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SPECIAL SECTION
THE CONOWINGO RESERVOIR

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

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Abstract

The Conowingo Reservoir is situated at the lower terminus of the Susquehanna River watershed, immediately above Chesapeake Bay. Since construction, the reservoir has been filling with sediment to the point where storage capacity is nearly exhausted. The potential for release of accumulated sediments, organic matter, and nutrients, especially through the action of storm scour, causes concern for water quality in Chesapeake Bay. We used hydrodynamic and eutrophication models to examine the effects of watershed loads and scour loads on bay water quality under total maximum daily load conditions. Results indicate 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. This material settles to the estuary bottom and is mineralized in bed sediments. Carbon diagenesis spurs oxygen consumption in bottom sediments and in the water column via release of chemical oxygen demand. The nutrients are recycled to the water column and stimulate algal production. As a result of a scour event, bottom-water dissolved oxygen 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. Surface chlorophyll increases 0.1 to 0.3 mg m^{-3} during the summer growing season.

Core Ideas

- Reservoir sedimentation can adversely impact water quality downstream.
- Infilling of Conowingo Reservoir results in increased sediments and nutrients passed through to Chesapeake Bay.
- Sediments are not a threat to water quality in Chesapeake Bay.
- Nutrients and organic matter associated with sediments contribute to eutrophication in Chesapeake Bay.

Reservoir sedimentation results in management problems worldwide (Renwick, 1996; Chanson, 1998; Jansson and Erlingsson, 2000; Sumi et al., 2004; Fu et al., 2008). The economic losses associated with diminished storage and power generation are obvious. Environmental degradation associated with reservoir sedimentation is less obvious. Sediment deposits behind dams accumulate pollutants including nutrients (James and Barko, 1997; Powers et al., 2013) and heavy metals (Linnik and Zubenko, 2002; Arnason and Fletcher, 2003; Audry et al., 2004). As reservoirs fill, they retain smaller fractions of their sediment load, allowing sediments and associated pollutants to pass downstream. The potential also exists for scour events to resuspend polluted sediments from the reservoir bottom and route this material downstream as well.

The Conowingo Reservoir, USA, is an example of a reservoir that has virtually exhausted its sediment storage capacity (Langland, 2015). A recent study (USACE, 2014) concluded that the reservoir is in a state of dynamic equilibrium. Sediment loading to the reservoir from the watershed is balanced by sediment flowing over the dam and into Chesapeake Bay, situated immediately downstream (Fig. 1). The balance occurs over a time scale of years, however. The reservoir accumulates sediment from the watershed until a major storm event (recurrence interval 4–5 yr) causes bottom scour and mass sediment discharge to the bay. Following the scour event, increased reservoir storage allows for sediment accumulation until the next event. Increased quantities of sediment may also pass downstream due to reduced deposition at flows insufficient to generate scour events (Hirsch, 2012).

Chesapeake Bay is one of many coastal systems worldwide characterized by hypoxic "dead zones" (Diaz and Rosenberg, 2008). A total maximum daily load (TMDL) has recently been enacted for the bay (USEPA, 2010) aimed at alleviating hypoxia and other water quality impairments. Loss of storage in the Conowingo Reservoir may counter or negate sediment and nutrient load reductions planned under the TMDL, which assumes continued reservoir deposition at the rate that prevailed during the hydrologic period used in determination of the TMDL (1991–2000).

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Abbreviations: ADH, Adaptive Hydrodynamics; CBEMP, Chesapeake Bay Environmental Model Package; DO, dissolved oxygen; HM, hydrodynamic model; PIP, particulate inorganic phosphorus; SAV, submerged aquatic vegetation; TMDL, total maximum daily load; TSS, total suspended solids; WQM, water quality model; WSM, watershed model.

Fig. 1. Chesapeake Bay. Time series results for the water column and benthic sediments are presented at Station CB3.3C.

The present work has two objectives. The first is to determine the impact of a major scour event in the Conowingo Reservoir on water quality in Chesapeake Bay. This objective is addressed by simulating the impact of scour from a January 1996, storm on factors regulated in the TMDL: dissolved oxygen, chlorophyll, and water clarity. The second objective is to examine the effect of storm timing on water quality. This objective is addressed by simulation of synthetic storms in June and October 1996. The marginal effects of January, June, and October storms on regulated factors are compared to no-storm conditions.

Materials and Methods

The Chesapeake Bay Environmental Model Package

This investigation involves the use of multiple predictive environmental models and the transfer of information between the models. Water quality in Chesapeake Bay is computed by the Chesapeake Bay Environmental Model Package (CBEMP), which consists of three independent models: a watershed model (WSM), a hydrodynamic model (HM), and a water quality or eutrophication model (WQM). The WSM (Shenk and Linker, 2013) incorporates the entire Chesapeake Bay watershed and provides daily computations of flow, solids loads, and nutrient loads at the Conowingo outfall, at the heads of other tributaries, and along the shoreline below the tributary inputs. Daily flows from the WSM are one set of inputs to the Computational Hydrodynamics in Three Dimensions hydrodynamic model (Kim, 2013). The HM computes surface level, three-dimensional velocities and vertical diffusion on a timescale measured in minutes for the tidal Chesapeake Bay system. Daily nutrient and solids loads from the WSM and hourly transport processes from the HM drive the Corps of Engineers Integrated Compartment Water Quality Model of the bay and tributaries (Cerco et al., 2010). The WQM computes in three dimensions: physical properties including suspended solids; algal production; and elements of the aquatic carbon, nitrogen, phosphorus, silica, and oxygen cycles. A predictive sediment diagenesis component (DiToro, 2001) and a submerged aquatic vegetation component (Cerco and Moore, 2001) are attached to and interact with the model of the water column.

The HM and the WQM operate on a 50,000-cell computational grid that extends from the mouth of the bay to the heads of tide of the bay and major tributaries (Fig. 1). Computational cells are quadrilateral ($\sim$1 km × $\sim$1 km × 1.5 m) and vary in number from 1 to 19 in the vertical to represent bathymetric variations. The primary application period for the models covers the decade from 1991 to 2000. The 1991 to 2000 hydrologic record is retained for this study, and the hydrodynamics for all but a few model runs (described subsequently) are transferred directly from Cerco et al. (2010).

The WQM is exactly as calibrated and described by Cerco et al. (2010) and as utilized by the EPA Chesapeake Bay Program in development of the 2010 TMDL (USEPA, 2010). Watershed loads for the present investigation are from WSM Phase 5.3.2 and incorporate the projected land uses, management practices, waste loads, and atmospheric deposition on which the TMDL is based.

One other model provided information utilized in the CBEMP. A detailed Adaptive Hydrodynamics (ADH) model computed two-dimensional hydrodynamics and sediment transport in the Conowingo Reservoir (Scott and Sharp, 2013). Sediment erosion or scour from the bed of Conowingo under various conditions was computed in ADH and added to the loads at Conowingo computed by the WSM and used by the WQM. Since the ADH application period was 2008 to 2011, while the CBEMP application period was 1991 to 2000, an algorithm described subsequently was applied to adjust calculated scour from the ADH application for use in the CBEMP.

Conowingo Bed Sediments

Information on the Conowingo bed sediments was assembled to characterize the nutrient composition of material scoured from the bottom and carried over the dam. Langland (personal communication, 2012) provided observations from 22 sediment cores collected at multiple locations in the reservoir circa 1990 (Hainly et al., 1995). Sediments from the upper 60 cm were composited into a single sample and analyzed for ammonium plus organic nitrogen, nitrate + nitrite, and total phosphorus. The nitrogen analyses were summed into total nitrogen. All analyses were reported on a unit mass sediment basis. Total nitrogen and total phosphorus observations from an additional 29 cores, collected in August 1996, were obtained from Durlin and Schaffstall (1997). Observations from 21 cores, collected in 2000, were obtained from Edwards (2006). Sediments from these cores were analyzed at multiple depth increments. The surficial samples, typically 30 to 60 cm deep, were utilized in this investigation.

Conowingo Outfall Observations

Observations of suspended solids and particulate nutrients at the Conowingo outfall were assembled from multiple sources. Particulate nitrogen, particulate phosphorus, and total suspended solids (TSS) concentrations were retrieved from the Chesapeake Bay Program Water Quality Database (CBP, 2013). More than 100 samples, collected at roughly monthly intervals, were available from the years 2005 to 2011. Particulate nitrogen and phosphorus concentrations were converted to a sediment mass basis through division by TSS concentration. Observations from January 1996 and October 2010–September 2011 were provided by Blomquist (J. Blomquist, unpublished data, 2012). These datasets included observations collected at flows sufficient to initiate mass sediment scour in the reservoir (roughly 11,000 $m^3\ s^{-1}$, Langland and Hainly, 1997). Scour flows occurred in January 1996, March 2011, and September 2011. The 1996 observations included suspended sediment, ammonium plus organic nitrogen (filtered and unfiltered), nitrate + nitrite (filtered), and total phosphorus (filtered and unfiltered). Total nitrogen was obtained by summing the unfiltered ammonium plus organic nitrogen and nitrate + nitrite concentrations. Particulate nutrient concentrations were obtained as the difference between unfiltered and filtered analyses. Particulate nutrient concentrations were placed on a sediment mass basis through division by suspended sediment concentration. The 2010–2011 observations included suspended sediment, particulate nitrogen, and particulate phosphorus concentration. Direct analyses were conducted of the fractional nitrogen and phosphorus composition of suspended solids.

Calculation of Scour

Determination of the marginal impact of reservoir scour during January 1996 requires identification and quantification of the fraction of scoured material in the total load passing over the Conowingo Dam. The WSM incorporates algorithms to calculate particle settling and erosion in the Conowingo Reservoir. The algorithms are parameterized to optimize agreement between computed and observed sediment and nutrient concentrations flowing over the Conowingo Dam throughout the multiyear WSM application period. During this study, we determined that little or no scouring of bottom material was calculated during the January 1996 flood event. As a result, computed solids concentrations (Fig. 2a) and, potentially, particulate nutrient concentrations were less than observed. Consequently, for this study, solids and nutrient loads from erosion were calculated independently, based on computations from the ADH

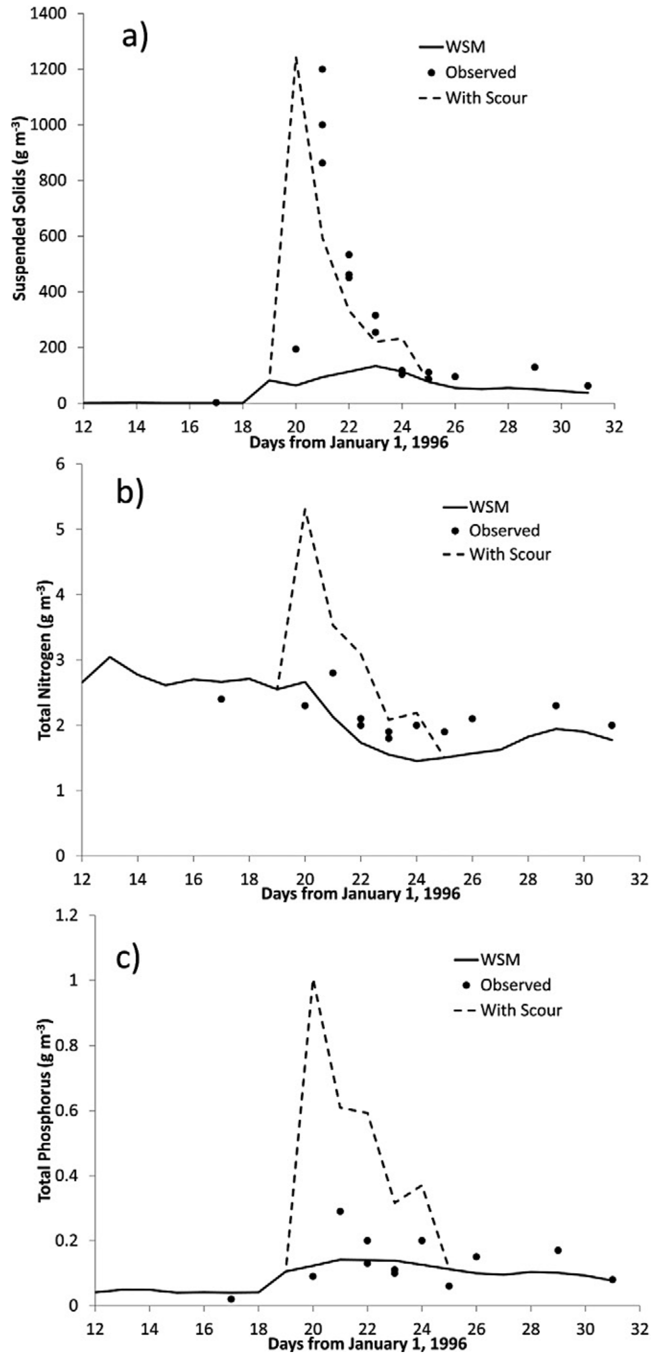

Fig. 2. Observed and computed (a) suspended solids, (b) total nitrogen, and (c) total phosphorus concentrations at the Conowingo outfall during January 1996. Computations are shown with and without estimated scour load. WSM, watershed model.

model for the Conowingo Reservoir, and added to the WSM loads for the January 1996 event.

The ADH application period, 2008 to 2011, differed from the WQM application period, 1991 to 2000. A procedure to apply ADH calculations to the 1996 storm was developed on the basis of the volumetric flow in excess of the threshold for scour. The year 2011 contained two erosion events, an unnamed event in March and Tropical Storm Lee in late August. The excess volume for each event was computed by integrating flow over time for the period during which flow exceeded 11,000 $m^3\ s^{-1}$. The amount of solids eroded during each event was taken as the difference between computed loads entering and leaving the Conowingo Reservoir. Solids loads leaving the reservoir in excess of loads entering were taken as evidence of net erosion from the bottom. (Net erosion does not include material scoured from the bottom and redeposited within the reservoir.) Net erosion for January 1996 was calculated by linear interpolation of the two 2011 events, using excess volume as the basis for the interpolation. The analysis was conducted for three major sediment classes used in the WQM: clay, silt, and sand. The total scour load for the 1996 event was apportioned to individual days on the basis of flows and inspection of the 2011 record. Nutrient loads associated with bottom erosion were calculated by assigning fractional nitrogen and phosphorus compositions, characteristic of the sediment cores, to the eroded solids. Loads of organic matter, quantified as organic carbon, were based on organic nitrogen loads using the observed carbon-to-nitrogen ratio, 8 g g^{-1}, at the Conowingo outfall (Cerco and Noel, 2004).

Scenario Procedure

Chesapeake Bay scenarios are patterned after those used in determination of the TMDL. Each is 10 yr in duration and incorporates the hydrologic record that occurred from 1991 to 2000. The record includes a major scour event in the Conowingo Reservoir that occurred in January 1996. The event included the second-highest daily flow observed at Conowingo since the inception of the modern management era in 1985, 17,600 m^3 s^{-1}, as well as three of the top-10 daily flows in that period. The 11,000 m^3 s^{-1} threshold for scour was exceeded on 20, 21, and 22 January.

The first scenario addressed the effect of storm scour of solids and nutrients. For this scenario, runoff at major tributary inputs, distributed flows, and solids and nutrient loads, under TMDL conditions, were obtained from the WSM. These were input to the WQM on a daily basis, according to the watershed area contributing to each surface cell in the computational grid. The WSM loads at the Conowingo outfall were supplemented with scour loads computed as described above. The marginal impact of scour loads was determined by comparison to a base run without scour loads

Runoff events with flows sufficient to scour reservoir sediments occur at various times of the year. Floods occur in the Susquehanna River in late winter and early spring due to precipitation and snowmelt. Tropical storm events are most common during late summer and early fall, although the notorious Tropical Storm Agnes occurred in June 1972 (CRC, 1976). The effect of the storm-generated loads, from the watershed and from reservoir scour, will vary depending on the season of storm occurrence. A set of scenarios was completed to investigate effects of storm seasonality. First, a base run was conducted with the January 1996 storm flows and loads extracted from the record. The marginal impact of the January storm, including watershed and scour loads, was determined through comparison of this base case to conditions computed with the January storm. Two synthetic storms were created by moving the January 1996 storm to June and October 1996. Marginal effects of these storms were likewise determined through comparison to the base scenario with no storm. All scenarios were conducted based on TMDL conditions. Revised hydrodynamics were completed for the three new scenarios (June storm, October storm, no storm) to capture the effects of circulation and stratification as well as loading.

Routing Nutrients between Models

The WSM treats all particulate nitrogen as a component of its single organic nitrogen variable. Nitrogen scoured from the reservoir bottom was combined with this organic nitrogen and routed into two WQM variables: dissolved organic nitrogen and refractory particulate organic nitrogen. The split between the two WQM variables (0.16 g m^{-3} dissolved, the remainder particulate) was based on observations at the Conowingo outfall (Cerco and Noel, 2004). The WSM has no component analogous to the WQM organic carbon suite. Organic carbon loads were based on organic nitrogen loads using the observed carbon-to-nitrogen ratio, 8 g g^{-1}, at the Conowingo outfall (Cerco and Noel, 2004).

The WSM splits particulate phosphorus between organic phosphorus and particulate inorganic phosphorus (PIP). Phosphorus scoured from the reservoir bottom was combined with the WSM loads and routed into three WQM variables: dissolved organic phosphorus, refractory particulate organic phosphorus, and PIP. The splits (0.005 g m^{-3} dissolved, 58% of remainder refractory, 42% of remainder PIP) were based on observations at the Conowingo outfall (Cerco and Noel, 2004).

Results and Discussion

Conowingo Sediment Composition

Cores were collected in three surveys over a 10-yr period (Table 1). The mean nitrogen fraction of sediment solids was unchanged from 1990 to 1996 ($p > 0.05$) but declined between 1996 and 2000 ($p < 0.05$). Mean phosphorus fraction decreased from 1990 to 1996 ($p < 0.05$) than increased from 1996 to 2000 ($p < 0.05$). In the absence of monotonic trends or rationale to account for the differences, results from all cores were pooled into a population of samples. The preponderance of nitrogen observations was in the range of 3 to 4 mg N g^{-1} solids with a mean of 3.5 mg N g^{-1} solids. The preponderance of phosphorus observations was in the range 0.5 to 1.3 mg P g^{-1} solids with a mean of 0.93 mg P g^{-1} solids.

Composition of Solids in the Conowingo Outfall

Examination of the nitrogen and phosphorus fractions of solids at the Conowingo outfall indicates a relationship between composition and flow (Fig. 3). The nutrient fraction decreases as the flow increases. At flows >6000 m^3 s^{-1}, the composition of particles in the outfall resembles the composition of bottom

Table 1. Nutrient fraction of solids collected in sediment cores and at the Conowingo outfall.

	Nitrogen	Phosphorus
	mg g^{-1}	
1990 sediment cores	3.501	0.961
1996 sediment cores	3.783	0.722
2000 sediment cores	3.112	1.171
1996 outfall, Q > 11,000†	0.689	0.304
2011 outfall, Q > 11,000	2.683	1.077

† Q = flow (m^3 s^{-1}).

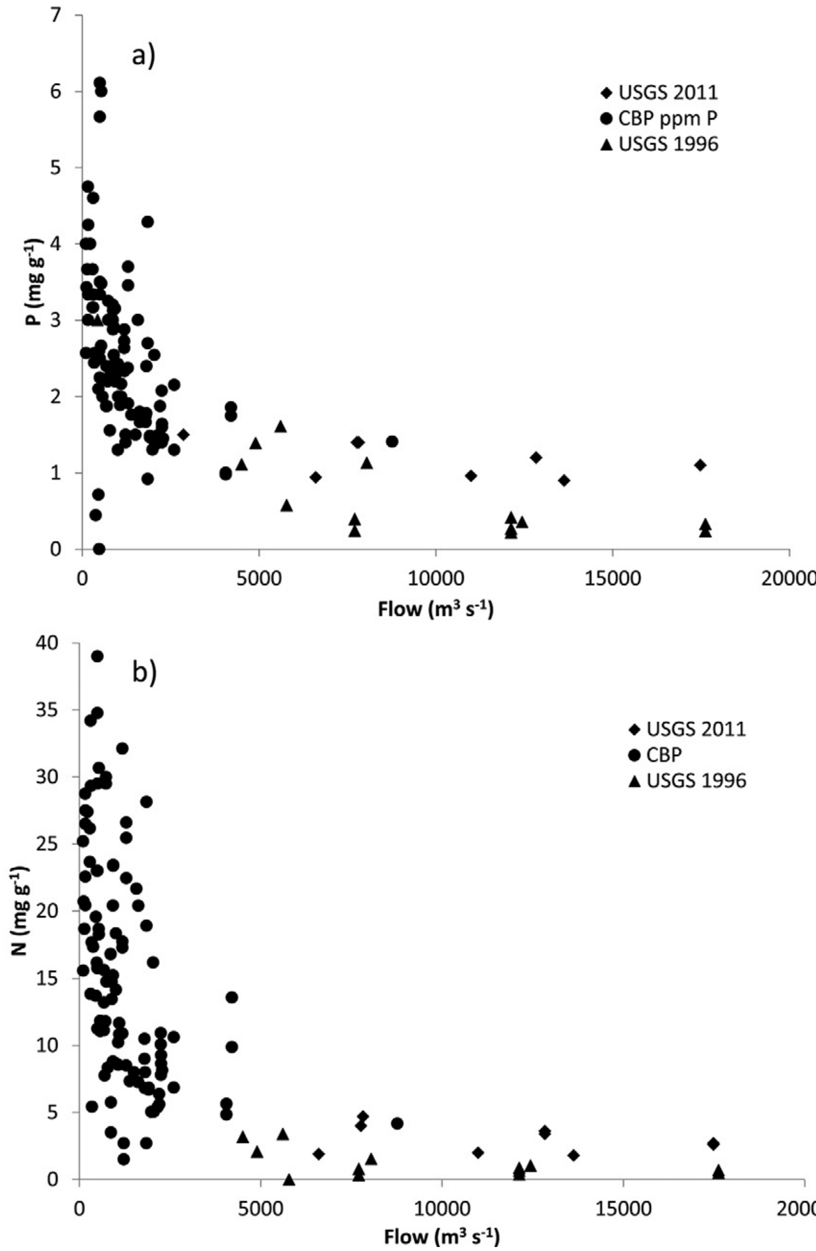

Fig. 3. Solids (a) nitrogen and (b) phosphorus fractions vs. flow at the Conowingo outfall. Observations include long-term monitoring by the Chesapeake Bay Program, the 1996 storm event, and the 2011 Tropical Storm Lee.

sediments. The resemblance is apparent at flows insufficient to erode bottom sediments. We suggest the resemblance indicates a common origin for particles in bottom sediments and particles in the outfall at flow >6000 $m^3 s^{-1}$. The median mass nitrogen-to-phosphorus ratio in particles at low flow ($Q < 2000$ $m^3 s^{-1}$) is 6.0 and resembles the Redfield composition for phytoplankton (N:P = 7.2 by mass). The median mass nitrogen-to-phosphorus ratio at high flows ($Q > 10{,}000$ $m^3 s^{-1}$) is much less, 2.24. We suggest the outflowing particles at low flows are formed by primary production within the reservoir. At higher flows, the residence time of the reservoir is short and particle composition at the outfall resembles particles entering the reservoir from upstream.

Computed Scour and Observed Outfall Concentrations

The daily scoured solids loads calculated for January 1996 via the excess volume procedure were added to the daily Conowingo outfall loads computed by the WSM. Nutrient scour loads, based on the scoured solids loads and characteristic composition of bottom sediments (3 mg N g^{-1} solids and 1 mg P g^{-1} solids), were likewise added to the WSM loads. Concentrations at the outfall, with and without scour, were obtained through division of loads by the observed flow. The addition of scour loads resulted in remarkable agreement between computed and observed suspended solids (Fig. 2a). The WSM nitrogen and phosphorus concentrations were frequently less than observed during the storm interval (Fig. 2b, Fig. 2c). Addition of the calculated scour loads, however, produced concentrations considerably in excess of the observations.

The preponderance of solids at the outfall during the 1996 event was from bottom scour (Fig. 2a), yet the nutrient content of the solids was less than the mean content of bottom sediments observed in any survey (Table 1). The evidence indicates the composition of material scoured in 1996 was much less than the preponderance of observations of bottom composition. There is no way of knowing why the 1996 composition was at the extreme low end of observations from sediment cores. (The 1996 cores were collected after the storm. Effectively, we know what did not flow over the dam.) Before the event, lower nutrient composition may have prevailed over the extent of the reservoir or erosion may have come from a location characterized by low nutrient composition. The 1996 flood itself originated in an unusual chain of events including snowmelt and the break-up of ice dams (Langland, 1998). The anomalous 1996 composition presents a dilemma for management scenarios. What composition should be used in subsequent scenario analysis? The 1996 composition, which accompanied the 1996 event and was observed during the scenario period 1991 to 2000? Or the characteristic bottom sediment composition based on multiple sediment cores and surveys? The scenarios presented here utilize characteristic bottom sediment composition as the composition of eroded sediments. In the absence of projections of future sediment composition, these represent the most likely estimate. This election is supported by noting that characteristic bottom sediment composition is consistent with outfall composition observed as late as 2011, during a tropical storm event (Table 1). This approach provides a set of "worst case" scenarios compared with 1996 conditions. However, several key management scenarios were run with the 1996 composition, presenting a range of potential outcomes (Cerco and Noel, 2014).

Load Summary

Loads at the Conowingo outfall are summarized in Table 2. The existing and TMDL loads are from the WSM (Shenk and Linker, 2013), which calculates little or no scour. Existing loads are based on 2010 land use, management practices, and point-source loads within the watershed. The TMDL loads are based on implementation of management practices and point-source controls as detailed in the TMDL (USEPA, 2010). Scour loads are calculated as described above. The TMDLs are projected to yield 25% reductions in phosphorus and solids loads and 30% reduction in nitrogen load, when the hydrologic record from 1991 to 2000 is used. Particulate nitrogen is incorporated in the WSM organic nitrogen variable, which comprises less than half the total nitrogen load. Particulate phosphorus, however, makes up more than 80% of the total phosphorus load. The solids and phosphorus load reductions are equivalent because phosphorus controls are, effectively, sediment controls. Scoured material comprises more than 80% of the total solids and total phosphorus load computed for the 1996 event, based on TMDL conditions in the watershed. Scour dominates the total phosphorus load even when the observed 1996 nutrient composition is used to characterize the solids. Scour is roughly half of the total nitrogen load computed for the 1996 event, based on TMDL conditions in the watershed. Scour represents a lower fraction of the total nitrogen load than total phosphorus even though the scoured nitrogen load is greater than the scoured phosphorus load. The lesser fraction of scoured nitrogen in the total load occurs because dissolved nitrogen contributes a large portion of the total nitrogen load, whereas dissolved phosphorus is a small fraction of the total phosphorus load.

Marginal Effect of a January Scour Event

The Chesapeake Bay TMDL is intended to maintain three aspects of water quality: clarity, chlorophyll, and dissolved oxygen (DO). Consequently, we emphasize results in these three areas. Water clarity is reported as the coefficient of diffuse light attenuation and is calculated via an optical model that takes into account the influence of chlorophyll, TSS, color, and other factors (Gallegos et al., 2006). Phytoplankton are quantified in the model as carbonaceous biomass. Their computed concentration is reported as chlorophyll, however, since phytoplankton observations are usually reported as chlorophyll concentration. The saline portions of Chesapeake Bay are subject to no chlorophyll standard. Phytoplankton are a crucial influence, however, on whether bay waters meet DO and water clarity standards. Oxygen consumption associated with the decay of organic carbon fixed by phytoplankton is the primary mechanism for the occurrence of bottom-water hypoxia, while light attenuated by the chlorophyll pigment and by particulate organic matter contributes to poor water clarity.

Results are presented in the form of difference plots. The differences are defined as scenario minus base. In this case, the scenario is TMDL loads augmented by scour in the reservoir. The base is TMDL loads with no scour. The difference plots emphasize the marginal effect of the scenario conditions, which can be small relative to the magnitude and range of computed base conditions. The presentations are organized such that a positive marginal difference indicates a scenario value greater than base conditions. Model comparisons to observations and presentations of base conditions have been reported elsewhere (e.g., Cerco et al., 2010; Cerco and Noel, 2013, 2014) and are not repeated. Results are presented in two formats: time series plots and spatial plots averaged over relevant time scales. The primary location for time series of water quality and sediment-water fluxes is Station CB3.3C, located in upper Chesapeake Bay (Fig. 1). The station is situated at the head of a deep trench that runs up the bay channel and experiences recurrent bottom-water hypoxia. Maintenance of DO standards at this station is one of the most demanding challenges for the TMDL. Spatial plots are averaged over the submerged aquatic vegetation (SAV) growing season (April–October) during which the water clarity standard applies or the summer months when hypoxia prevails (June–August).

The scour loads produce a tremendous increase in computed light attenuation during the January storm (Fig. 4a). During the 1996 SAV growing season (Fig. 5) and in later years, however, the change in light attenuation resulting from storm scour is negligible. The median increase in growing-season attenuation in any year is $<0.01\ m^{-1}$, compared with median base light attenuation $\approx 0.8\ m^{-1}$. By the time growing season arrives, most of the solids associated with the storm have settled out.

Computed surface chlorophyll decreases during the scour event (Fig. 4b) due to increased light attenuation from scoured solids. Computed chlorophyll increases, however, in the first growing season following the event. The increase in chlorophyll persists into subsequent years, although the magnitude of the increase diminishes with time. The extent of the increase is widespread, with an average increase of 0.1 to 0.3 $mg\ m^{-3}$ extending into the lower Potomac River and below the mouth of the Potomac in the mainstem bay (Fig. 5) in the first

Table 2. Loads at the Conowingo outfall for existing (2010) and total maximum daily load (TMDL) conditions. Loads without scour are compared with scour loads computed for two different solids nutrient fractions.

	Time period	Flow	Total N	Organic N	Total P	Particulate P	Total suspended solids
		$m^3\ s^{-1}$	kg				t
Based on 2010 land use and management practices	Daily average	1,170	147,949	62,931	6,314	5,222	3,056
TMDL loads	Daily average	1,175	104,067	46,058	4,718	3,872	2,307
TMDL, Jan. 1996 storm, no scour	19–25 Jan. daily average	9,260	842,820	354,771	73,726	49,248	57,837
	Storm total	64,822	5,899,740	2483,400	516,081	344,739	404,862
Scour load based on bottom sediment composition				7,116,000		2,372,050	2,372,050
Scour load based on 1996 outfall composition				1,779,000		949,000	2,372,050

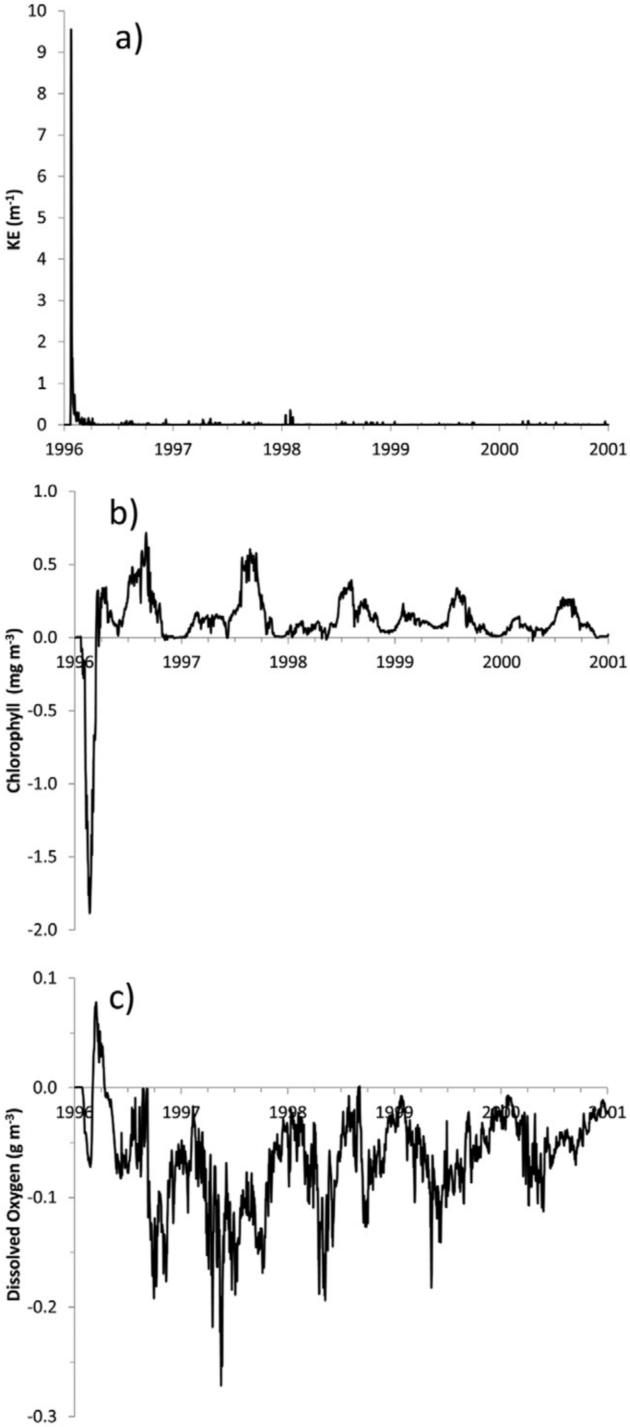

Fig. 4. Marginal changes at Station CB3.3C in computed (a) light attenuation (KE), (b) surface chlorophyll, and (c) bottom dissolved oxygen as a result of estimated January 1996 scour loads. Positive values indicate an increase over values computed without scour loads.

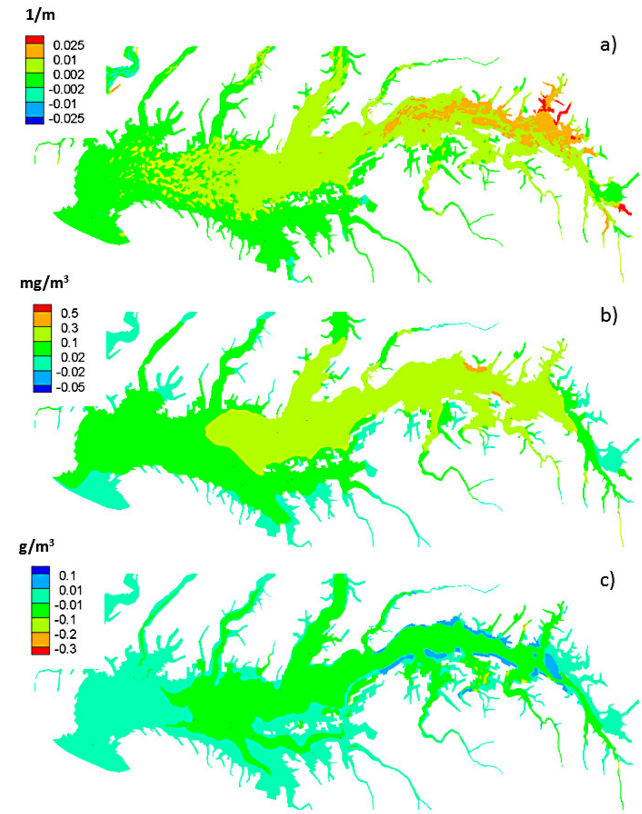

Fig. 5. Marginal changes in computed (a) light attenuation, (b) surface chlorophyll, and (c) bottom dissolved oxygen as a result of estimated January 1996 scour loads. Positive values indicate an increase over values computed without scour loads. Attenuation and chlorophyll are averaged over the submerged aquatic vegetation growing season, April–October 1996. Dissolved oxygen is averaged over the months of prevailing hypoxia, June–August 1996.

growing season following the event. The pathway for nutrients scoured in winter to stimulate phytoplankton in summer leads through bottom sediments. Particulate nutrients associated with scoured solids settle to the bottom. During the warmer months, diagenesis in the bottom sediments releases the nutrients to the water column (Fig. 6), where they stimulate phytoplankton production. Over time, processes including burial and washout remove the sediment nutrients from the active surface sediment layer and the stimulus provided by additional sediment nutrient release diminishes.

Bottom DO declines by as much as 0.2 g m^{-3} as a result of the storm scour (Fig. 4c). In the summer following the storm event, the DO decline is spatially extensive but limited to 0.1 g m^{-3} when averaged over the season. The mechanism is primarily oxidation of organic matter deposited subsequent to the storm event (Fig. 6a). As represented in the diagenesis model (DiToro, 2001), oxidation of organic carbon is accompanied by reduction of sulfate to sulfide. A portion of the sulfide is oxidized at the sediment–water interface, resulting in sediment oxygen consumption (Fig. 6b). In the absence of sufficient DO for complete oxidation of the sulfide, the balance is released to the water column as chemical oxygen demand. The effect of scour on DO consumption diminishes with time. The time series indicate, however, that the decrease of DO in 1997 exceeds the decrease in 1996. This phenomenon is an artifact of the different base DO concentrations in the two years. The generally higher bottom DO concentrations that prevail in the 1997 base case can fall farther than the bottom DO concentrations in the 1996 base case. In contrast to the overriding concern with DO depletion, DO increases, up to 0.1 g m^{-3}, are computed in some shoal areas due to stimulated algal oxygen production. The additional production results from additional nutrients, made available via sediment diagenesis (Fig. 6c, Fig. 6d).

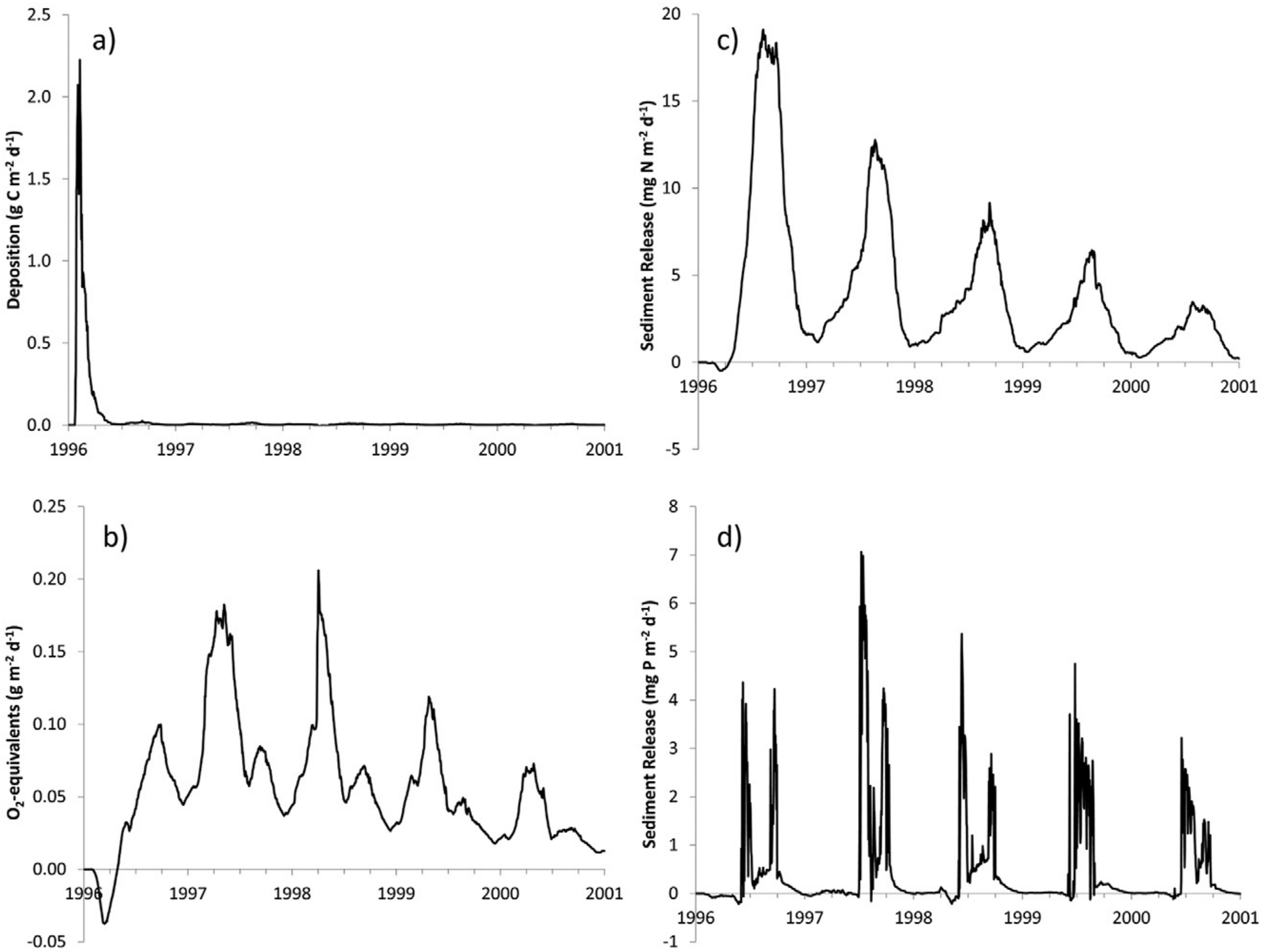

Fig. 6. Marginal changes at Station CB3.3C in computed (a) organic carbon deposition, (b) sediment respiration, (c) sediment ammonium release, and (d) sediment phosphorus release as a result of estimated January 1996 scour loads. Positive values indicate an increase over values computed without scour loads. Sediment respiration is a combination of oxygen consumed at the sediment–water interface and of oxygen-demanding materials released to the water column.

Storm Seasonal Effects

As with the scour effects, results are presented in the form of difference plots that highlight the influence of scenario conditions. For this analysis, however, the marginal influence includes the total storm load (scour and watershed) compared with a base case of no storm. All three storm events, January, June, and October, demonstrate an enormous, immediate response in light attenuation due to solids loads (Fig. 7a). At Station CB3.3C, the increase in attenuation from the January storm is of greater magnitude but lesser duration than the increase in the other months. The damped responses in June and October are due to a feedback effect between SAV and solids settling. The tendencies for SAV beds to damp waves, reduce bottom shear stress, and retain solids are well-known in Chesapeake Bay and elsewhere (Ward et al., 1984; Carr et al., 2010; Gurbisz and Kemp, 2014). Within the model, these effects are represented by reduced bottom shear stress and enhanced settling of particulate organic matter in the presence of SAV (Cerco et al., 2013; Cerco and Moore, 2001). In January, aboveground SAV is virtually absent from the upper bay, and solids rapidly pass to the region around CB3.3C and then to the lower bay. In June and October, however, the seasonal freshwater SAV beds act to retain solids in the upper bay. Less material passes to the region around CB3.3C and below. The influence of the storm-generated solids load on attenuation persists for ~90 d for the June and October storms. For both the January and October storms, the added solids are virtually gone before the subsequent SAV growing season (Fig. 8). The minor increase in light attenuation during the growing season, approximately 0.025 m^{-1}, is a secondary effect due to primary particle production stimulated by storm-generated nutrient loads. The June storm occurs during the SAV growing season, and the seasonal-average light attenuation (Fig. 8) is affected both by additional solids loads and by primary particle production. The seasonal-average increase in attenuation is the same magnitude as for the January and October storms, but the spatial extent of increased attenuation is greatest for the June storm.

Computed surface chlorophyll concentration decreases immediately as the storm flows pass through the upper bay (Fig. 7b) due to increased light attenuation from solids loads. Nutrients introduced by the storm stimulate chlorophyll production in each subsequent SAV growing season. The marginal increase in chlorophyll concentration is highest for the June storm, approximately 8 mg m^{-3} at CB3.3C, and least for the October storm, 2 mg m^{-3}. The region of increased chlorophyll concentration is also most extensive for the June storm (Fig. 9). This effect is promoted by the introduction of nutrients at the beginning of the season of maximum production.

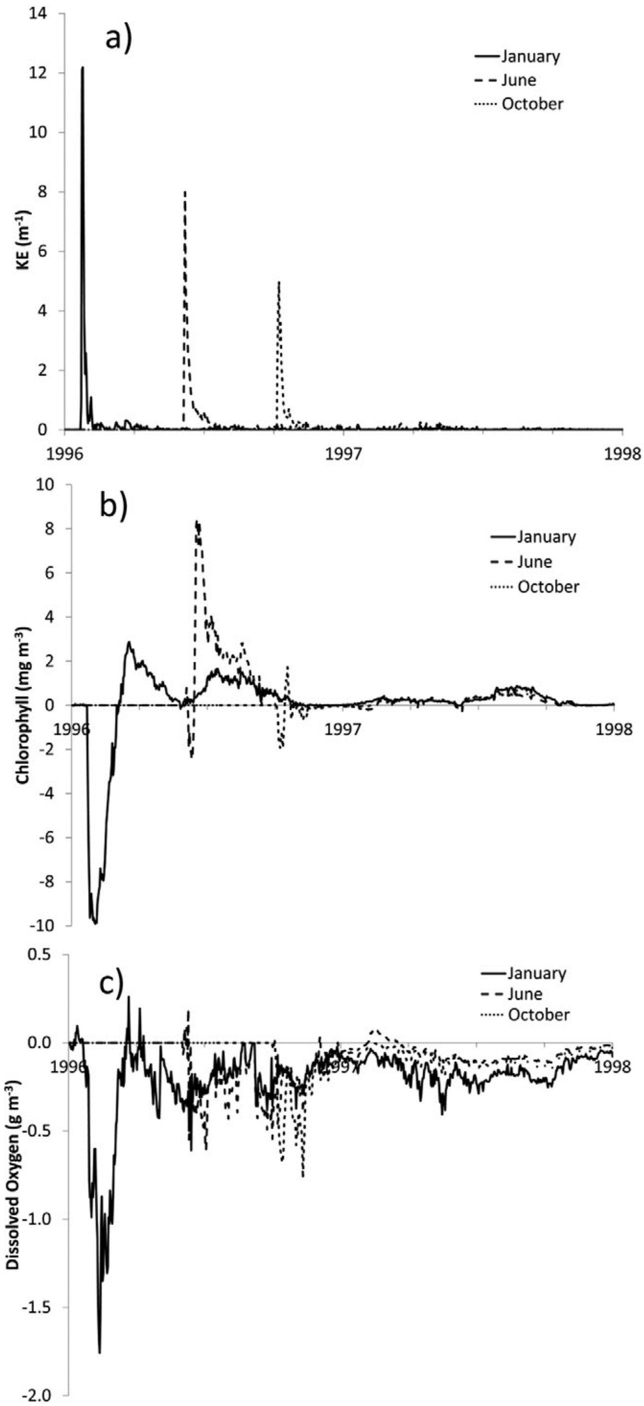

Fig. 7. Marginal changes at Station CB3.3C in computed (a) light attenuation (KE), (b) surface chlorophyll, and (c) bottom dissolved oxygen as a result of storms occurring in January, June, and October 1996. Marginal changes include reaction to the entire storm load, both watershed and bottom scour. Positive values indicate an increase over values computed without the storm.

For the January storm, about 5 months pass between the loading and the summer production season. For the October storm, 8 months pass, allowing time for the added nutrients to be flushed from the system or buried to deep, inactive bottom sediments.

The time series of DO response to storms is complex and influenced, among other factors, by the prevailing DO concentration at the time of the storm. All storms generate an immediate DO decrease in bottom waters (Fig. 7c).

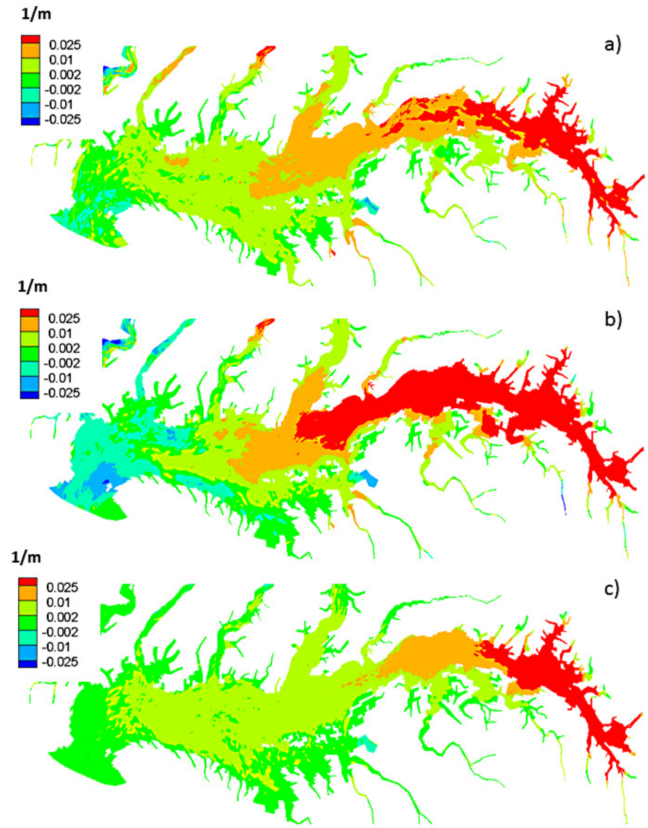

Fig. 8. Marginal changes in computed light attenuation due to storms in (a) January, (b) June, and (c) October 1996. Marginal changes include reaction to the entire storm load, both watershed and bottom scour. Positive values indicate an increase over values computed without the storm. Results from the January and June storms are averaged over the submerged aquatic vegetation growing season, April–October 1996, while results from the October storm are averaged over the submerged aquatic vegetation growing season, April–October 1997.

The decrease is due to a combination of factors, including increased salinity stratification, diminished algal primary production, and oxidation of organic material in storm loads. The decline is greatest in January because the prevailing DO concentration, 10 to 12 g m^{-3}, provides sufficient margin for a large decrease. In contrast, the prevailing bottom DO concentration at CB3.3C in June is ~1 g m^{-3}, thereby limiting the amount by which DO can decrease at this location. The January storm also generates greater DO decrease at CB3.3C in subsequent years than the June or October storms. This effect occurs because solids pass to the region of CB3.3C in January whereas they are retained in the upper bay and in SAV beds in June and October. The response to the June storm is more clearly illustrated in the spatial plots (Fig. 10), which indicate the effect of the June storm on bottom DO is much more extensive and of greater magnitude than for the alternate storms. In particular, DO depletion moves up the flanks of the deep trench into water that is usually well aerated. Extensive portions of the bay exhibit seasonal average decline greater than 0.3 g m^{-3}, whereas declines of this magnitude are absent or nearly so for the other storms. Contrasted to the response in deeper water, computed DO in shoal areas increases due to oxygen production that accompanies the enhanced algal primary production.

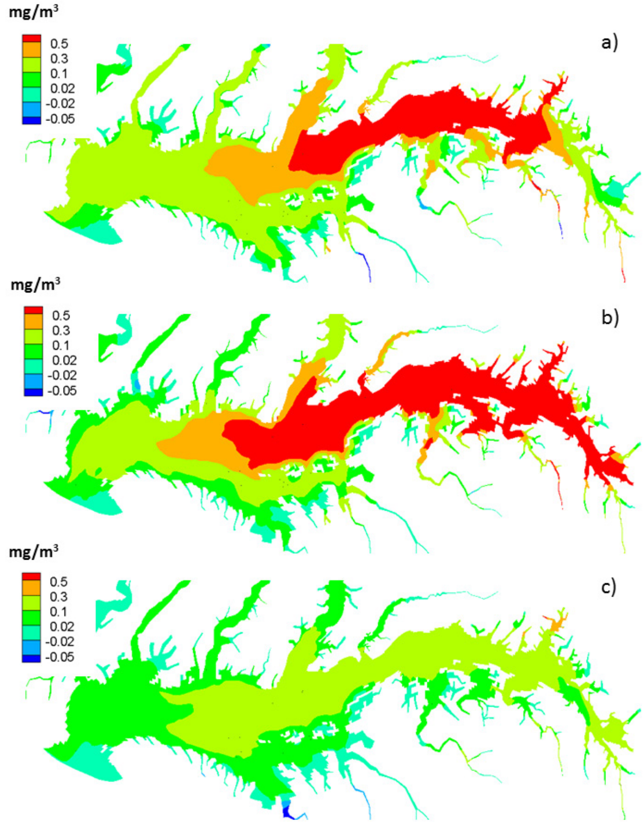

Fig. 9. Marginal changes in computed surface chlorophyll due to storms in (a) January, (b) June, and (c) October 1996. Marginal changes include reaction to the entire storm load, both watershed and bottom scour. Positive values indicate an increase over values computed without the storm. Results from the January and June storms are averaged over the submerged aquatic vegetation growing season, April–October 1996, while results from the October storm are averaged over the submerged aquatic vegetation growing season, April–October 1997.

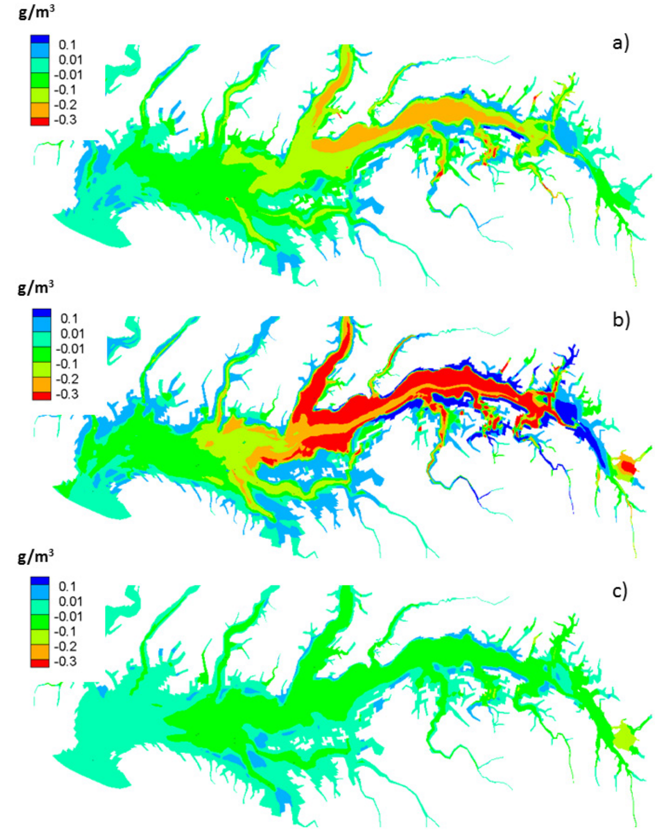

Fig. 10. Marginal changes in computed bottom dissolved oxygen due to storms in (a) January, (b) June, and (c) October 1996. Marginal changes include reaction to the entire storm load, both watershed and bottom scour. Positive values indicate an increase over values computed without the storm. Results from the January and June storms are averaged over June–August 1996, while results from the October storm are averaged over June–August 1997.

Scour vs. Watershed Loads

The solids load resulting from scour in Conowingo Reservoir during a storm event can be immense relative to the load from Susquehanna watershed during the same event (Table 2). We estimate more than 80% of the solids load produced by the January 1996 event resulted from scour. Suspended solids produced by scour are not a threat to the water quality standards established by the TMDL, however. The solids settle quickly with minor quantifiable effects. Rather, the organic matter and nutrients associated with the solids lead to detrimental effects on water quality. Our study indicates that diagenesis of deposited material creates oxygen demand, which is exerted as sediment oxygen consumption and/or release of reduced, oxidizable material to the water column. Diagenetic nutrient releases stimulate algal production. Settling and decay of this algal material also contributes to bottom-water hypoxia, although at Station CB3.3C, immediate deposition of organic matter from storm scour exceeds the marginal contribution from added algal production in subsequent seasons (Fig. 6a).

Comparison of the solids nutrient content observed at flows high enough to cause erosion ($Q > 11{,}000$ m^3 s^{-1}) indicates nutrient content was three to four times higher during Tropical Storm Lee than during January 1996 (Fig. 3). The reason—or reasons—for the differences cannot be definitively identified. The 1996 and 2011 storms occurred in different seasons (January versus August) and differences in properties of material washed from the land surface are expected. The mechanisms behind the floods also differed. The 2011 flood was primarily a meteorological event while the 1996 flood was partly due to the build-up and release of water trapped behind ice dams. The unique origin of the 1996 flood and Conowingo dam operation intended to release the flood waters may have caused bottom erosion from a different portion of the reservoir than in 2011.

Our finding that solids scour load exceeded watershed load during the January 1996 storm contrasts with reports that scour is a lesser fraction of total storm load (Langland, 2015). Scott and Sharp (2013) indicate the proportion of scour load to watershed load during Tropical Storm Lee was the inverse of the January 1996 event: approximately 80% of the total solids load during the Lee event was from the watershed rather than from scour as in January 1996. The difference is not due to the magnitude of the scour loads that are comparable: 2.64 $\times 10^6$ t for Tropical Storm Lee (Scott and Sharp, 2013) vs. 2.37 $\times 10^6$ t for January 1996 (Table 2). Rather, the difference is in the loading which is not from scour: 4×10^5 t for January 1996 (Table 2) vs. 10.5×10^6 t calculated at the Conowingo outfall during Tropical Storm Lee (Scott and Sharp, 2013). We must recognize that the 1996 and 2011 storm events were fundamentally different. Tropical Storm Lee was a meteorological event that passed over the lower portion of the Susquehanna Watershed (Palinkas et al., 2014). This portion of the entire watershed contains several subwatersheds that produce notably high sediment loads. The 1996 flood was generated, in part, by snowmelt (Langland, 1998) which is relatively "clean" with regard to sediment content. Therefore, we expect the ratio of watershed load to scour load to differ for these two events. A message from these contrasting results is that there is no "typical" yet "extreme" event. Each extreme event has its own characteristics.

Our model indicates that the timing of a storm, as well as the associated loads, influences the impact on the bay. A late spring storm results in more severe subsequent hypoxia than a storm of identical magnitude in fall or winter. In the section above, "Storm Seasonal Effects," we emphasize the oxidation of organic matter and the availability of storm-generated nutrients at the beginning of the annual period of maximum temperature and productivity. The volume of summer hypoxia is also enhanced by greater stratification in the wake of the stormflows. At CB3.3C, an increase in salinity stratification of 2 ppt persists for 30 d following initiation of the storm and an influence on stratification is evident for 8 wk or more. Data analysis indicates the volume of early-summer hypoxia is, indeed, related to bay stratification (Murphy et al., 2011), and analysis of our own model indicates the bottom-water DO concentration is highly and negatively correlated with mid-bay salinity stratification (Cerco and Noel, 2013).

Implications for Water Quality

Our results indicate that suspended solids load associated with a scour event present little threat to bay water quality through their impact on water clarity; the solids settle out quickly. These results are supported by independent model studies and by observations. The short-term residence of suspended solids in the water column calculated in this study is similar to the model study by Palinkas et al. (2014) which calculated ~98% of the sediment load associated with Tropical Storm Lee had settled out after 18 d. Observations on SAV near the Susquehanna River mouth indicate winter and spring river flows have little effect on the size of the SAV bed (Gurbisz and Kemp, 2014), similar to our calculation of negligible effect of October and January storms on growing-season light attenuation. Sediment loads can and do adversely affect SAV when the loads occur during critical periods of the SAV life cycle (Moore et al., 1997; Gurbisz and Kemp, 2014) through processes including short-term light attenuation, burial, and scour. These effects are independent of the seasonal water clarity standards, however, and are largely beyond quantification with a predictive model. Our results indicate the organic matter and nutrients associated with scoured sediments are detrimental to bay water quality. The potential for damage to the bay has been voiced previously (Langland and Hainly, 1997; Hirsch, 2012), although we are unaware of previous calculations of the magnitude of the effect. The organic matter and nutrients from a scour event are likely to produce a summer-average increase in surface chlorophyll of 0.1 to 0.3 mg m^{-3} and a bottom-water DO decline of ~0.1 g m^{-3}. These marginal impacts are small relative to the normal intra- and interannual variations in chlorophyll and DO observed in the bay. The DO decline is significant, however, in view of the effort, expressed in the TMDL, to maintain a minimum of 1 g m^{-3} DO in deep bottom water. The TMDL (USEPA, 2010) prohibits any decline below DO standards. The impact of reservoir infill and scour on water quality standards is explored further by Linker et al. (2016).

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