Long-term Seasonal Trends of Nitrogen, Phosphorus, and Suspended Sediment Load from the Non-tidal Susquehanna River Basin to Chesapeake Bay

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1. Background

- Reduction of nitrogen (N), phosphorus (P), and suspended sediment (SS) loads has been a principal focus of Chesapeake Bay Watershed management for decades.
- Susquehanna River is of special interests because it is the largest tributary to Chesapeake Bay in terms of freshwater discharge (60%), TN load (62%), and TP load (34%) (Belval and Sprague,1999).
- Seasonal loading trends need to be examined to capture impacts of seasonality (e.g., variations in temperature and rainfall, fertilizer application, denitrification, benthic recycling of P, etc).
- In the lower Susquehanna River, N, P, and SS have been trapped by a reservoir system consisted of Lake Clarke, Lake Aldread, and the Conowingo Reservoir.
- The Conowingo Reservoir, the largest reservoir in the system, was projected to reach its sediment storage capacity (SSC) in 2024-2029 (Langland 2009). At that time, nutrient and sediment delivery from Susquehanna River to Chesapeake Bay would increase considerably.
- Recent analysis has suggested that increased net scouring of sediment in the Conowingo Reservoir may already be occurring at flow rates much lower than the previously reported scour threshold (Hirsch, 2012).

2. Research Objectives

- Reconstruction of seasonal loading trends for N, P, and SS in the Susquehanna River Basin to assess reduction progress.
- Evaluation of the relative changes in N, P, and SS loads discharging into and emanating from the reservoirs to assess the reservoir performance in nutrient and sediment retention.

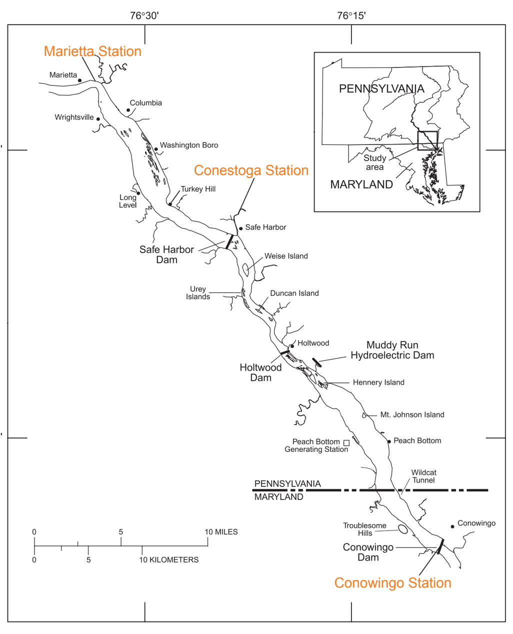
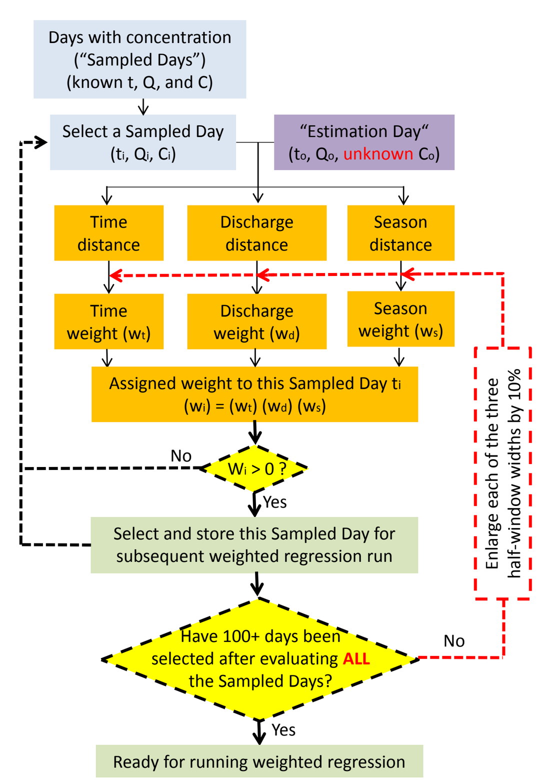


Fig. 1. Map of the monitoring sites and reservoir system in the lower Susquehanna River.

3. Study Area and Data

- The Conowingo Station below the reservoirs (located in Maryland) monitors about 99% of streamflow in the Susquehanna River Basin; it was considered as the outlet of the reservoir system (**Fig. 1**).
- The Marietta and Conestoga Stations in Pennsylvania were considered as the inlets of the reservoir system. Together, the two sites monitor about 97.6% of the watershed monitored by Conowingo (**Fig. 1**).
- Streamflow and water-quality data were compiled at the three sites. The latter included concentration measurements for eight nutrient and sediment constituents, namely, SS, TP, DP, TN, DN, dissolved orthophosphate (DOP), dissolved nitrate plus nitrite (DNOx), and dissolved ammonia plus organic N (DKN).

4. Estimation Method



- We applied a recently developed method called "weighted regressions on time, discharge, and season (WRTDS)" (Hirsch et al. 2010) to estimate daily concentration and load for nutrient and sediment.
- In general, WRTDS produces two types of estimates for both concentration and load – so-called the "true-condition" and "flow-normalized" estimates. For each "Estimation Day":
  - ■ WRTDS selects 100 or more "surrounding Sample Days" (**Fig. 2**) to fit a weighted regression to estimate the true-condition concentration and load (**Fig. 3a**); and
  - ■ In addition, WRTDS considers the full history of hydrological flows over long-term cycles (i.e., all discharges occurring on the calendar date of the Estimation Day) to estimate the flow-normalized concentration and load (**Fig. 3b**).

Fig. 2. Flowchart illustrating the first step of the WRTDS method – selection of data to be used in the weighted regression. The objective is to find at least 100 "Sampled Days" that are sufficiently "proximate" to the "Estimation Day" for which concentration (C_0) is to be estimated. For a Sampled Day with parameters of time (ti), measured discharge (Q_i), and measured concentration (C_i), the proximity to the "Estimation Day" (with known parameters to and Q_0) is calculated for each of the three dimensions, i.e., time, discharge, and season.

- We have focused on the analysis of flow-normalized loads because these estimate can largely remove the dramatic influence of random variations in streamflow and reveal more clear inter-annual trends.
- The daily flow-normalized loads were averaged to calculate seasonal loadings for each season.
- PP and PN seasonal loads were inferred by subtracting DP and DN from TP and TN seasonal loads, respectively. Similarly, dissolved hydrolysable P (DHP) was inferred by subtracting DOP from DP seasonal loads.

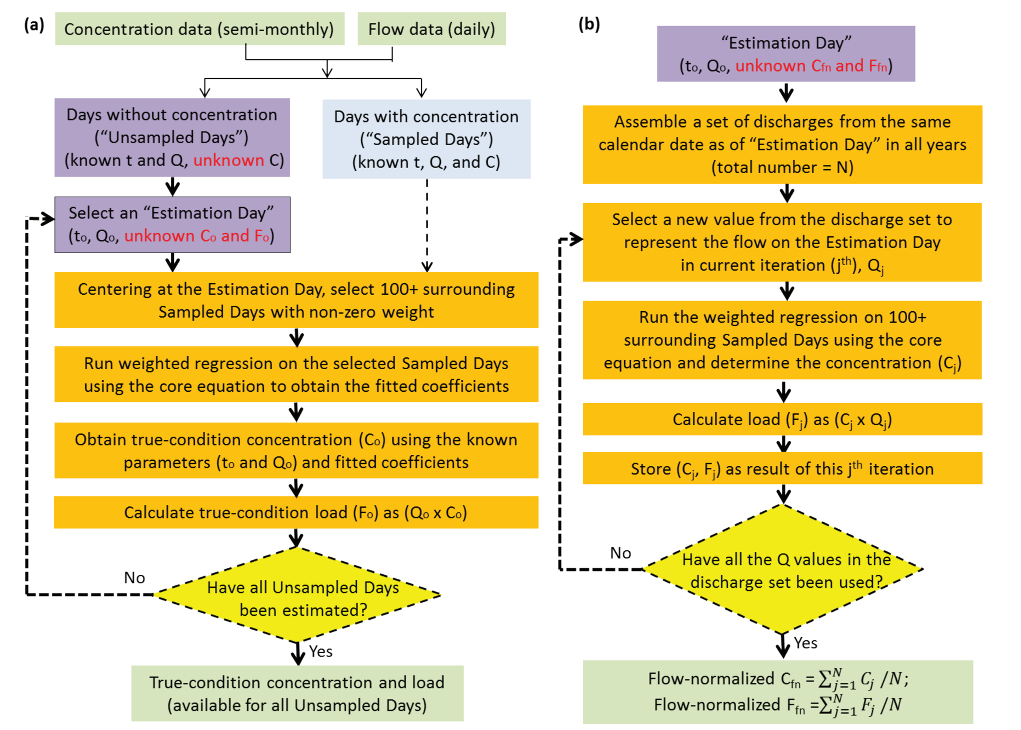


Fig. 3. Flow diagrams illustrating the WRTDS method for calculating (a) the "true-condition" estimates of concentration and load for all "Unsampled Days", and (b) the "flow-normalized" estimates of concentration and load for an "Estimation Day." Note that (1) the algorithm in (a) is also applied to all the "Sampled Days" to calculate "true-condition" estimates of concentration and load, and (2) the algorithm in (b) is repeated for each day in the record to achieve a complete time series of daily flow-normalized estimates of concentration and load.

5. Results and Discussion

5.1. Suspended Sediment

- The combined flow-normalized SS loads from Marietta and Conestoga show consistently downward trends in all four seasons (**Fig. 4**).
- The flow-normalized SS loads at Conowingo show generally "fall-and-then-rise" trends in most seasons (**Fig. 5**).
- Overall, the SS load at Conowingo has digressed increasingly far from the TMDL goal. The deteriorating situation of SS load at Conowingo can be largely attributed to the impact of the reservoirs.

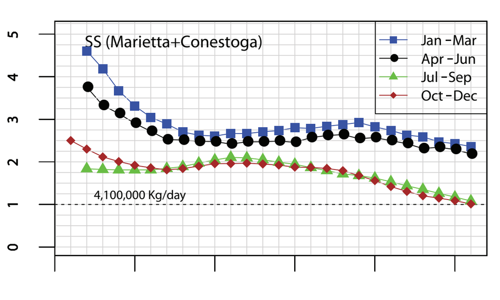


Fig. 4. Seasonal averages of flow-normalized SS load from Marietta and Conestoga (reservoir input).

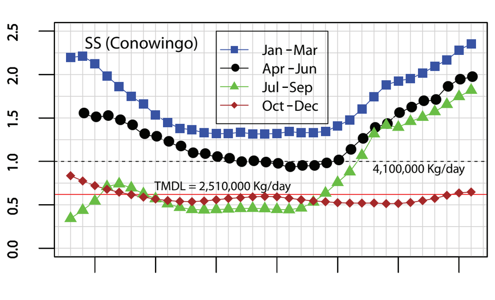


Fig. 5. Seasonal averages of flow-normalized SS load at Conowingo (reservoir output).

Note: in **Fig. 4** and **Fig. 5**, all loads have been normalized by the median of long-term annual loads at Conowingo (located at y = 1.0).

5.2. Phosphorus

- The combined flow-normalized TP loads from Marietta and Conestoga also show downward trends in all four seasons (**Fig. 6**).
- The flow-normalized TP loads at Conowingo show very similar "fall-and-then-rise" trends in all four seasons (**Fig. 7**), closely following the SS trend.
- Overall, the TP load at Conowingo has digressed increasingly far from the TMDL goal. The effect is clearly related to particulate species – PP shows the same "fall-and-then-rise" trend, whereas DP shows downward trends in all seasons. The deteriorating situation of PP load at Conowingo can be largely attributed to the impact of the reservoirs.

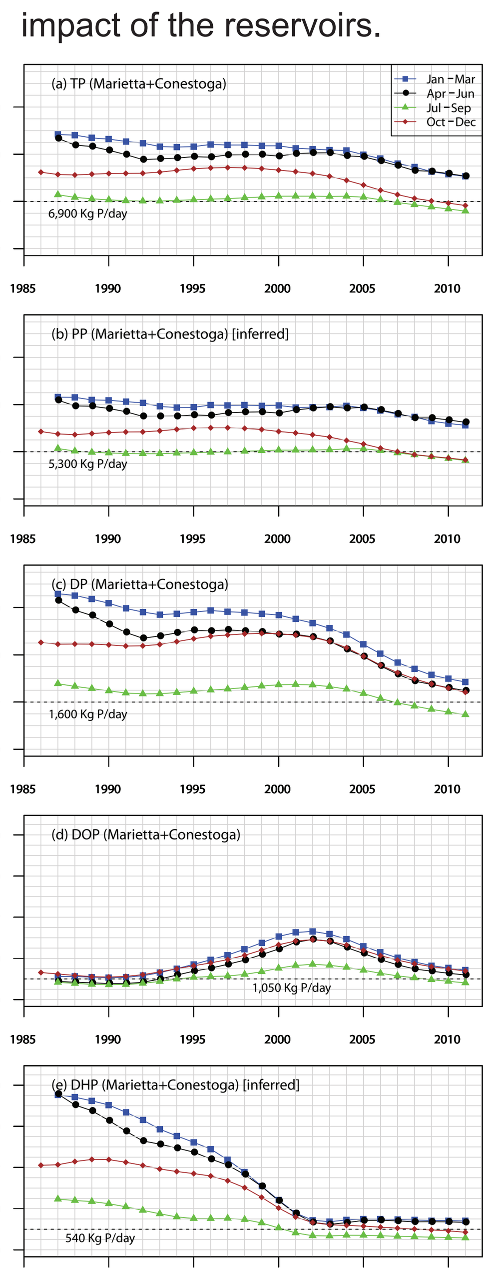


Fig. 6. Seasonal averages of flow-normalized load of (a) TP, (b) PP, (c) DP, (d) DOP, and (e) DHP from Marietta and Conestoga (reservoir input).

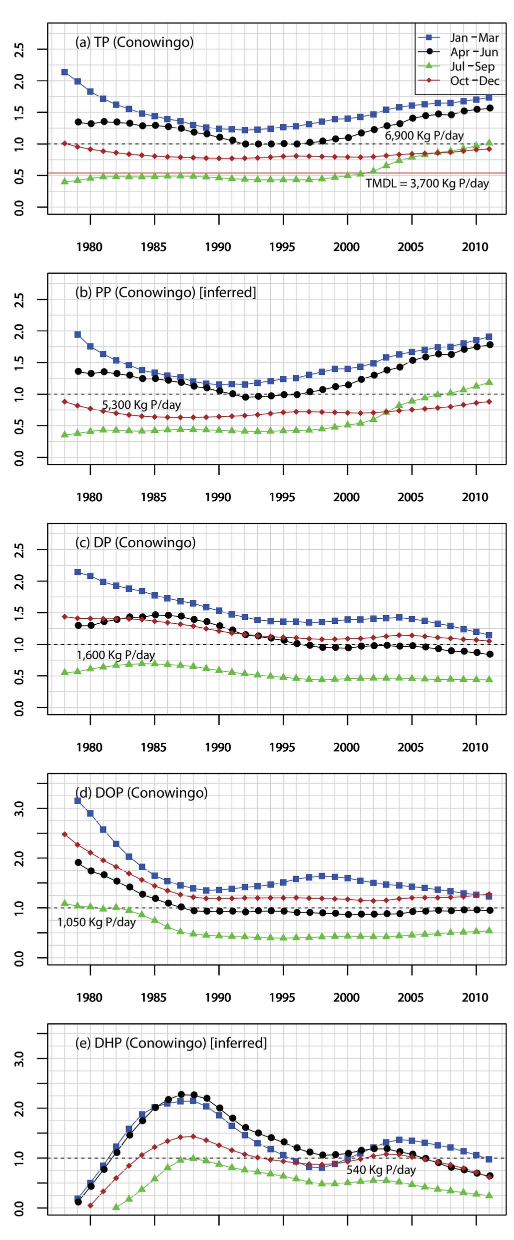


Fig. 7. Seasonal averages of flow-normalized load of (a) TP, (b) PP, (c) DP, (d) DOP, and (e) DHP at Conowingo (reservoir output).

Note: in **Fig. 6** and **Fig. 7**, all loads have been normalized by the median of respective long-term annual loads at Conowingo (located at y = 1.0 in each panel). In addition, estimates for panel labeled as "inferred" were obtained from data that were inferred rather than measured (i.e., PP = TP – DP; DHP = DP – DOP).

5.3. Nitrogen

- The combined flow-normalized TN loads from Marietta and Conestoga show downward trends in all four seasons (**Fig. 8**).
- The flow-normalized TN loads at Conowingo also show long-term trends that are similar among all four seasons, but opposite to those of SS and TP at Conowingo (i.e., "rise-and-then-fall"), with the peak load occurring in the late 1980s (**Fig. 9**).
- Overall, the TN load at Conowingo has been brought closer and closer to the TMDL goal. The major contributor to the TN reduction is DN. In comparison, PN shows upward trend in most seasons in recent years, which can be largely attributed to the impact of the reservoirs.

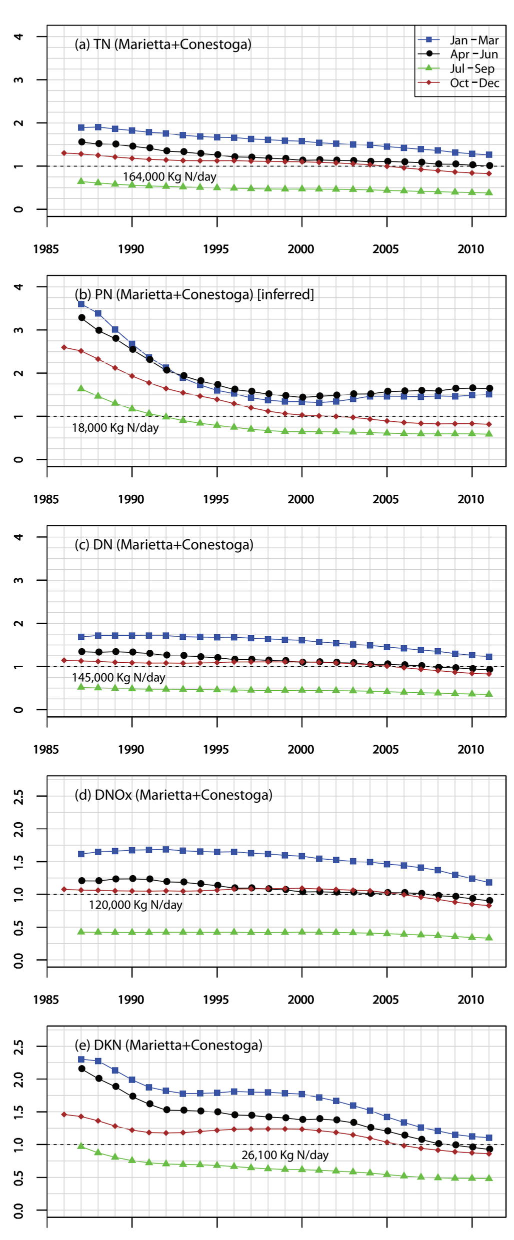


Fig. 8. Seasonal averages of flow-normalized load of (a) TN, (b) PN, (c) DN, (d) DNOx, and (e) DKN from Marietta and Conestoga (reservoir input).

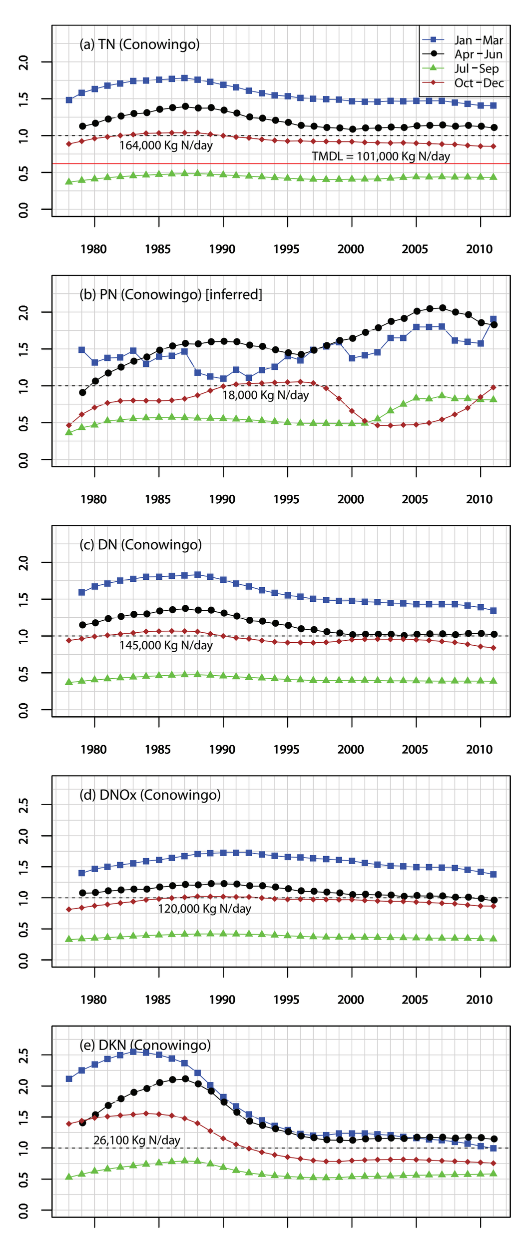


Fig. 9. Seasonal averages of flow-normalized load of (a) TN, (b) PN, (c) DN, (d) DNOx, and (e) DKN at Conowingo (reservoir output).

Note: in **Fig. 8** and **Fig. 9**, all loads have been normalized by the median of respective long-term annual loads at Conowingo (located at y = 1.0 in each panel). In addition, estimates for panel labeled as "inferred" were obtained from data that were inferred rather than measured (i.e., PN = TN – DN).

5.4. Changes in Reservoir Inventory

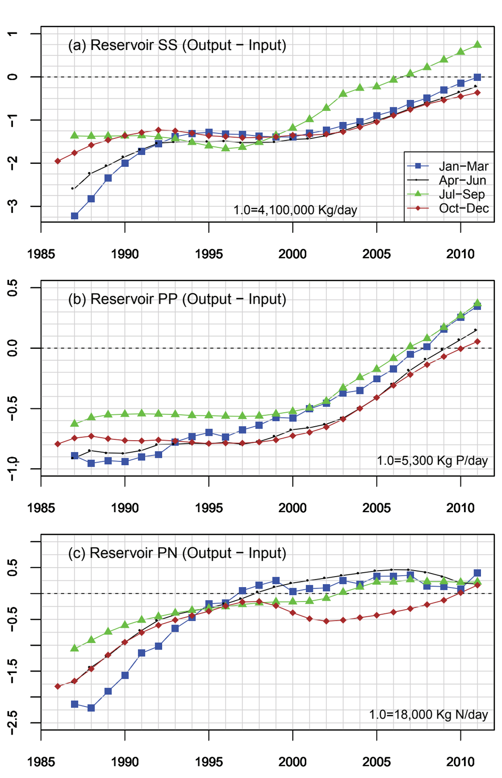


Fig. 10. Rates of storage change in (a) SS, (b) PP, and (c) PN within the reservoir system based on flow-normalized load. All rates of change have been normalized by the median of respective long-term annual loads at Conowingo.

- The reservoir system shows gradually diminishing capacity to trap new inputs of SS, PP, and PN (**Fig. 10**) over the last two to three decades. The seasonal flow-normalized estimates indicate an overall annual net loss for SS in 2011, for PP in 2009, and for PN in 2004, respectively.
- However, it should be noted that flow-normalized trends in input and output loadings do not reflect the best estimate of "true conditions" for any given year.
- In terms of true-condition loadings, our estimate of cumulative SS deposition from 1996 to 2010 indicates that the reservoir is about 90% full as of 2010.
- Evolution of SS concentration vs. streamflow relation shows that the reservoir system is becoming increasingly sensitive to highflow events (data not shown).

6. Conclusions

- Long-term trends of flow-normalized N, P, and SS load generally followed similar patterns in all four seasons, implying that changes in watershed function and land use had similar impacts on nutrient and sediment load at all times of the year.
- Flow-normalized loads of N, P, and SS have been generally reduced in the Susquehanna River above the reservoir system (representative of about 96% of the non-tidal Susquehanna River Basin) in the last two to three decades, which can most likely be attributed to a suite of management control actions on point, agricultural, and stormwater sources.
- Flow-normalized loads of SS, PP, and PN at the outlet of the Conowingo Reservoir have been generally rising since the mid-1990s. The reservoirs' capacity to trap these materials has been diminishing, and the Conowingo Reservoir has neared its sediment storage capacity.
- The changes in reservoir performance will pose significant new kinds of challenges to attainment of total maximum daily load goals for the Susquehanna River, and particularly if also accompanied by increases in storm frequency and intensity due to climate change. Accordingly, the reservoir issue may need to be factored into the proper establishment of regulatory load requirements and the development of watershed implementation plans.

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