findings of the assessment and detail components that contributed to the report.

Flow, Sediment Transport, and Change in Storage Volume, 1900–2012

Langland (2015) presented a historic analysis of sediment loads to the three-reservoir system, sediment loads leaving the reservoir system, and changes in storage volume. Langland (2015) noted that sediment loading from the watershed peaked in the early decades of the 20th century. The loads were a result of land disturbances such as mining, timbering, and agricultural practices. Watershed sediment loads have been diminishing since the mid-1980s although there is a great deal of interannual and multiannual variation in loads, driven by sequences of wet and dry years.

Langland (2015) reiterated the findings of Lang (1982) that significant scour of Conowingo bed sediments commences when river flow exceeds $\approx$11,300 $m^3 s^{-1}$ (400,000 $ft^3 s^{-1}$). Scour of the smallest sediment-size fractions likely begins at lesser flows, and scour and redeposition at lesser flows may also occur. Flow of 11,300 $m^3 s^{-1}$ is the threshold for "mass wasting" when significant quantities of sediment are eroded from the reservoir bottom and passed over the Conowingo Dam outfall. Flows sufficient to cause mass wasting have a recurrence interval of approximately 5 yr and are most likely to occur in spring, although the highest discharges occur in late summer and autumn as a result of tropical storm events. A significant finding from Langland (2015) is that even during scour events, the preponderance of sediment leaving Conowingo Reservoir originates in the watershed, not in the reservoir bottom. Scour load averages 30% of the watershed load.

The Langland (2015) report reinforces the "unintended benefit" the reservoir system has performed in decreasing sediment loads Chesapeake Bay. From 1928 to 2012, approximately 60% of the watershed sediment load was trapped in the reservoir system. The report also emphasizes that this benefit is nearly exhausted. As of 2011, Conowingo Reservoir was 92% filled.

Numerical Analysis of Recent Sediment Scour and Deposition Dynamics

Sediment management strategies for Conowingo Reservoir include sediment removal through dredging. Dredging operations will alter reservoir bathymetry and influence subsequent sediment erosion and deposition. A predictive sediment transport model is required to project the future erosional and depositional processes. Scott and Sharp (2014) described application of the ADH hydrodynamic model (Savant et al., 2011) coupled to SEDLIB (Brown et al., 2012) sediment transport libraries. ADH is a two-dimensional finite volume model that represents Conowingo Reservoir with a mesh of 20,000 elements. SEDLIB incorporates 10 sediment grain sizes ranging from clays and silts to sand.

Calibration and validation of a reservoir sediment transport model can be challenging because of the sporadic nature of suspended solids observations. For Conowingo Reservoir, the primary dataset consists of suspended sediment concentrations observed at the outlet. Observations are limited during extreme events when most transport and erosion take place. Consequently, Scott and Sharp (2014) determined to calibrate the model to long-term reservoir characteristics (Langland, 2015), including net reservoir sediment retention and net scour during erosion events. Erosion rates and critical shear stresses for erosion were measured at multiple depths in sediment cores collected from eight locations in the reservoir (Scott, 2014). Calibration was achieved through minor adjustments to observed critical shear stresses.

Scott and Sharp (2014) simulated sediment transport in Conowingo Reservoir using 2008 to 2011 hydrologic conditions and four bathymetric datasets: 1996, 2008, 2011 (observed) and reservoir-full conditions (projected). They concluded that bed scour and net deposition have changed little since 2008, suggesting the reservoir is at or near a state of "dynamic equilibrium" with regard to sediment loading and discharge.

Impact of Reservoir Sediment Scour on Water Quality in a Downstream Estuary

Cerco and Noel (2014, 2016) shift the focus of the study from the reservoir to the downstream receiving water, Chesapeake Bay. They examine the impact of a reservoir scour event on estuarine water quality, specifically DO concentration, chlorophyll concentration, and light attenuation. Their investigation uses coupled multidimensional hydrodynamic (Kim, 2013) and eutrophication models (Cerco et al., 2010) of the bay. Similar combinations are in widespread use to investigate eutrophication and related issues in estuaries and coastal seas (Moll and Radach, 2003; Robson and Hamilton, 2004; Fennel et al., 2011). Two distinguishing features of the models used herein are representations of sediment transport for multiple grain sizes (Cerco et al., 2013) and of diagenetic processes in bottom sediments (DiToro, 2001). Both features prove essential in diagnosing the effect of reservoir scour on downstream water quality.

The most significant finding by Cerco and Noel (2016) is that increased suspended solids loads are not a threat to bay water quality. For most conditions, solids scoured from the reservoir settle out before the season during which light attenuation is critical. The organic matter and nutrients associated with the solids are, however, detrimental. As illustrated in the model, this material settles to the estuary bottom and is mineralized in bed sediments. Carbon diagenesis spurs oxygen consumption in bottom sediments and release of reduced materials to the water column. Nutrients are recycled to the water column and stimulate algal production. As a result of a winter scour event, computed bottom-water DO in the subsequent summer declines up to 0.2 g m^{-3}, although the decline is 0.1 g m^{-3} or less when averaged over the summer season.

Cerco and Noel (2016) emphasize the significance of nitrogen loading generated by a scour event. The hypoxic volume of Chesapeake Bay is closely linked to the nitrogen load from the Susquehanna River (Hagy et al., 2004; Murphy et al., 2011), and the TMDL requires reductions in nitrogen loads. Based on analysis of bottom sediment composition in the reservoir, the quantity of particulate nitrogen eroded during a scour event is three times the quantity of phosphorus. Previous studies (Langland and Hainly, 1997; Hirsch, 2012) emphasized additional phosphorus rather than nitrogen, however, because the preponderance of nitrogen load is in dissolved form.

Impact of Reservoir Infill on Water Quality Standards

The projected impact of reservoir scour on downstream water quality is small when compared with normal intra- and interannual variations. The most detrimental projected effect is a DO decline of 0.1 g m^{-3} or less over a summer season (Cerco and Noel, 2016). This amount is significant, however, when the minimum bottom-water DO concentration, after implementation of the TMDL, is projected to be 1 g m^{-3} in some regions of the Chesapeake Bay. Moreover, regulatory requirements prohibit any increase in nutrient load beyond the TMDL or diminishment of water quality below standards. The impact of reservoir infill, with an emphasis on regulatory requirements, is examined by Linker et al. (2016).

Linker et al. (2016) review the specifications of the TMDL and detail the assessment used to evaluate attainment of standards. For assessment purposes, the Chesapeake Bay system is divided into 92 segments, determined by multiple criteria including geometry, salinity, and living resources. The assessment examines, for each segment and water quality standard, the percentage of time and volume that the water quality component (DO, chlorophyll, water clarity) is outside an allowed exceedance. Attaining DO standards in the volume–time integral represented by deep-channel water from June to September is critical to the TMDL. For three segments in the upper bay, between 1 to 15% of the volume–time integral is outside the standards even under TMDL conditions, necessitating a temporary variance. A reservoir scour event places an additional 1% of the volume–time integral outside of DO standards.

A unique aspect of the Linker et al. (2016) approach is examination of an alternative view of the implications of reservoir infill. The LSRWA emphasizes the impact of a major scour event. The study concludes the flow threshold for mass wasting is not substantially reduced by reservoir infill and does not consider the potential for increased frequency of scour events. An alternate picture is presented by Hirsch (2012), however. His statistical analyses suggest that additional sediment and nutrient loading from the reservoir occur at flows lower than the threshold for mass wasting. Because the lower flows have more frequent return intervals, additional loading will occur more often than mass-wasting events. The statistical analysis provides no insight into the mechanisms behind the additional loading. Linker et al. (2016) examined the scenario of more frequent loading events by increasing bottom erosion in their own model of the Conowingo Reservoir to yield 50 and 100% increases in phosphorus and sediment loading, consistent with Hirsch's (2012) projections. Under this alternate scenario, nonattainment of the deep-water DO standard remains limited to three segments, although the magnitude of exceedance is greater than for a single scour event. The scenario of more frequent loading events adds from 1 to 3% of the volume–time integral to the amount outside of DO standards.

Findings of the Lower Susquehanna River Watershed Assessment

The LSRWA concludes that the Conowingo Reservoir is currently in a state of "dynamic equilibrium" with regard to sediment loading. In this state, sediments accumulate in the reservoir until an episodic scouring event occurs. The scour event increases storage capacity, allowing for more deposition until the reservoir gradually fills and another scour event occurs. Dynamic equilibrium does not imply equality of sediment inflow and outflow on a daily, monthly, or annual basis. The balance occurs over a period of years, determined by the frequency of scour events.

The LSRWA examined several management actions to reduce the amount of sediment available for a future scour event. These included (i) reducing sediment yield from the upstream watershed, (ii) minimizing deposition in the reservoir by routing sediment around or through Conowingo Dam, and (iii) recovering volume in the reservoir by dredging. No alternative is completely satisfactory. Opportunities to reduce sediment load beyond the amount already called for in the TMDL are minor and costly. Additional load reductions are especially difficult in view of the "legacy" sediments situated throughout the watershed. Bypassing sediment around the dam results in a dilemma. Storage capacity is maintained, but at the cost of routing directly to the Chesapeake Bay the organic matter and nutrients one would prefer to retain behind the dam. Dredging, coupled with off-site disposal, increases storage capacity and results in net benefits to the bay. Costs are high, however, and virtually continuous operations are required to offset the continuous sediment load from the watershed. The LSRWA concluded that direct nutrient management and mitigation in the watershed could be the more effective than relying on sediment management options alone.

Remaining Issues

The major unsettled issue following this study is the nature of future sediment, organic matter, and nutrient loading from Conowingo Reservoir. The LSRWA examined a single event that occurred at a river flow well above the threshold for mass wasting. Implicit in the LSRWA approach is the assumption that future scour events will be isolated, infrequent events. The LSRWA included measures of critical shear stress for erosion and of erosion rates in Conowingo bed sediments (Scott, 2014). These were incorporated into the reservoir sediment transport model, which indicated relatively small change in flow threshold for mass wasting as a result of reservoir infill. At reservoir full bathymetry, the threshold is 9400 m^3 s^{-1} (Scott, personal communication, 2013), compared with 11,000 m^3 s^{-1} reported by Lang (1982) for the bathymetry as it existed circa 1980. The recurrence interval for flows of 9400 m^3 s^{-1} is 2 to 3 yr (Langland, 2015). The alternate future scenario is for more frequent loading events at lesser flows. The statistical analysis of Hirsch (2012) indicates that additional sediment and nutrient loads now occur at flows as low as 4200 m^3 s^{-1}. Flows of this magnitude occur several times per year on average. Resolution of these alternate scenarios based on available data is unlikely. Both approaches suffer from the fact that suspended sediment observations during loading events are sparse. Careful reservoir budgets need to be constructed following sampling of reservoir inputs and outputs during routine conditions and extreme events.

A second and, perhaps, less controversial issue involves the nature and reactivity of organic matter and nutrients scoured from the reservoir bottom and carried over the dam. At present, particulate carbon and nitrogen are considered to be refractory organic matter, falling into the G_2 and G_{NR} classifications of Westrich and Berner (1984). Particulate phosphorus is split between refractory organic matter and a nonreactive mineral form. These determinations are based on the frameworks of the eutrophication and sediment diagenesis models. The fractions allocated to each classification and the reaction rates (Cerco and Noel, 2014) are based on empirical calibrations of both models. The empirical values characterize particulate matter flowing over the dam under a wide range of conditions and may not specifically represent material scoured from the bottom. A series of experiments to determine the composition and reactivity of nutrients in reservoir bottom sediments is planned to fill this knowledge gap. Based on these measures, alterations in the model frameworks or state variables may follow.

In summary, a reservoir scour event is not an environmental catastrophe for the downstream Chesapeake Bay. Reservoir infilling does have negative consequences, however. Violations in dissolved oxygen standards are projected as a result of additional loading from organic matter and nutrients no longer retained behind the dam. To maintain standards, nutrient load reductions in the watershed beyond the TMDL are required. These reductions are approximately 1.1×10^6 kg yr^{-1} for nitrogen and 1.2×10^5 kg yr^{-1} for phosphorus (Linker et al., 2016).

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