Decadal-scale Changes in Sediment and Nutrient Delivery from Conowingo Reservoir to Chesapeake Bay: Statistical Evaluations of Reservoir Trapping using Long-Term Monitoring Data

Qian Zhang
Monitoring Data Analyst, UMCES @ Chesapeake Bay Program Office
(Formerly, PhD Student, DoGEE, Johns Hopkins University)

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Background: LSRRS (Conowingo)

Objective
To quantify the long-term trends in sediment and nutrient loads at sites above and below the system, with special focus on particulate vs. dissolved species trend comparison.

Monitoring sites:
- **Reservoir input:**
  Marietta + Conestoga (SRBC)
  (~97% of Susquehanna drainage area)
- **Reservoir output:**
  Conowingo (USGS)
  (~99% of Susquehanna drainage area)

Monitoring Data:
- Daily discharge data (USGS)
- Concentration: 26-37 days per year
  - SS: Suspended sediment
  - P: Phosphorus
  - N: Nitrogen

Method:
- **WRTDS** [to obtain daily estimates]
**WRTDS Method**

- **Daily flow & sparse concentration at a sampling site**
  - WRTDS (Hirsch *et al.*, 2010)
  - WRTDS (Hirsch *et al.*, 2010)
    - Weighted Regressions on Time, Discharge, and Season
    - \( \ln(C) = \beta_0 + \beta_1 t + \beta_2 \ln(Q) + \beta_3 \sin(2\pi t) + \beta_4 \cos(2\pi t) + \epsilon \)
    - One single model (coefficient set) for each day of estimation;
    - No assumption on fixed C-Q relations over time or season;
    - Better estimation performance;
    - Adopted in a wide range of studies.

**Daily conc. and load estimates**
**WRTDS Method**

- **Daily flow & sparse concentration at a sampling site**
- **WRTDS (Hirsch et al., 2010)**
- **Daily conc. and load estimates**

**Susquehanna TN Load on Jan 1**
(TN: total nitrogen)

- "True-condition" load (understand ecosystem impacts)
- "Flow-normalized" load (assess management progress)
What have been the flow-normalized seasonal trends at Conowingo Dam?

Marietta + Conestoga (26,460 mi²)

LSRRS (Reservoir System)

Conowingo (27,100 mi²)

(Zhang, Brady, Ball, STOTEN, 2013)
Which sub-species has driven the TP trend?

Marietta + Conestoga (26,460 mi²)

LSRRS (Reservoir System)

Conowingo (27,100 mi²)

(Zhang, Brady, Ball, STOTEN, 2013)
Are these trends due to changes in the **upstream watershed** or reservoirs?

(Zhang, Brady, Ball, STOTEN, 2013)
Are these trends biased by storm-flow samples?

Marietta + Conestoga (26,460 mi²)

LSRRS (Reservoir System)

Conowingo (27,100 mi²)

(Zhang and Ball, unpublished data)
Follow-up Work by Zhang, Hirsch, and Ball (2016)

- To quantify the **broad long-term changes** in reservoir net deposition.
- To better understand the **uncertainties** of the statistical analyses, particularly with **limited monitoring data at extremely high flows**.
- To quantify the **relative importance** of:
  
  (A) Infrequent events at very high flows (above-scour* levels) vs.
  
  (B) Frequent events at moderate to high flows (sub-scour levels).

*400,000 cfs or 11,300 m³/s (Gross et al., 1978)*

[Major concern to managers and modelers]

**Conowingo Daily Discharge**

- **(B) sub-scour** [99.9%]
- **(A) above-scour** [18 days; 0.1%] “Big Concern”

Temporal Changes in $C-Q$ Relationships: **LOWESS Curves**

**Total Phosphorus (TP)**  

*(Zhang, Hirsch, Ball, ES&T, 2016)*
Temporal Changes in C-Q Relationships: WRTDS $\beta_2$ Coefficients

$$ln(C_i) = \beta_{0,i} + \beta_{1,i} t_i + \beta_{2,i} ln(Q_i) + \beta_{3,i} \sin(2\pi t_i) + \beta_{4,i} \cos(2\pi t_i) + \varepsilon_i$$

Time | Discharge | Season
--- | --- | ---

Input-Output Analyses: Net Deposition in the Reservoir

Marietta (25,900 mi²)
(Concentration Data: SRBC)
(Discharge Data: USGS)

Conestoga (470 mi²)
(Concentration Data: SRBC)
(Discharge Data: USGS)

Unmonitored (730 mi²)
(Extrapolation from Conestoga using area ratio: 1.36)

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

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

Net Deposition
(Input > Output)
or Net Scour
(Input < Output)

(Zhang, Hirsch, Ball, ES&T, 2016)
Q: What are the trends in Output/Input (O/I) ratio?

“Centerline” formed by the annual median of 365 daily true-condition O/I ratios in each year from 1987 to 2013

(Zhang, Hirsch, Ball, ES&T, 2016)
Input-Output Analyses: Uncertainty Analysis on O/I Ratio

Q: What are the uncertainties in O/I ratio trend?

100 “bootstrap” replicates → 100 model runs for O and for I → 100 “centerlines” (annual medians) → Mean & the 95% CI

(Zhang, Hirsch, Ball, ES&T, 2016)
Q: Are trends in O/I ratio biased by the differential highflow sampling at Marietta and Conowingo?
Input-Output Analyses: Sensitivity to Differential Highflow Sampling

Q: Are trends in O/I ratio biased by the differential highflow sampling at Marietta and Conowingo?

**Sensitivity analysis** with **equally-censored samples** ($Q < 15,000 \, m^3/s$)

(a) Suspended Sediment
- Net scour (>1)
- Net deposition

(b) Total Phosphorus
- Net scour (>1)
- Net deposition

(Zhang, Hirsch, Ball, *ES&T*, 2016)
**Q: Is the O/I trend associated with highflow only?**

**Total Phosphorus (TP) (SS similar)**

**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/
(Zhang, Hirsch, Ball, ES&T, 2016)

**Input-Output Analyses: O/I Ratio by Flow Class**

![Diagram showing O/I trend by flow class](image)
Q: Which flow class has contributed the most to mass delivery?

Conowingo Flow Classes
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- $Q_{scour}$: ~ 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.
Inter-annual comparisons of WRTDS true-condition loadings are influenced by:

(A) the particular history of flows occurred in a given year and
(B) change in the WRTDS regression surface, i.e., system function.

Developed 3 “stationary” WRTDS models that represent historical conditions of reservoir performance in 3 different years -- 1990, 2000, 2010.
What is the significance of the **Susquehanna** trend in the NTCBW context?

- **NTCBW** = sum of 9 RIM rivers (non-tidal parts)
- **NTCBW average load** in 1979-2012:
  - ~62% of flow from Susquehanna
  - ~65% of TN from Susquehanna
  - ~46% of TP from Susquehanna
  - ~41% of SS from Susquehanna
- **NTCBW rises** in particulate species in 2002-2012:
  - ~92% of SS due to Susquehanna
  - ~68% of TP due to Susquehanna
- **NTCBW—SUS**: similar trend contrast
  - dissolved species: down
  - particulate species: up

*Source: USGS (Zhang, Brady, Boynton, Ball, JAWRA, 2015)*
Conclusions

• Declined reservoir input of dissolved & particulate constituents.
• Increased reservoir output of particulate constituents (SS and TP).
• Decreased net deposition of SS and TP under a wide range of flow conditions, including sub-scour levels.
• Mass of delivery across Conowingo dominated by moderately high flows.
• Conclusions supported by uncertainty and sensitivity analyses.
• Recommendations for future research:
  ✓ Continued monitoring and modeling of loads (and uncertainties!)
  ✓ Continued monitoring and modeling of nutrient biogeochemistry
  ✓ Continued evaluation of Conowingo infill’s effects on Bay water quality
  ✓ Consideration of reservoir processes/effects under a wide range of flow conditions (including extreme flows and moderately high flows)
Management Implications

• The largest reservoir in the Lower Susquehanna River (the largest tributary to the Bay) is no longer an effective trap (of particulate constituents).

• The key assumptions on reservoir performance adopted in the development of 2010 Chesapeake Bay TMDL are no longer valid.

• The Bay Program Partnership needs to improve the representation of the reservoir system performance in its Phase 6 Watershed Model, using multiple lines of monitoring and modeling information.

  [Jun 2017: The Phase 6 Model will be released.]

• The Bay Program Partnership needs to evaluate the options to allocate jurisdictional targets to offset the additional loads due to Conowingo infill.

  [May 2017: The CBP PSC will make the final decision.]

  [Dec 2017: The EPA will release the final Phase III WIP targets.]
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Related Publications