Effects of Reservoir Filling on Sediment and Nutrient Removal in the Lower Susquehanna River Reservoir: An Input-Output Analysis based on Long-Term Monitoring

Qian Zhang,¹ Robert Hirsch,² William Ball ¹,³

¹ Dept. of Geography & Environmental Engineering, Johns Hopkins University (JHU)
² U.S. Geological Survey (USGS), Reston VA
³ Chesapeake Research Consortium (CRC)

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Photo of Conowingo Dam from www.chesapeakeboating.net
Background

• Nutrient and sediment loadings (non-tidal Chesapeake) (Zhang et al., JAWRA, 2015)
  • Recent rise in fall-line loading of sediments (SS) and sediment-bound nutrients (PP, PN) (including Susquehanna, James, and Rappahannock Rivers).
  • Susquehanna River accounts for ~92% and ~68% of SS and TP rise in 2002-2012.
• Susquehanna contribution to RIM tributaries (Zhang et al., JAWRA, 2015)
  • ~62% of flow, ~65% of TN, ~46% of TP, and ~41% of SS for 1979-2012.
• Conowingo Reservoir
  • Previously (1978) reported sediment scour threshold: 11,300 m³/s (400,000 cfs).
STAC Review Report on LSRWA

Section “Reduced deposition associated with reservoir infilling has been neglected”

“Net trapping efficiency is the sum of increases in average annual scour and decreases in average annual deposition. However, the simulations and calculations in the study only considered the increase in scour ... Without having the model simulate the full range of changes due to the loss of trapping efficiency, the report’s authors have introduced a large uncertainty into the results, and it is one that surely leads to an underestimate of the impact of the filling of Conowingo ... This issue underlies a significant weakness in the report, which is that it focuses its inquiry on the impact of large, but infrequent, scour events rather on the total impact of the change in trapping efficiency of the reservoir system.”
• Need to quantify the broad declines in reservoir performance in the last three decades.

• Need to explore **relative importance** of:
  
  (A) **Infrequent events at very high discharges** (> 11,000 m$^3$/s or 400,000 cfs) vs.
  
  (B) **Frequent events at moderate and high discharges** (sub-scour levels).

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**Background**

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![LSRRS Map](image)
To provide new insights on sediment and nutrient processing within the reservoir system in the monitored period of 1986-2013 (~30 years)

Objectives

1. Identify temporal change in system function \((C \text{ vs } Q \text{ above & below reservoir})\)
   Graphical analysis of “raw” \(C, Q\) data to obtain \(C, Q\) relationships

2. Elucidate trends in particulate loadings above and below the reservoir
   WRTDS analysis of \(C, Q\) observations to obtain “flow-normalized” trends

3. Conduct input-output (mass-balance) analyses around LSRRS (net deposition vs \(t\))
   WRTDS analysis of \(C, Q\) observations to obtain “true-condition” estimates

4. Isolate effects of the temporally changing WRTDS regression surface \([C(Q, t_{\text{season}})]\)
   Application of “stationary” \(C(Q, t)\) surfaces on the same long-term flow data
Monitoring sites:
- **Above LSRRS:**
  Marietta + Conestoga
  (~97% of SRB drainage area)
- **Below LSRRS:**
  Conowingo
  (99% of SRB drainage area)

Available Data (all sites):
- Discharge data (daily);
- **SS, P, and N** data (25-40 sampled days per year)
1. Temporal changes in \( C-Q \) relationships above & below LSRRS

**Suspended Sediment (SS)**

**Total Phosphorus (TP)**
2. **Flow-normalized trends** in particulate loadings above & below LSRRS

Suspended Sediment (SS) loadings

“Flow-Normalized” Estimates by Season of Year

Marietta + Conestoga
(26,460 mi²)

LSRRS

Conowingo
(27,100 mi²)

(Zhang et al., STOTEN, 2013)
2. (cont’d) **Flow-normalized trends** in particulate loadings above & below LSRRS

Marietta + Conestoga
(26,460 mi²)

LSRRS

Conowingo
(27,100 mi²)

(Zhang *et al.*, *STOTEN*, 2013)
3. Input-output analyses: net deposition in the reservoirs over time

Marietta (25,900 mi$^2$)
(Concentration Data: SRBC)
(Discharge Data: USGS)

Conestoga (470 mi$^2$)
(Concentration Data: SRBC)
(Discharge Data: USGS)

Unmonitored (730 mi$^2$)
(Extrapolation from Conestoga using area ratio: 2.36)

Reservoir Input
(WRTDS “true condition” loadings over time)

Conowingo (27,100 mi$^2$)
(Concentration Data: USGS)
(Discharge Data: USGS)

Reservoir Output
(WRTDS “true condition” loadings over time)

Net Deposition
(Input > Output)

or Net Scour
(Input < Output)
3. (cont’d) Input-output analyses: sediment storage from mass balance

- 76% of initial slope
- 32% of initial slope

Graph showing the remaining storage capacity (in million tons) from 1925 to 2015.
3. (cont’d) **Input-output analyses: output/input ratios (1987-2013)**

- **Output/input ratio** < 1 → net deposition.
- **Travel time**: we used 35-day moving averages of both input and output to mitigate effects of travel time across the reservoir system. (Results insensitive to selection of averaging time.)
- SS and TP ratios have increased in recent years.

**Notes:**
- TP loads are dominated by **PP**
- TN loads are dominated by **DN**
3. (cont’d) Input-output analyses: uncertainty analysis on O/I ratio

Annual median values of O/I ratio

Averages (blue dots) & the 95% confidence intervals (black error bars) (based on estimation with 100 realizations of representative data sets)

- Trends in annual median O/I are qualitatively maintained based on the 100 realizations.
- TP ratios > SS ratios, suggesting that decreasing retention in recent years is more pronounced for the finer (and more P-enriched) sediments.
- TN ratios: recent rise reflects an increasingly larger quantity and fraction of PN in the reservoir output that deserves further study and management consideration.
Annual No. of excursions for O/I ratio for different cut-off thresholds

Averages (red dots) & the 95% confidence intervals (black error bars)

- The annual numbers of excursion: TN >> SS > TP.
- TN: the recent rise in excursions reflects an increasingly larger quantity and fraction of PN in the reservoir output.
3. Input-output analyses: O/I ratios by flow class

Conowingo Flow Classes
- $Q_1$: 25~396 m$^3$/s;
- $Q_2$: 399~787 m$^3$/s;
- $Q_3$: 790~1,464 m$^3$/s;
- $Q_4$: 1,467~7,646 m$^3$/s;
- $Q_5$: 7,674~20,077 m$^3$/s.
- $Q_{scour}$: ~11,000 m$^3$/s

Conowingo Dam on 9/12/2011, 3 days after peak discharge following Tropical Storm Lee (9/1 to 9/5)
REF: pubs.usgs.gov/sir/2012/5185/
3. (cont’d) **Input-output analyses: % contributions of loads by flow classes**

### Conowingo Flow Classes

- $Q_1$: 25~396 m$^3$/s;
- $Q_2$: 399~787 m$^3$/s;
- $Q_3$: 790~1,464 m$^3$/s;
- $Q_4$: 1,467~7,646 m$^3$/s;
- $Q_5$: 7,674~20,077 m$^3$/s.
- $Q_{scour}$: $\sim$ 11,000 m$^3$/s

- $Q_4$ has dominated the absolute mass delivery of $Vw$, $TN$ and $TP$ through the system despite its **sub-scour** status.

- $Q_4$ has also had a major contribution to $SS$ delivery.
Q: Are these results biased by differential highflow samplings at Marietta and Conowingo?

- The major distinction on highflow sampling lies in **15000-20000 m³/s**, for which 3 dates were sampled at Conowingo (i.e., **1996/01/21, 2004/09/20, and 2011/09/08**) but not Marietta.
Sensitivity analysis

- We have re-run WRTDS model on Marietta and Conowingo by using only those samples with $Q < 15000 \text{ m}^3/\text{s}$.
- Results are consistent with those based on all samples – SS and TP output/input ratio has been rising since the early 2000s.
4. Stationary-model analyses: effects of changing $C(Q, t_{season})$ surface

- Inter-annual comparisons of loading and net deposition based on standard WRTDS models are influenced by the particular time history of discharges that happened in a given year as well as the concentration regression surface, i.e., $C(Q, t_{season})$.

- To isolate and reveal changes in the concentration regression surface (which we presume to reflect changes in reservoir system function), we select three “stationary” WRTDS models:
  - **Step 1**: Build the standard WRTDS model.
  - **Step 2**: Select three 1-yr-wide $C(Q, t)$ surfaces from the standard model -- **1990, 2000, 2010**.
4. (cont’d) **Stationary-model analyses: effects of changing** $C(Q, t_{season})$ **surface**

- **Step 3:** Separately repeat each of these 1-year surfaces over the full record to produce three “stationary” surfaces for the full period of record.

- **Step 4:** Apply each surface to the same full period of record (of daily $Q$) to estimate daily $C$ and loads.

- **Step 5:** Conduct mass-balance analyses on input and output loads.

- **Step 6:** Establish confidence intervals by re-sampling (with replacement).

Because all scenarios use the same flow record, observed differences in load estimates are due to the difference in the assumed stationary $C(Q, t_{season})$.

*The resulting 3 alternative load estimates (based on models separated by a decade) will reflect impacts that are presumed to be due to a changing system.*
4. (cont’d) Stationary-model analyses: load vs. Q under 3 reservoir conditions

Differences in TP loading vs flow (Q) among three scenarios of stationary regression surface representing 1990, 2000, and 2010 reservoir conditions.
• Overall, diminished net trapping of TP and SS (similar patterns) has occurred under a range of flow conditions, including flows well below the scour threshold.

• These changes reflect diminished reservoir performance rather than climatic factors such as increased streamflow variability.
Cumulative **SS net deposition** for a **Wet (2011)**, an **Average (2005)**, and a **Dry Year (2001)** as predicted using **3 Model Scenarios** representing **reservoir condition in 1990, 2000 and 2010**

4. (cont’d) **Stationary-model analyses: storage under 3 reservoir conditions**

- **Wet Year (2011)**
  - No scour if TS Lee had occurred under the 1990 reservoir condition

- **Normal Year (2005)**
  - No scour if the high flow had occurred under the 1990 and 2000 reservoir conditions

- **Dry Year (2001)**
  - (Mildly) reduced net deposition even for the dry year scenario
Major Findings

• This retrospective study has evaluated reservoir performance in the last three decades using different types of modeling approaches, all of which consistently show decreased net deposition of SS and TP in Conowingo Reservoir.

• Decreased reservoir trapping has occurred under a wide range of flow conditions, including sub-scour levels. The 75th~99.5th percentile of flow at Conowingo (high but sub-scour levels) has dominated the absolute mass of delivery through the reservoir.

• Moreover, recent rise in TN output/input ratio may reflect an increasingly larger quantity and fraction of PN in the reservoir output that deserves attention and further study.

• The results are robust based on uncertainty analysis and are insensitive to the differential highflow samplings at Marietta and Conowingo.
Management Implications

• Future progress in Bay restoration will depend on accurate predictions of how SS/TP/TN inputs to the reservoirs will be modulated by processes taking place in the reservoirs.

• Our analyses can help constrain and inform the development of improved predictive models of reservoir performance, and particularly the (possible) incorporation of such models in the ongoing upgrade of the Chesapeake Bay Partnership’s Watershed Model.

• This retrospective study does NOT speak for the issue of future reservoir conditions.

• Additional monitoring and modeling of the reservoir is critically needed, including at least (a) reservoir input and output conditions, (b) bathymetry measurements, (c) nutrient distributions in reservoir bottom sediments, and (d) nutrient transport and fate under different flow conditions.
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- Bob Hirsch (research hydrologist, USGS)

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- Maryland Water Resources Research Center

Documents in mySTAC WorkZone:

QUESTIONS?
Statistical Method (WRTDS)  
Hirsch et al., JAWRA (2010); Zhang et al., SOTE (2013)

**Output A: “true-condition” daily concentration and load**
- Use *given day’s Q* and *proximate C* observations (Time-Discharge-Season) to estimate the best “true” estimates of conc. and loadings
- For understanding real impacts on the ecosystem (fluvial and estuarine response; historical effects on living resources)

**Output B: “flow-normalized” daily concentration and load**
- Use *full history of given calendar day’s Q* with *proximate C* observations to calculate “flow-normalized” estimates of conc. and loadings
- For assessing progress in management and watershed function (nutrient and sediment source control, BMPs, land use & cover)
The WRTDS Model

Nutrient concentration data (roughly semi-monthly) → Streamflow discharge data (daily)

“Sampled Days” (Days with concentration) (known and C)
“Unsampled Days” (Days without concentration) (known t and Q, unknown C)

Select a Sampled Day (t, Q, C)
Select an “Estimation Day” (t0, Q0, unknown true-condition concentration C0 and load F0)

Use the 100+ previously selected Sampled Days with non-zero weight (refer to Fig. A.1) and Eq. A.1 to run the weighted regression and obtain the fitted coefficients

Compute the true-condition concentration (Ct) using t0, Q0, and the fitted coefficients from the step above

Compute the true-condition load (Ft) as Ct x Q0

Have ALL Estimation Days been estimated?
Yes

True-condition concentration and load available for ALL Estimation Days

Have ALL the Q values in the discharge set we used been?
Yes

Calculate the flow-normalized concentration and load for the Estimation Day: Cn = \frac{\sum_{i=1}^{n} F_i}{n}
Fn = \frac{\sum_{i=1}^{n} F_i}{n}

Have ALL Estimation Days been estimated?
Yes

Flow-normalized concentration and load available for ALL Estimation Days

Reproduced from Zhang et al. (2013)
3. (cont’d) Input-output analyses: O/I ratios by flow class

Conowingo Flow Classes

\[ Q_1: 25\text{~}396 \text{ m}^3/\text{s}; \]
\[ Q_2: 399\text{~}787 \text{ m}^3/\text{s}; \]
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\[ Q_5: 7,674\text{~}20,077 \text{ m}^3/\text{s}; \]
\[ Q_{scour}: \sim 11,000 \text{ m}^3/\text{s} \]

Suspended Sediments (SS)

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Conowingo Dam on 9/12/2011, 3 days after peak discharge following Tropical Storm Lee (9/1 to 9/5)

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- $Q_5$: 7,674~20,077 m$^3$/s.

**Q$_{scour}$**: ~ 11,000 m$^3$/s

**Total Nitrogen (TN)**

Input-output analyses: O/I ratios by flow class

- $Q_1$: [0th, 25th]
- $Q_2$: (25th, 50th)
- $Q_3$: [50th, 75th]
- $Q_4$: (75th, 99.5th)
- $Q_5$: (99.5th, 100th)

Conowingo Dam on 9/12/2011, 3 days after peak discharge following Tropical Storm Lee (9/1 to 9/5)

REF: pubs.usgs.gov/sir/2012/5185/
4. (cont’d) Effects of the changing WRTDS regression surface \([C(Q, t_{season})]\)

**Frequency Plots of Ranked Loadings**

![Graph](image-url)

- **SS Output**
  - (a) Conowingo
  - No. of days exceeded per year
  - SS load, million kg/day
  - M₃ model (2010)
  - M₂ model (2000)
  - M₁ model (1990)

- **(b)**
- **(c)**
- **(d)**
  - No. of days exceeded per year
  - SS load, million kg/day
  - No. of days exceeded per year
  - No. of days exceeded per year
4. (cont’d) Effects of the changing WRTDS regression surface \([C(Q, t_{\text{season}})]\)
4. (cont’d) Effects of the changing WRTDS regression surface \( C(Q, t_{season}) \)

**Stationary-Model Summary (1)**

- Reservoir inputs of SS, TP, and TN have generally declined.
- Reservoir outputs of SS and TP have generally increased.
- Reservoir net deposition of SS and TP has declined greatly.
4. (cont’d) Effects of the changing WRTDS regression surface \([C(Q, t_{season})]\)

Differences in reservoir output loading vs flow for three scenarios of a stationary regression surface, representing 1990, 2000, and 2010 conditions.
Differences in reservoir output loading vs flow for three scenarios of a stationary regression surface, representing 1990, 2000, and 2010 conditions.

4. (cont’d) Effects of the changing WRTDS regression surface $[C(Q, t_{\text{season}})]$
Changes in Reservoir Trapping by Flow Intervals

(a) Reservoir Input

SS Input

(a) Net Increase in SS Stored

SS Net Dep.
4. (cont’d) Effects of the changing WRTDS regression surface \( [C(Q, t_{season})] \)

Differences in *net deposition rate vs flow* among three scenarios of a stationary regression surface representing 1990, 2000, and 2010 conditions