

An aerial photograph of the Conowingo Dam, a long concrete structure with multiple spillways, spanning a wide river. The river is surrounded by dense green forest. The water in the reservoir is a deep blue, while the water flowing over the dam is a lighter, more turbulent blue. The sky is a clear, pale blue.

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

Conowingo Dam

Qian Zhang

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

Chesapeake Bay Program STAR Seminar, October 24, 2016

USGS (2012, 2015)



Flux of Nitrogen, Phosphorus, and Suspended Sediment from the Susquehanna River Basin to the Chesapeake Bay during Tropical Storm Lee, September 2011, as an Indicator of the Effects of Reservoir Sedimentation on Water Quality

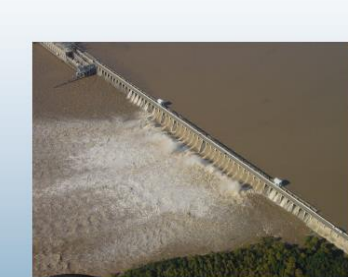


Scientific Investigations Report 2012–5185

U.S. Department of the Interior
U.S. Geological Survey



Sediment Transport and Capacity Change in Three Reservoirs, Lower Susquehanna River Basin, Pennsylvania and Maryland 1900–2012



Open-File Report 2014–1235

U.S. Department of the Interior
U.S. Geological Survey

LSRWA (2015)



Conowingo Reservoir Sedimentation and Chesapeake Bay: State of the Science

Carl E. Cocco*

Abstract
The Conowingo Reservoir is situated on the Susquehanna River, Maryland, and is the largest urban reservoir in the United States. Sedimentation in the reservoir is the result of human activities, including urbanization, agriculture, and industry. The reservoir is a critical component of the Chesapeake Bay ecosystem, providing a natural barrier to the bay and a source of sediment. The reservoir is also a source of nutrients, including nitrogen and phosphorus, which can contribute to eutrophication in the bay. The reservoir is a complex system, with a variety of factors influencing its sedimentation and nutrient dynamics. This report provides a comprehensive overview of the state of the science regarding the Conowingo Reservoir, including its sedimentation, nutrient dynamics, and the impact of human activities. The report also discusses the challenges facing the reservoir and provides recommendations for future research and management.

Core Ideas
• Reservoir sedimentation prevents sediments from entering Chesapeake Bay.
• Reservoir sediment storage capacity is nearly exhausted.
• Reservoir sediment storage capacity is nearly exhausted.
• Reservoir sediment storage capacity is nearly exhausted.

U.S. Department of the Interior
U.S. Geological Survey



Influence of Reservoir Infill on Coastal Deep Water Hypoxia

Lewis C. Lineker*, Richard A. Barfknecht, Carl E. Cocco, Gary W. Shenk, Richard Tian, Ping Wang, and Guido Tackx

Abstract
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Core Ideas
• The Conowingo Reservoir has been filling in with sediment for decades.
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U.S. Department of the Interior
U.S. Geological Survey

STAC (2014)

Review of the Lower Susquehanna River Watershed Assessment



STAC Review Report
August 2014
Annapolis, Maryland



STAC Publication 14-006

Johns Hopkins (2013, 2015, 2016)



Long-term seasonal trends of nitrogen, phosphorus, and suspended sediment load from the non-tidal Susquehanna River Basin to Chesapeake Bay

Q. Zhang*, D.C. Brady*, W.P. Ball*

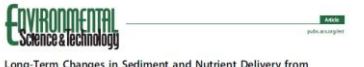
U.S. Department of the Interior
U.S. Geological Survey



LONG-TERM TRENDS OF NUTRIENTS AND SEDIMENT FROM THE NON-TIDAL CHESAPEAKE WATERSHED: AN ASSESSMENT OF PROGRESS BY RIVER AND SEASON*

Qian Zhang, Damien C. Brady, Walter R. Boynton, and William P. Ball*

U.S. Department of the Interior
U.S. Geological Survey



Long-Term Changes in Sediment and Nutrient Delivery from Conowingo Dam to Chesapeake Bay: Effects of Reservoir Sedimentation

Qian Zhang*, Robert M. Hoch*, and William P. Ball*

U.S. Department of the Interior
U.S. Geological Survey



An improved method for interpretation of riverine concentration-discharge relationships indicates long-term shifts in reservoir sediment trapping

Qian Zhang*, William P. Ball*, and Douglas L. Meyer*

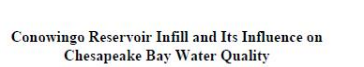
U.S. Department of the Interior
U.S. Geological Survey



Decadal-scale export of nitrogen, phosphorus, and sediment from the Susquehanna River basin, USA: Analysis and synthesis of temporal and spatial patterns

Qian Zhang*, William P. Ball*, and Douglas L. Meyer*

U.S. Department of the Interior
U.S. Geological Survey



Conowingo Reservoir Infill and Its Influence on Chesapeake Bay Water Quality

Qian Zhang*, William P. Ball*, and Douglas L. Meyer*

U.S. Department of the Interior
U.S. Geological Survey

USGS
science for a changing world

Flux of Nitrogen, Phosphorus, and Suspended Sediment from the Susquehanna River Basin to the Chesapeake Bay during Tropical Storm Lee, September 2011, as an Indicator of the Effects of Reservoir Sedimentation on Water Quality

• Non-point-source runoff is the largest source of sediment to the Chesapeake Bay.
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Journal of Environmental Quality
THE CONOWINGO RESERVOIR

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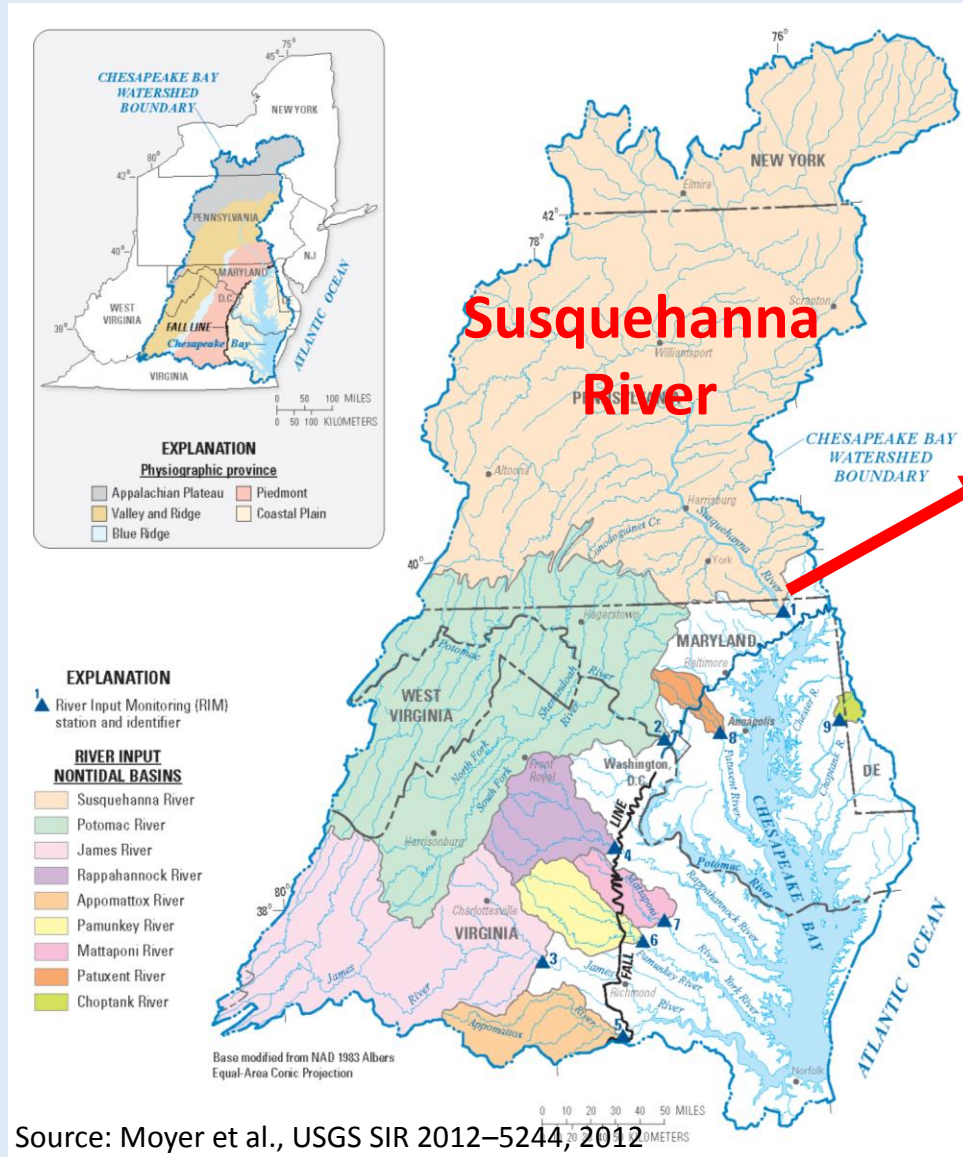
Journal of Environmental Quality
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Conowingo Reservoir Infill and Its Influence on Chesapeake Bay Water Quality

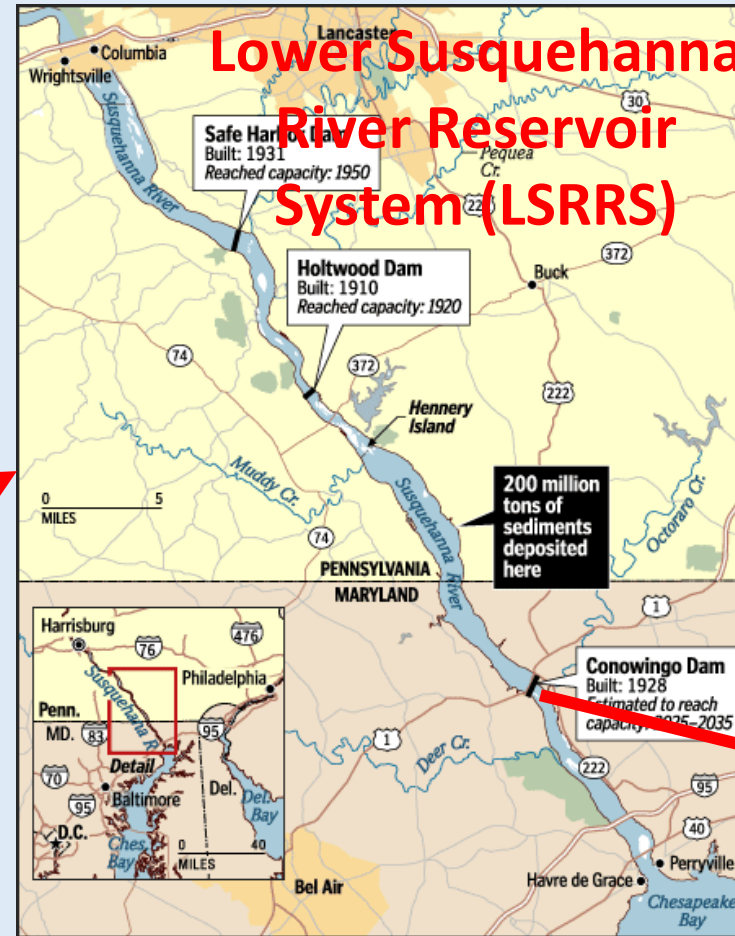
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Background: LSRRS (Conowingo)



Source: Moyer et al., USGS SIR 2012-5244, 2012



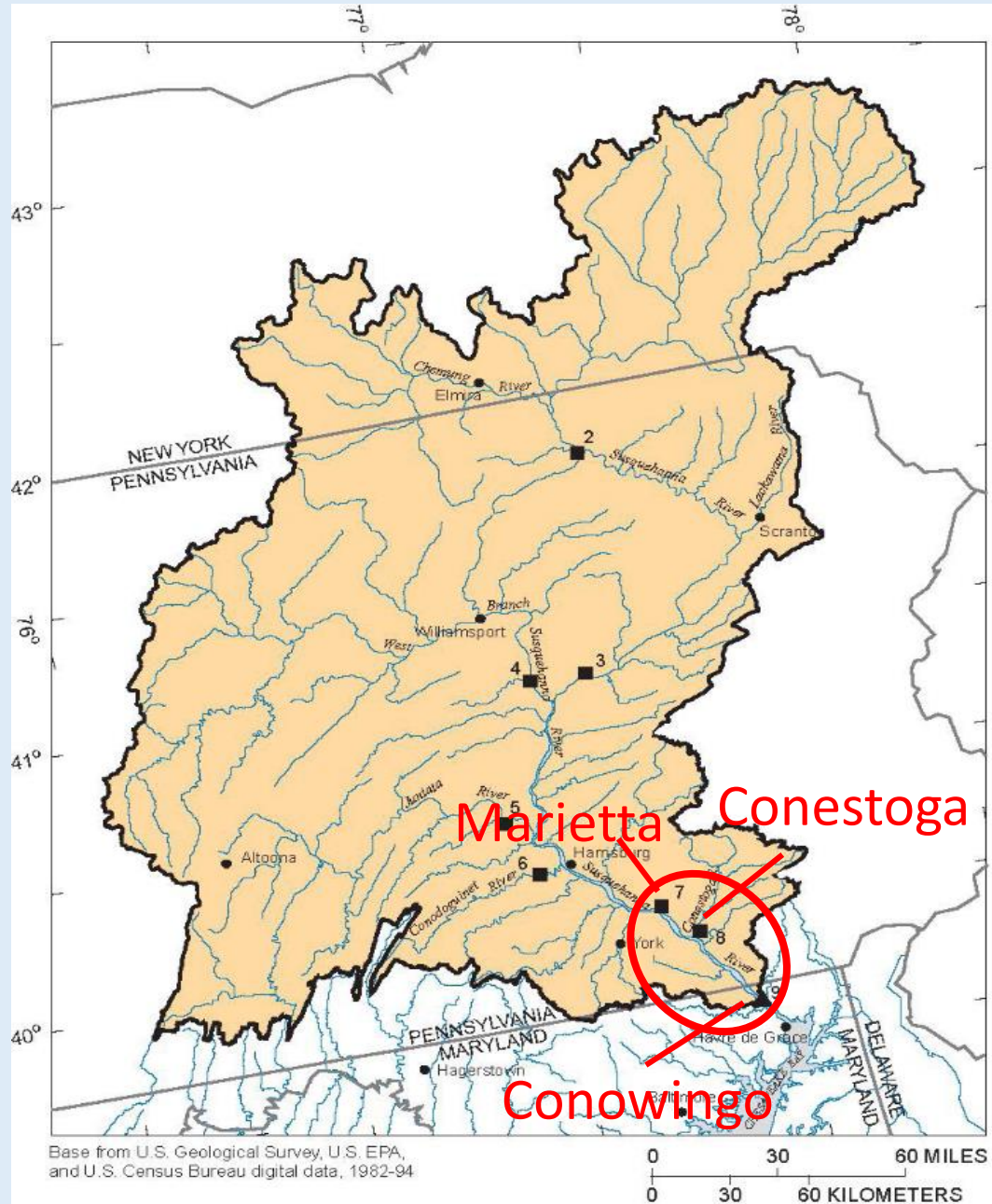
Objective

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



Zhang, Q.; Brady, D. C.; Ball, W. P., Long-term seasonal trends of nitrogen, phosphorus, and suspended sediment load from the non-tidal Susquehanna River Basin to Chesapeake Bay. *Sci. Total Environ.* **2013**, 452-453, 208-221, [doi: 10.1016/j.scitotenv.2013.02.012](https://doi.org/10.1016/j.scitotenv.2013.02.012).

Study Sites and Data



Monitoring sites:

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

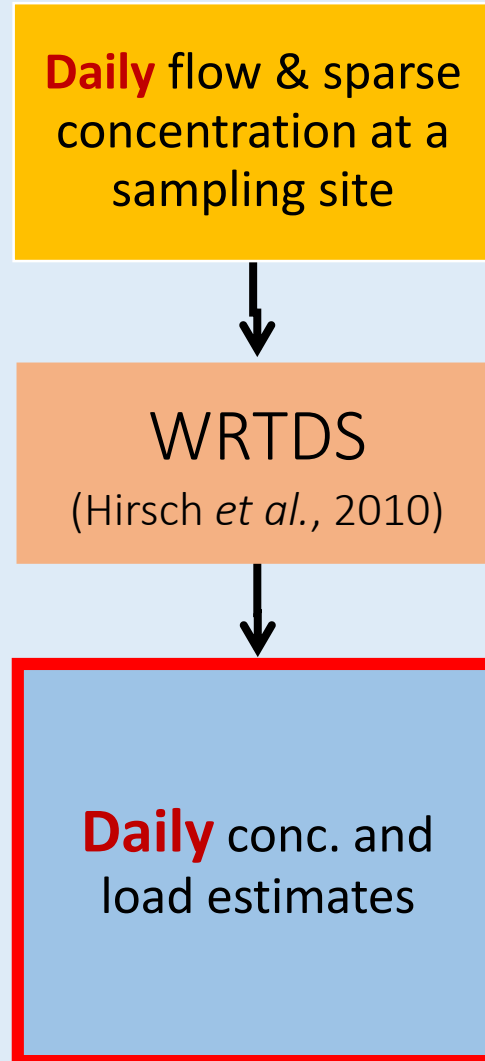
Monitoring Data:

- 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

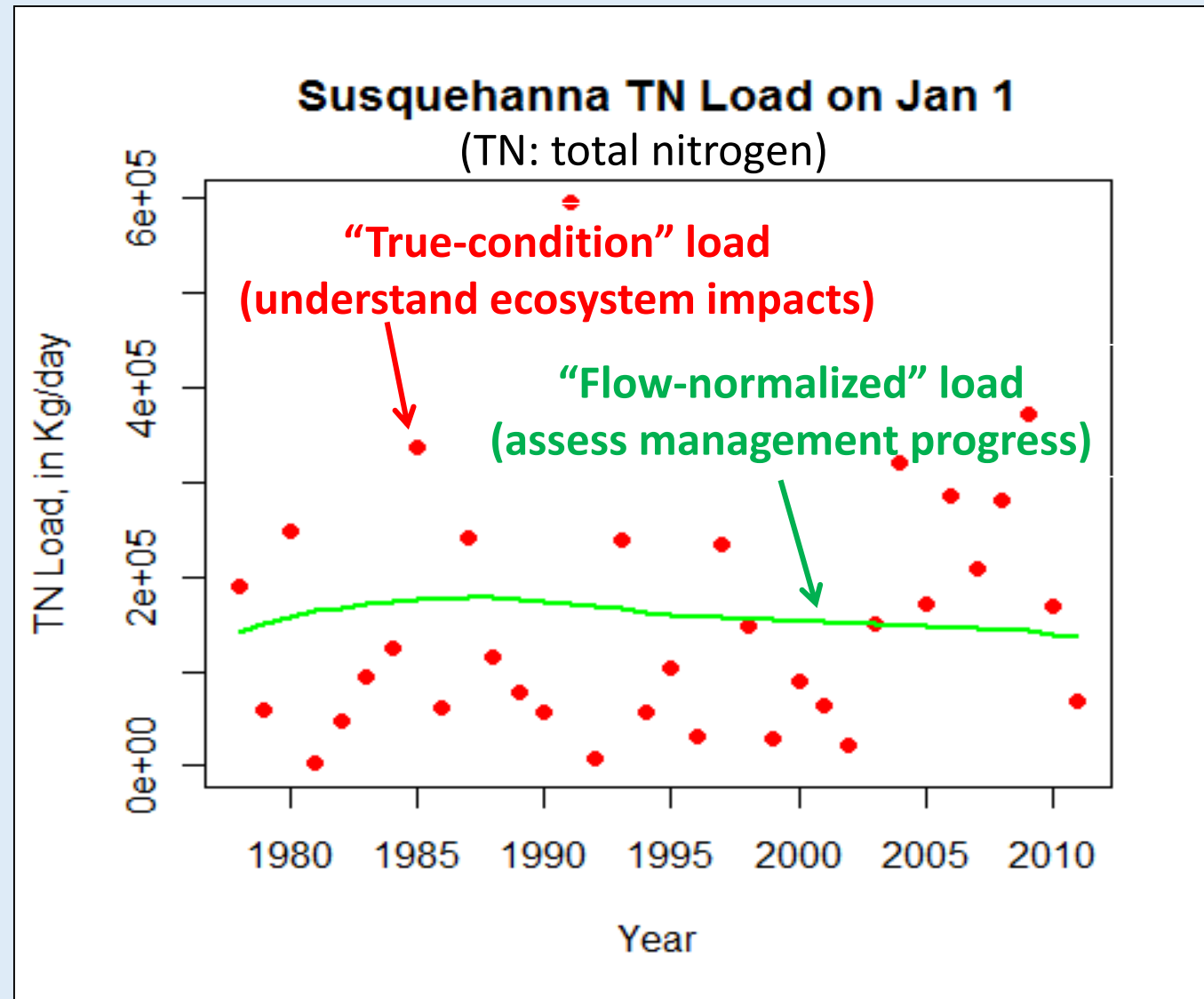
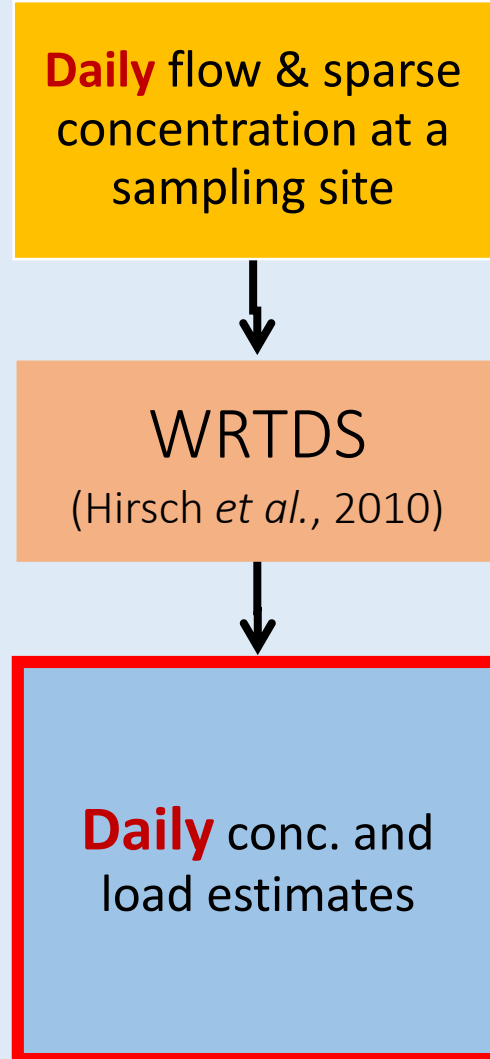


WRTDS (Hirsch *et al.*, 2010)
[**W**eighted **R**egressions on
Time, **D**ischarge, and **S**ea**s**on]

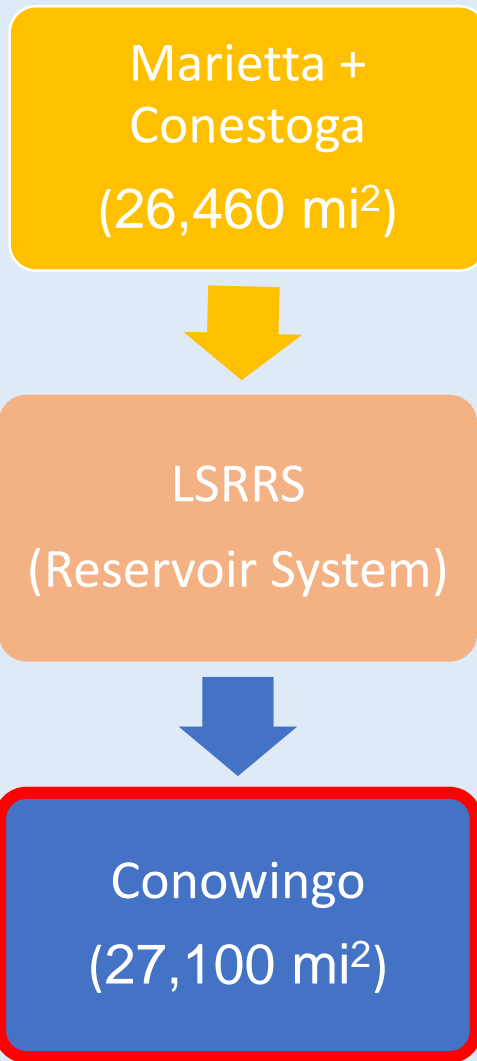
$$\ln(C) = \beta_0 + \beta_1 t + \beta_2 \ln(Q) + \beta_3 \sin(2\pi t) + \beta_4 \cos(2\pi t) + \varepsilon$$

- 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.

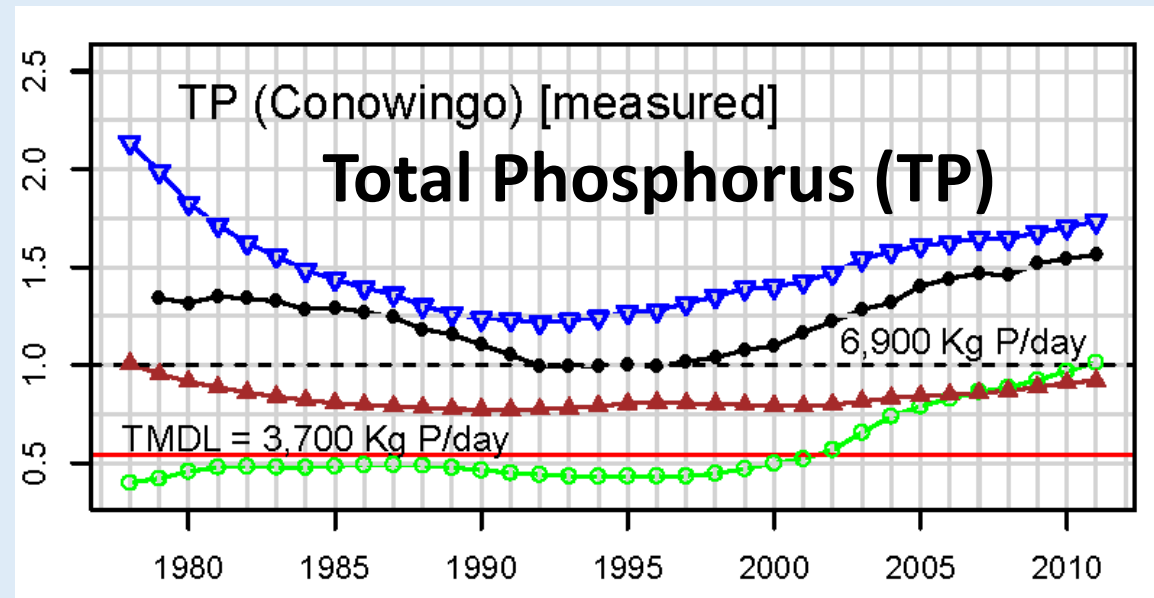
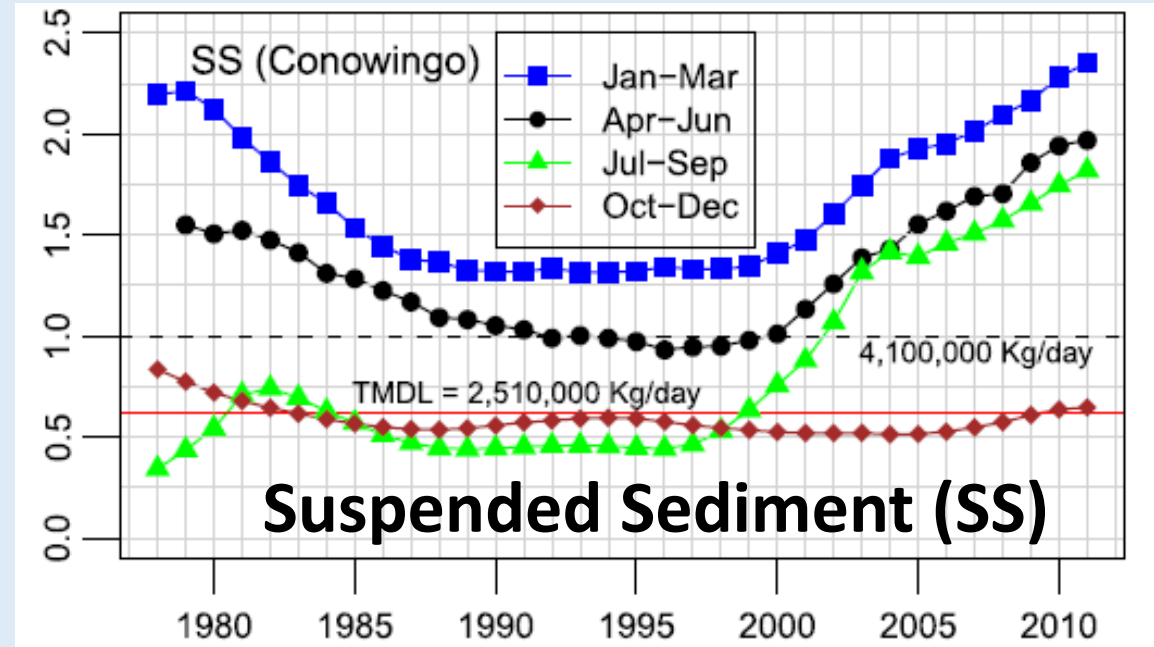
WRTDS Method



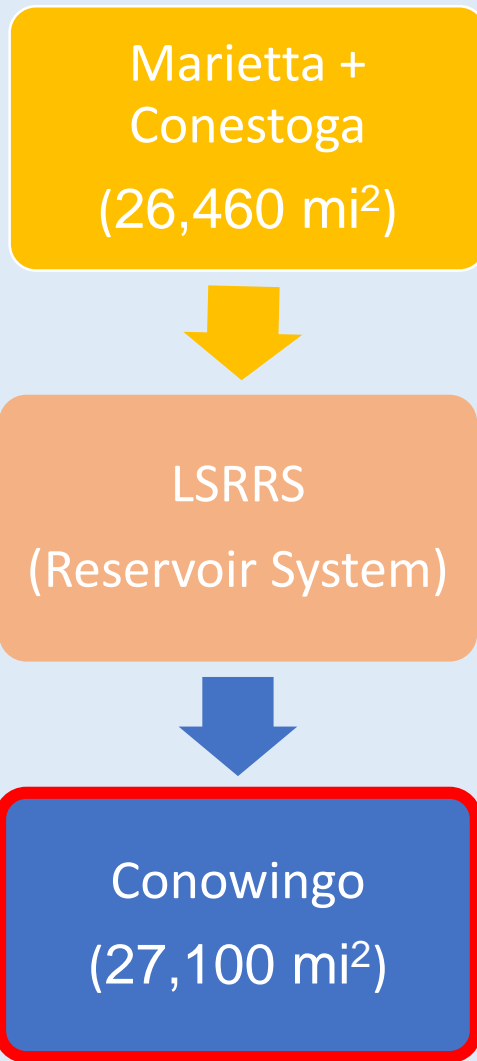
What have been the flow-normalized seasonal trends at **Conowingo Dam**?



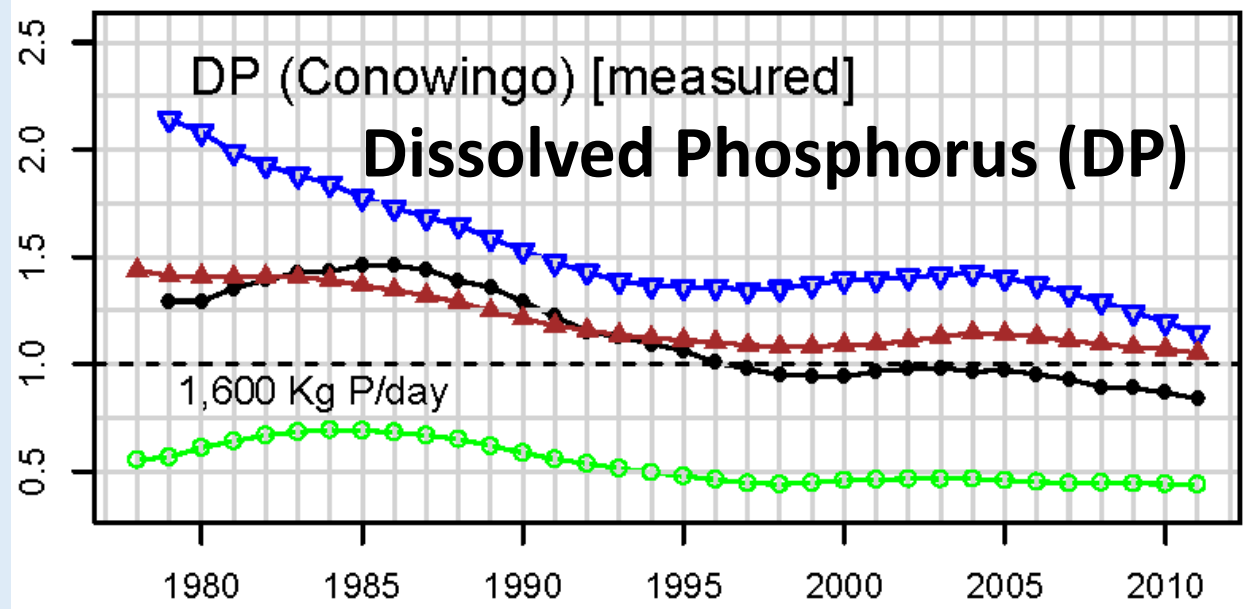
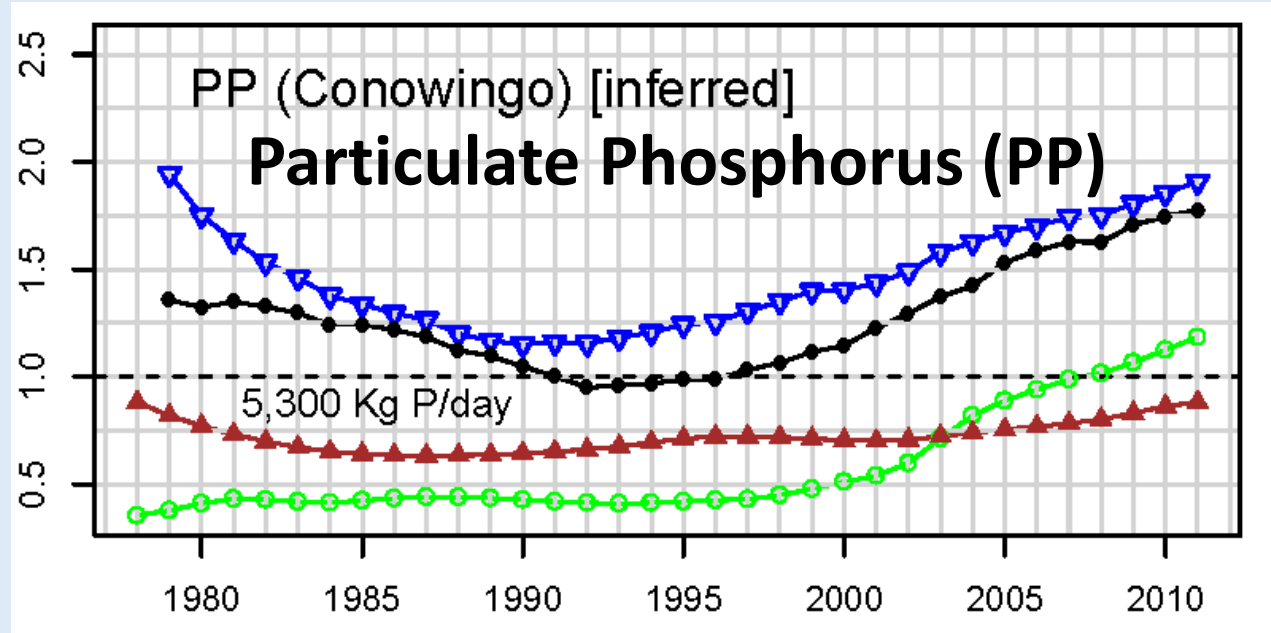
(Zhang, Brady, Ball, STOTEN, 2013)



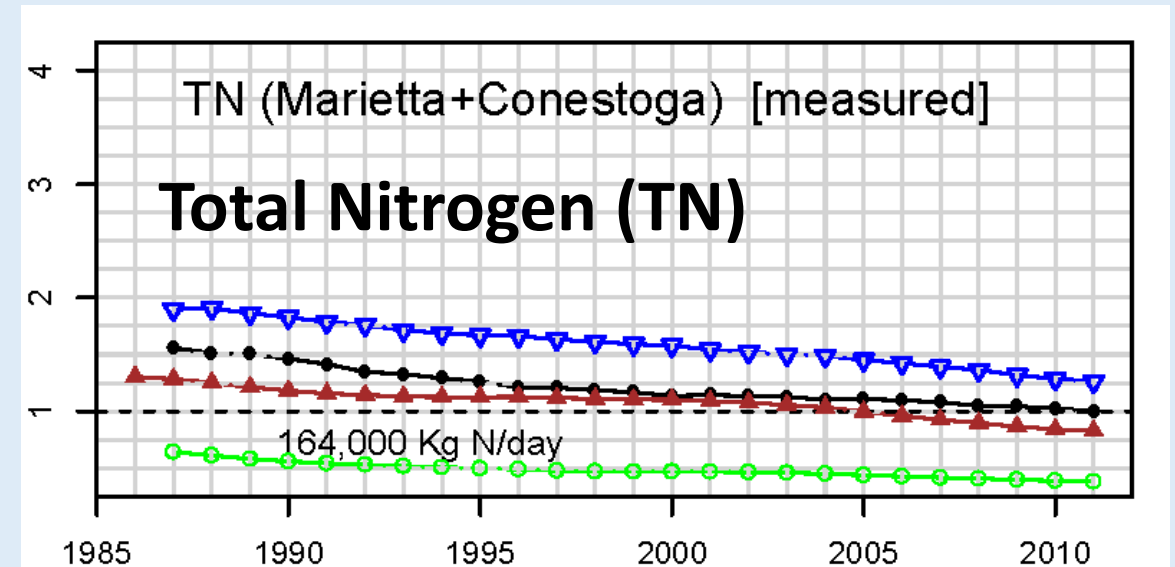
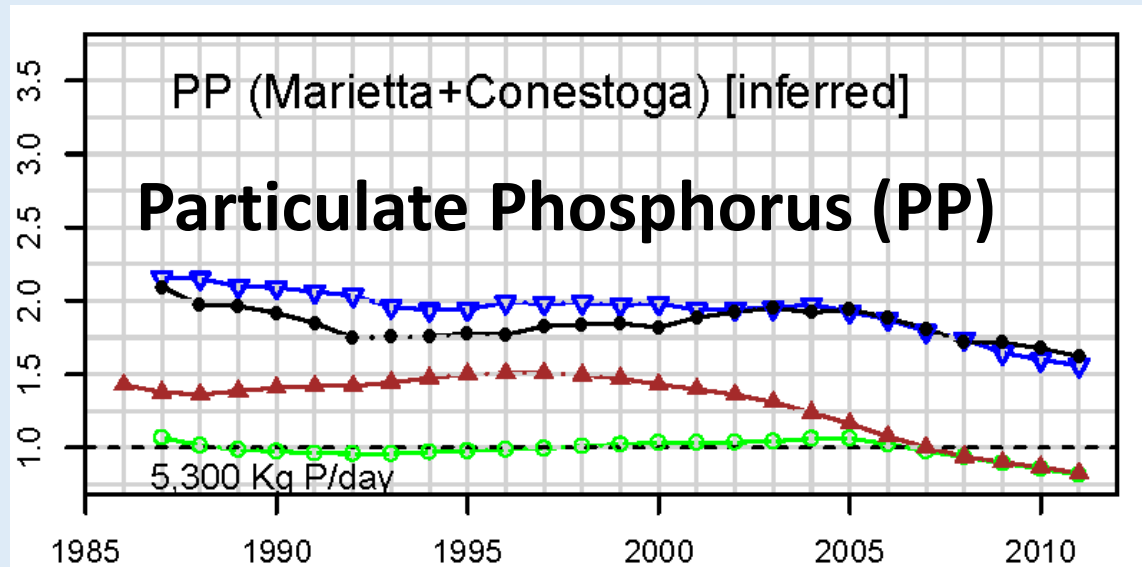
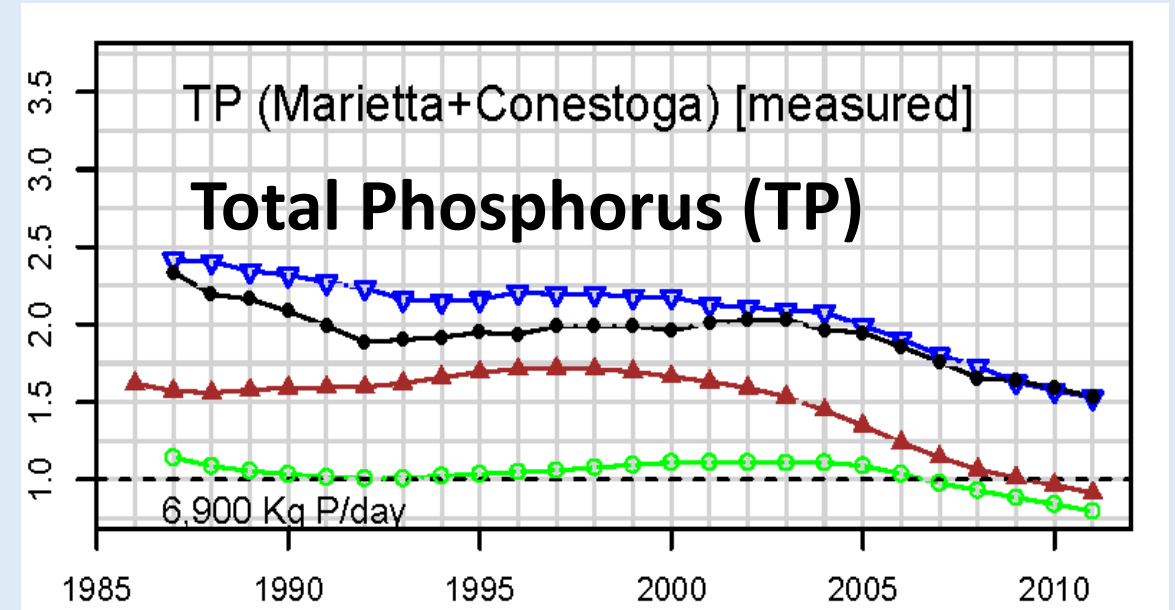
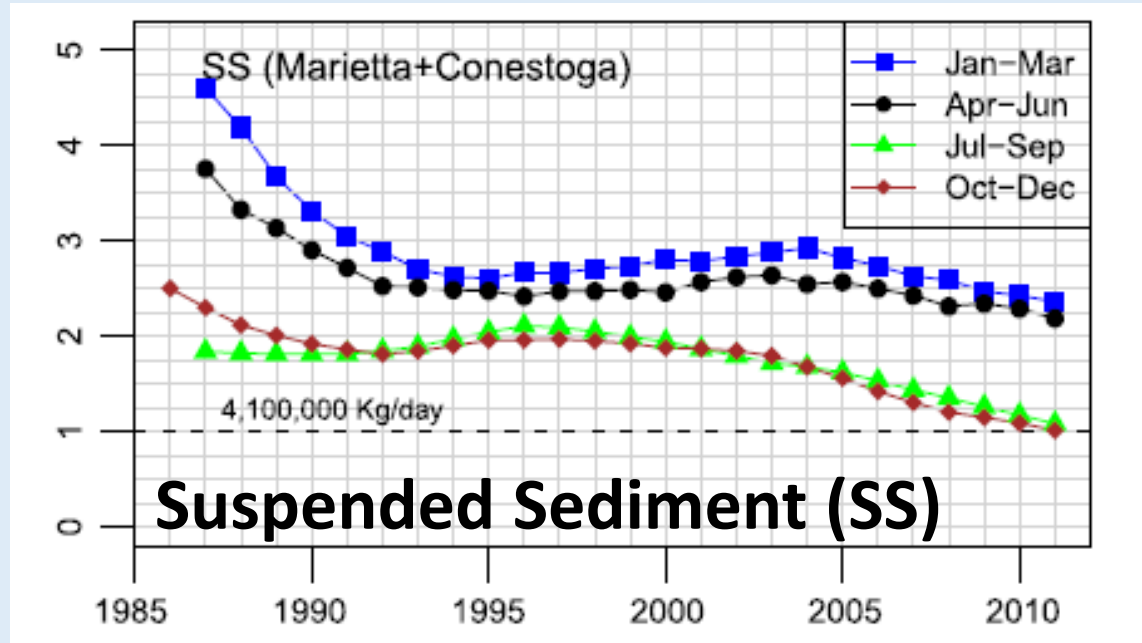
Which **sub-species** has driven the TP trend?



(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)

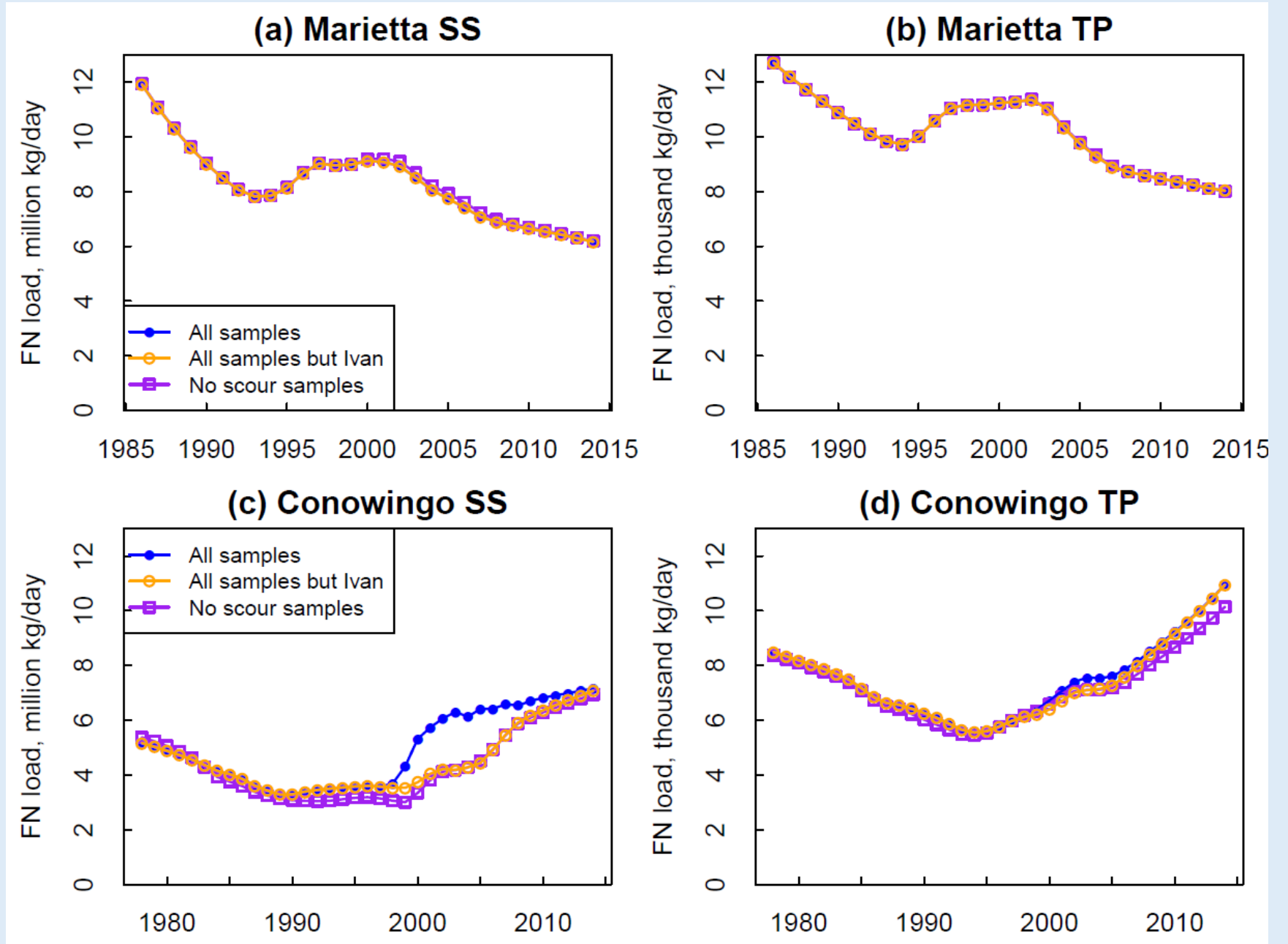


LSRRS
(Reservoir System)



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***.

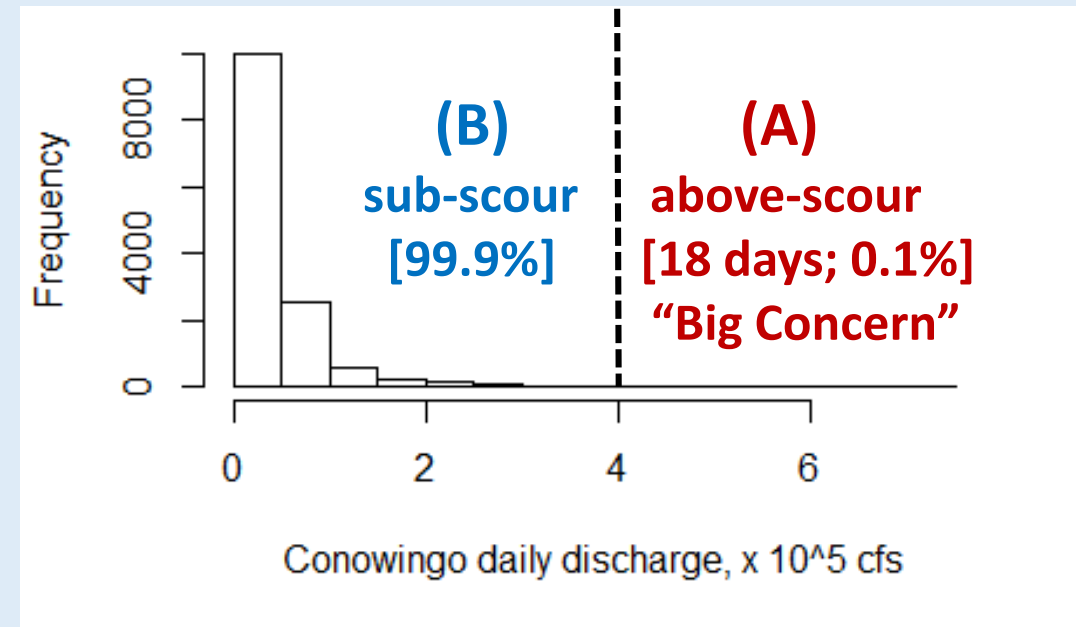
- To quantify the ***relative importance*** of:

(A) *Infrequent events at very high flows (above-scour* levels) vs.*

(B) *Frequent events at moderate to high flows (sub-scour levels).*

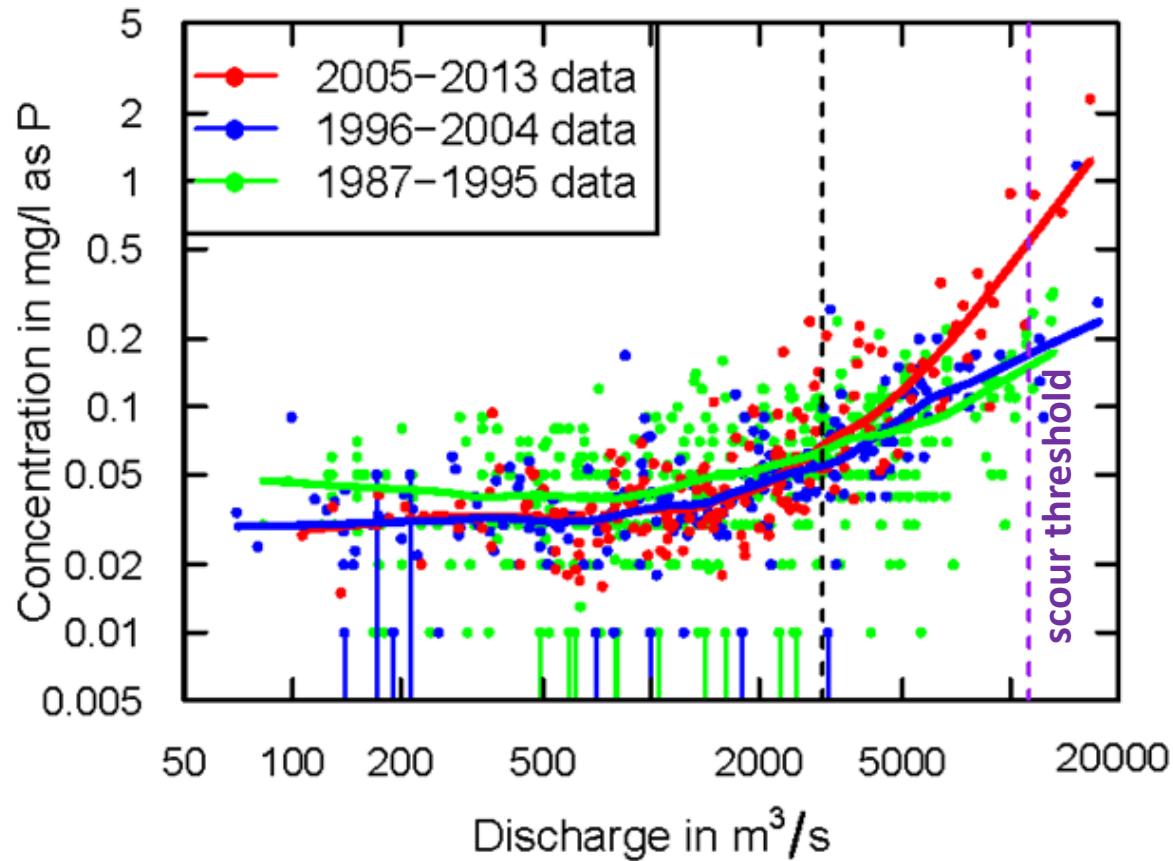
* **400,000 cfs** or **11,300 m³/s** (Gross et al., 1978)
[Major concern to managers and modelers]

Conowingo Daily Discharge

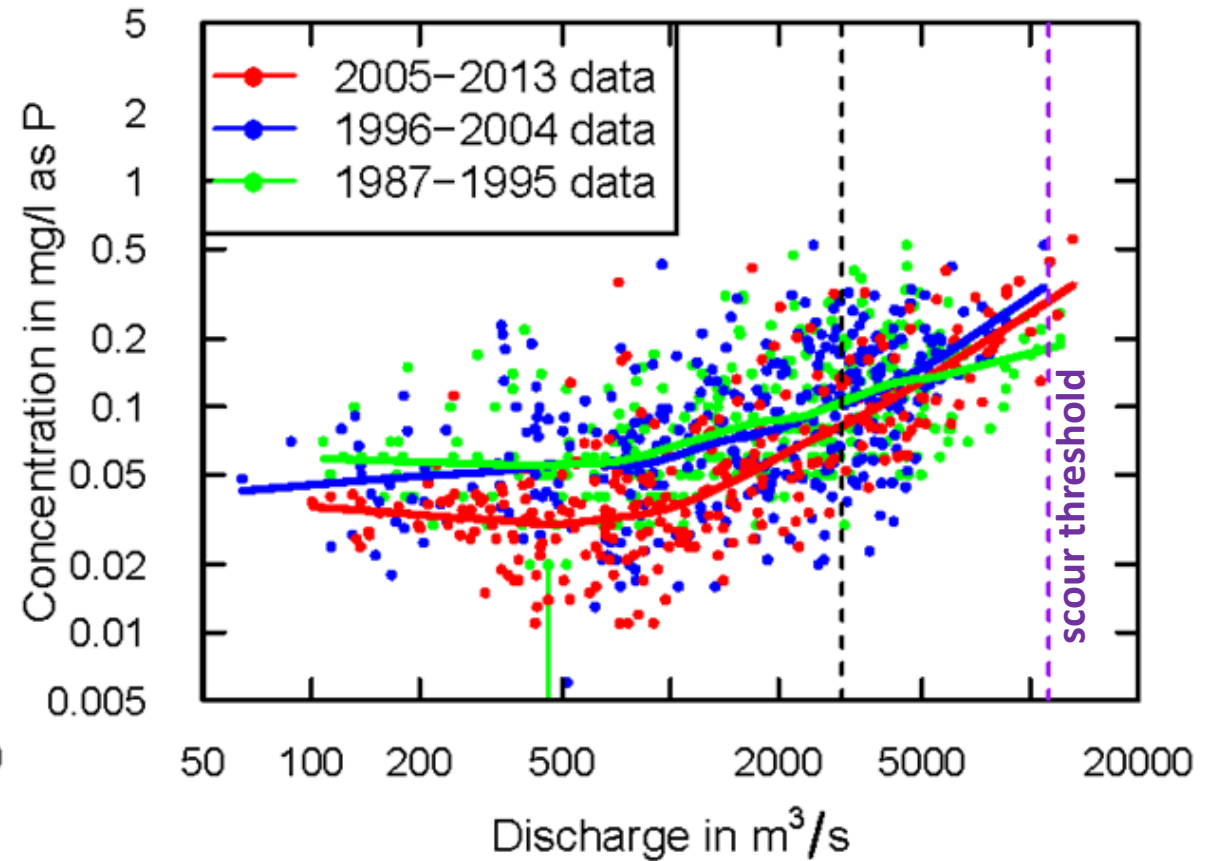


Temporal Changes in C - Q Relationships: LOWESS Curves

(c) Conowingo TP



(d) Marietta TP



Total Phosphorus (TP) [Results similar for SS]

* LOWESS curves fitted to C-Q data in periods of 1987-1995, 1996-2004, and 2005-2013

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

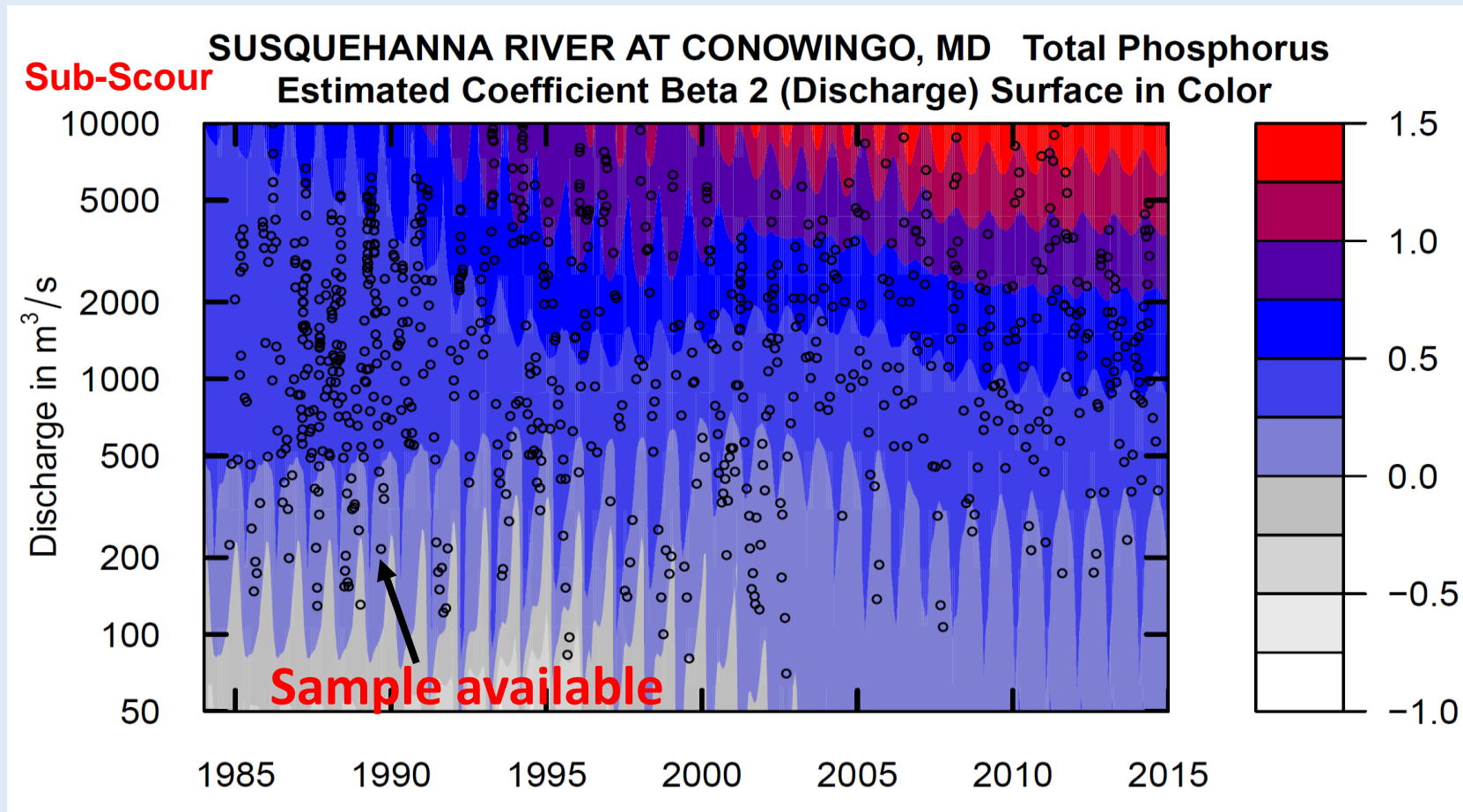
Temporal Changes in C - Q Relationships: **WRTDS β_2 Coefficients**

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

Time

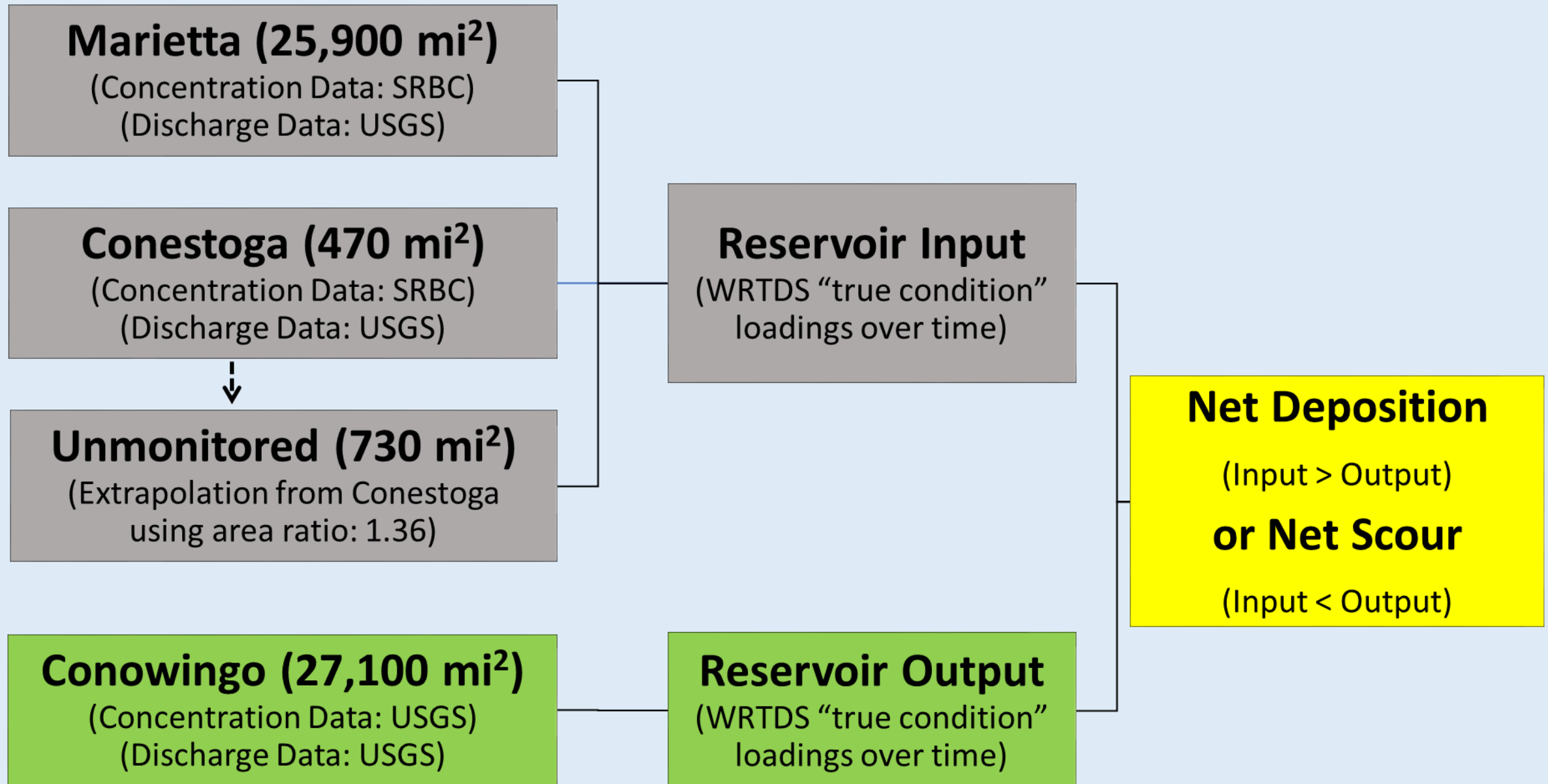
Discharge

Season



Zhang, Q.; Harman, C. J.; Ball, W. P., An Improved Method for Interpretation of Riverine Concentration-Discharge Relationships Indicates Long-Term Shifts in Reservoir Sediment Trapping. ***Geophys. Res. Lett.***, 2016, doi:10.1002/2016GL069945.

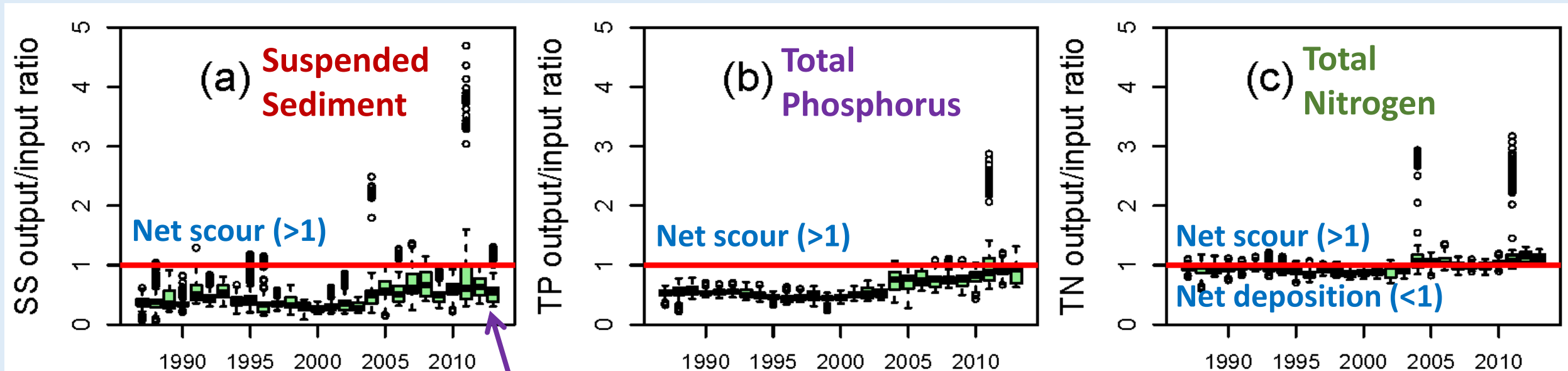
Input-Output Analyses: Net Deposition in the Reservoir



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

Input-Output Analyses: True-condition **O/I Ratio** (1987-2013)

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

Input-Output Analyses: Uncertainty Analysis on O/I Ratio

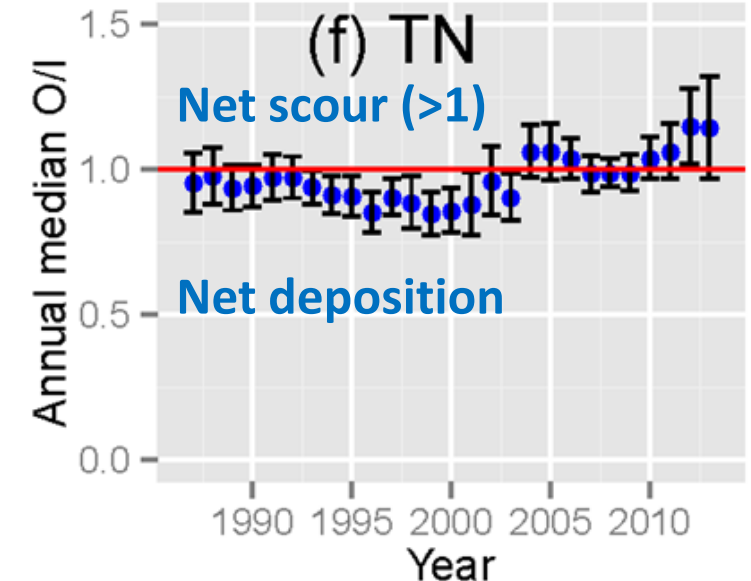
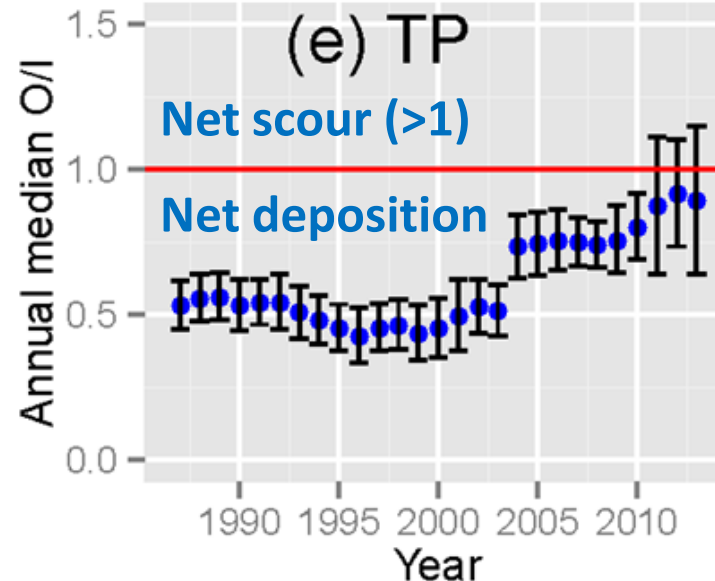
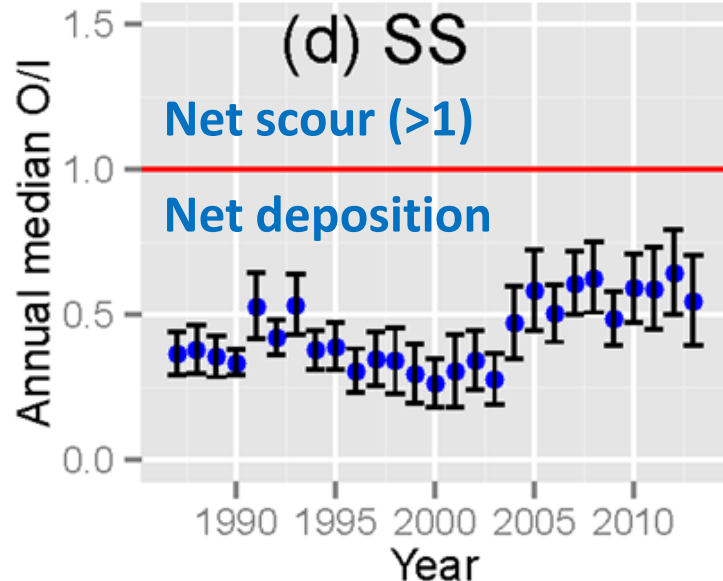
Q: What are the uncertainties in O/I ratio trend?

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

Suspended Sediment

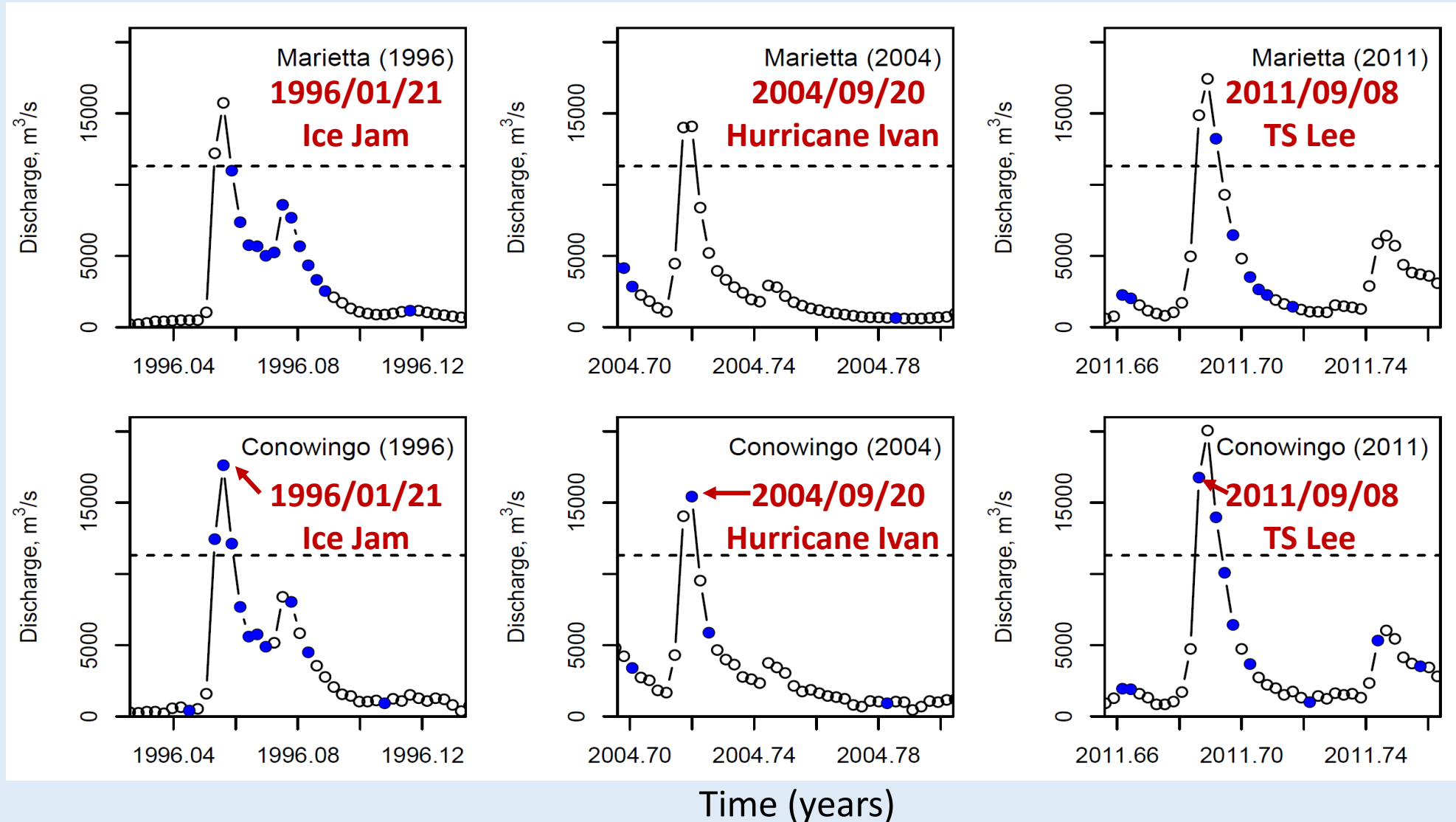
Total Phosphorus

Total Nitrogen



Input-Output Analyses: Sensitivity to Differential Highflow Sampling

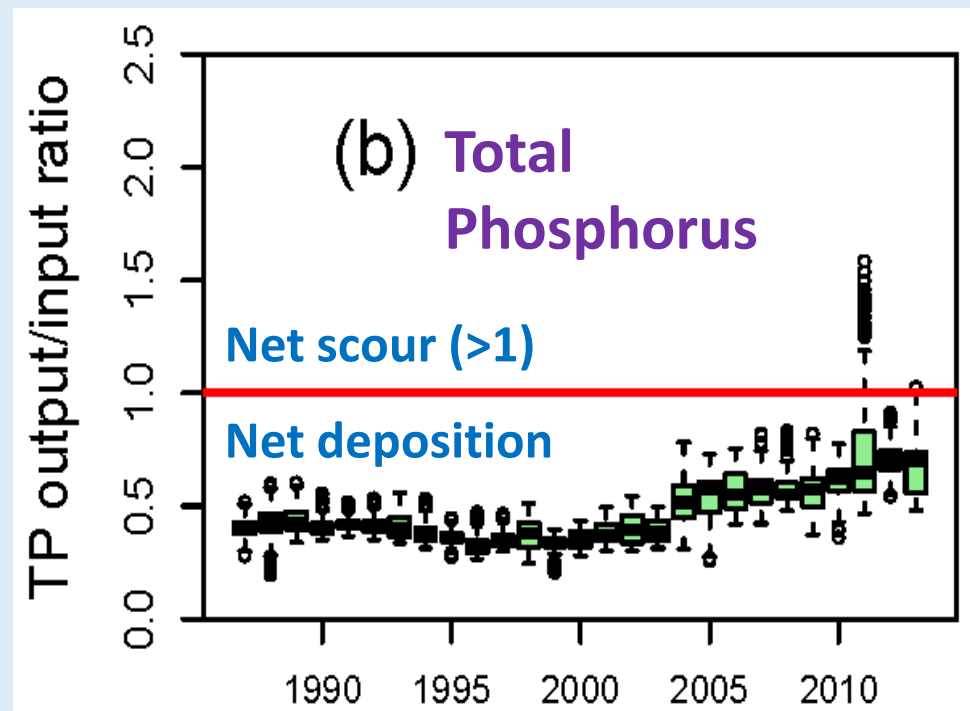
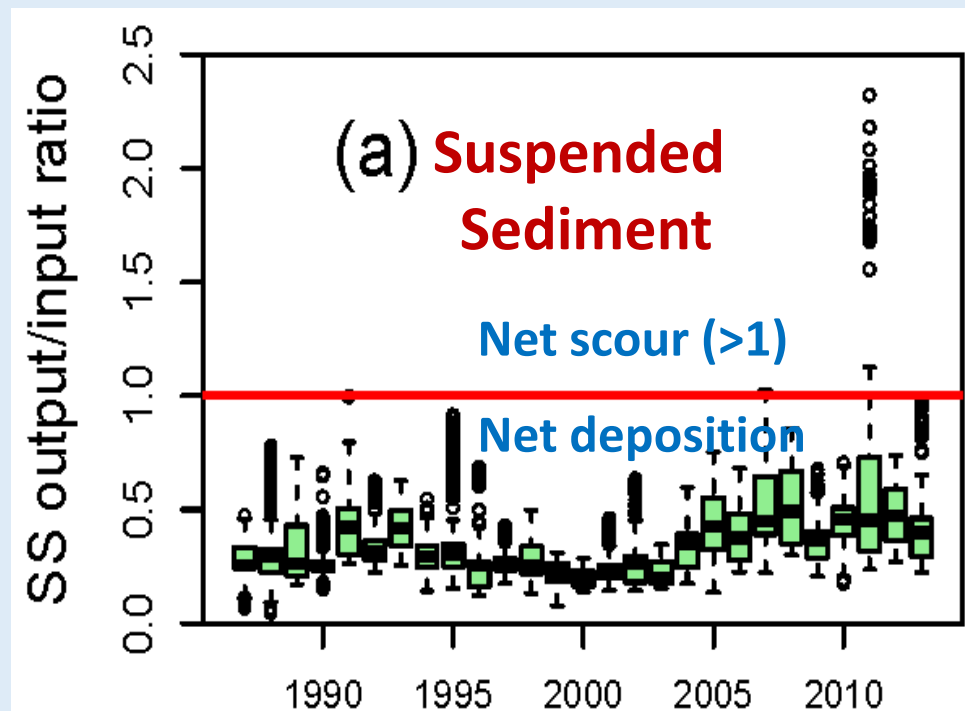
Q: Are trends in O/I ratio biased by the differential highflow sampling at Marietta and Conowingo?



Input-Output Analyses: Sensitivity to Differential Highflow Sampling

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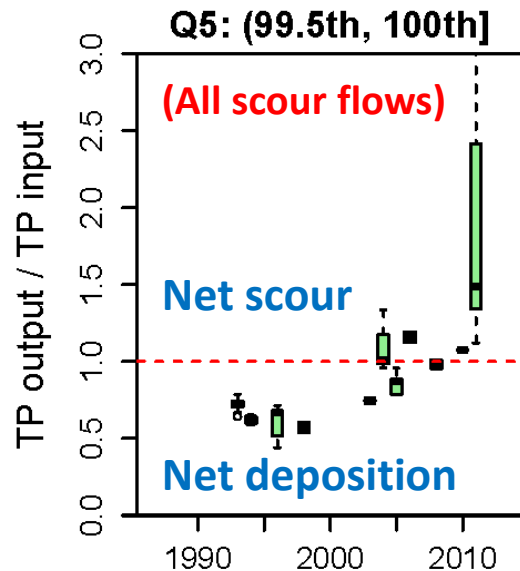
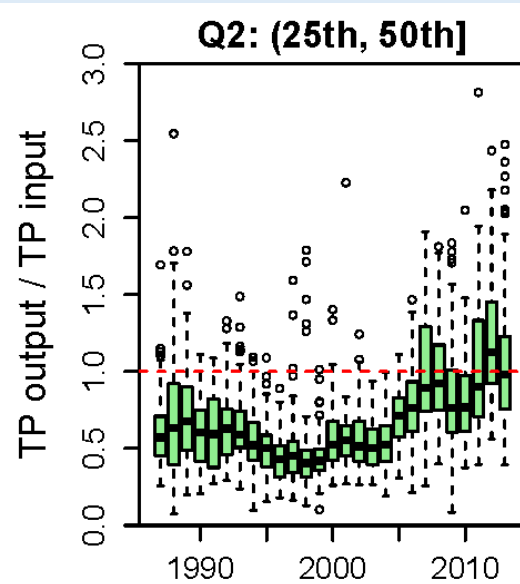
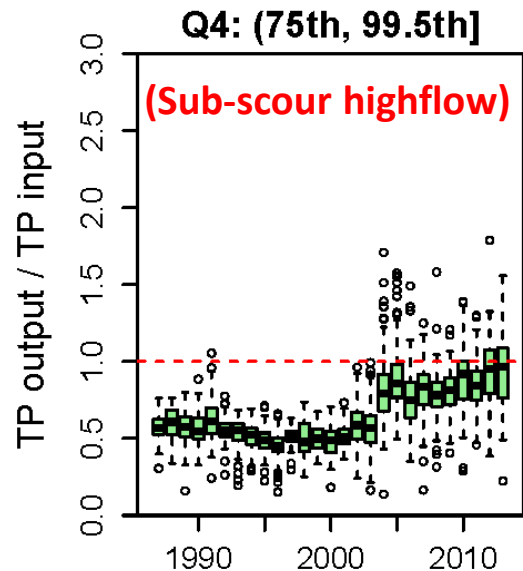
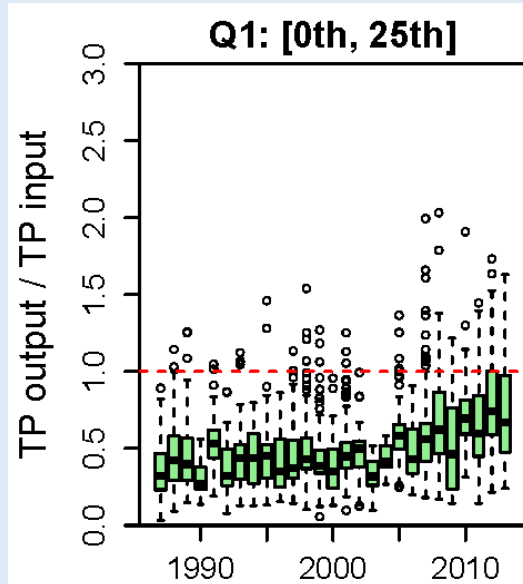
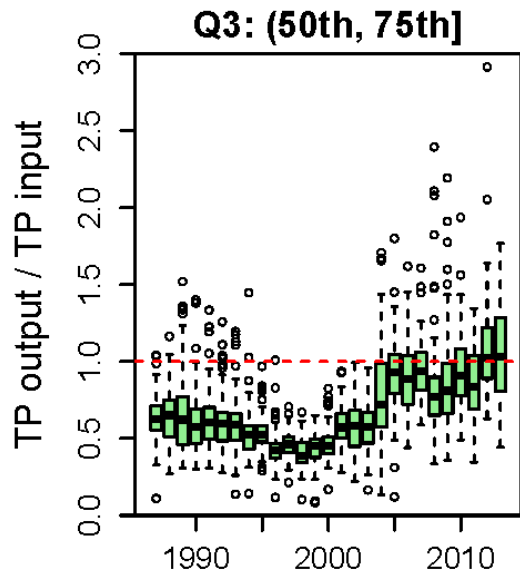
Sensitivity analysis with **equally-censored samples** ($Q < 15,000 \text{ m}^3/\text{s}$)



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

Q: Is the O/I trend associated with highflow only?

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



Conowingo Flow Classes

Q_1 : 25~396 m³/s;

Q_2 : 399~787 m³/s;

Q_3 : 790~1,464 m³/s;

Q_4 : 1,467~7,646 m³/s;

Q_5 : 7,674~20,077 m³/s.

Q_{scour} : ~ 11,000 m³/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: Contribution by Flow Class

Q: Which flow class has contributed the most to mass delivery?

Conowingo Flow Classes

Q_1 : 25~396 m³/s;

Q_2 : 399~787 m³/s;

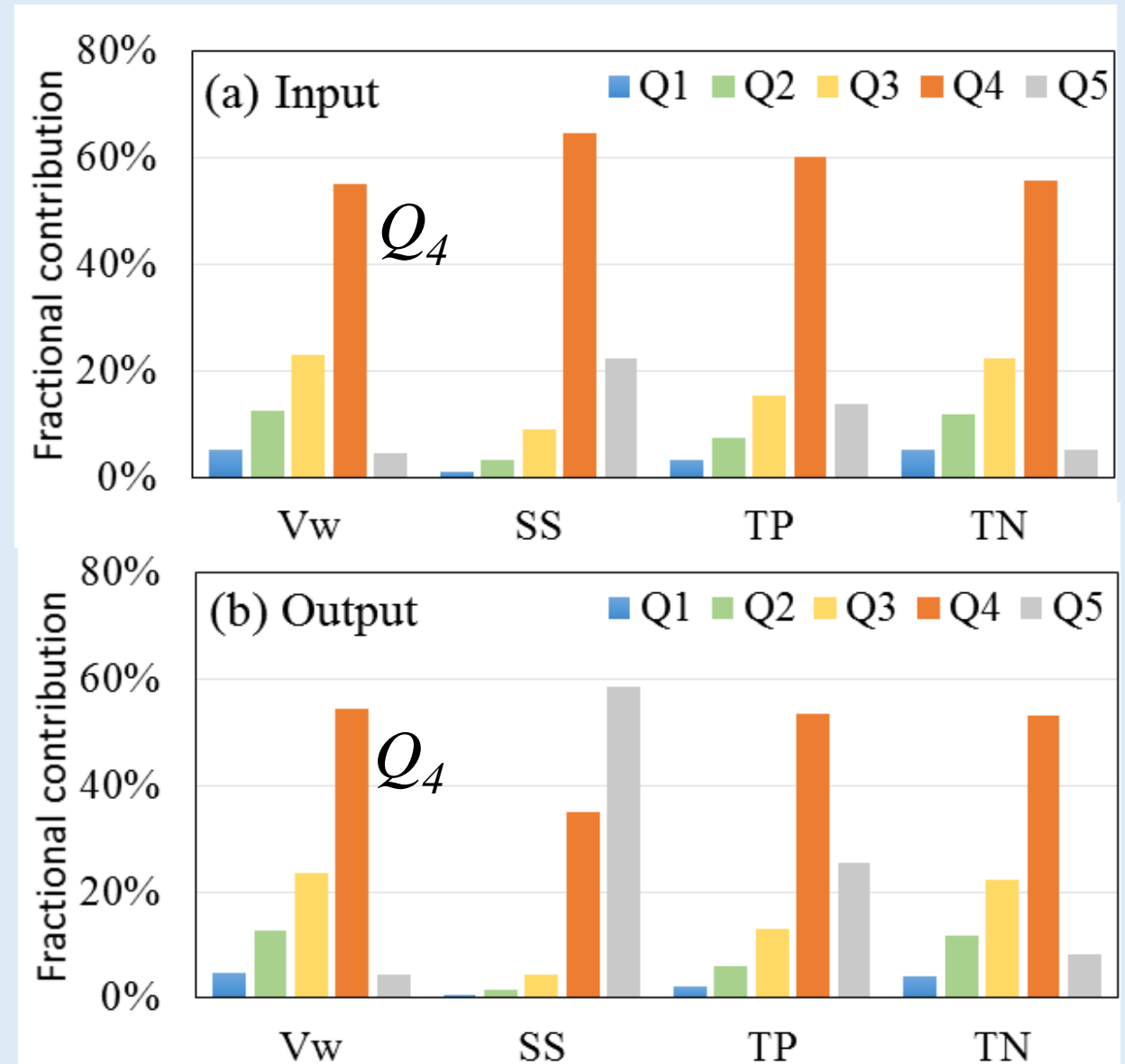
Q_3 : 790~1,464 m³/s;

Q_4 : 1,467~7,646 m³/s;

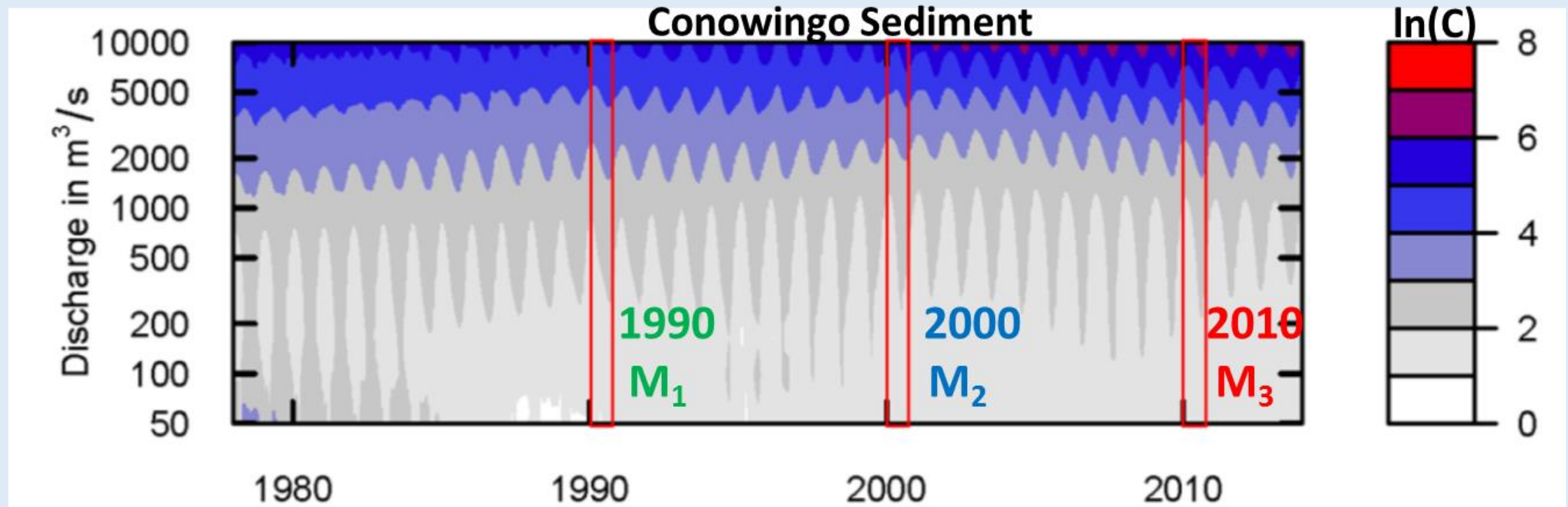
Q_5 : 7,674~20,077 m³/s.

Q_{scour} : ~ 11,000 m³/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.



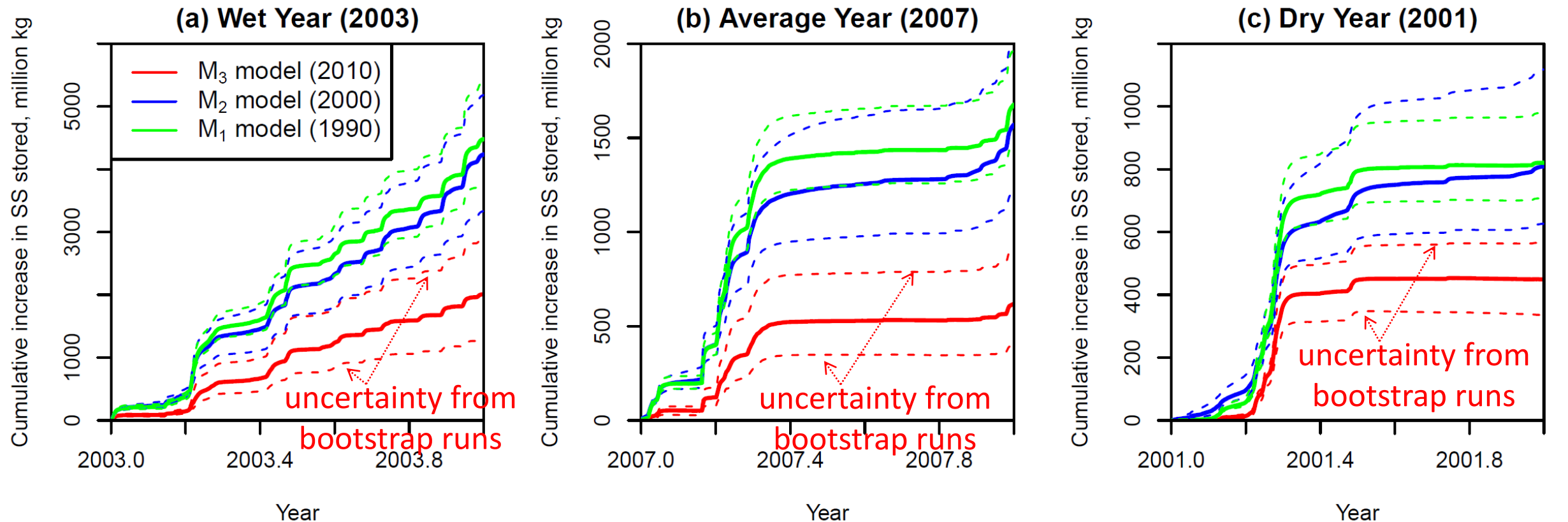
Stationary-Model Analyses: Effects of Changing $C(Q, t_{season})$ Surface



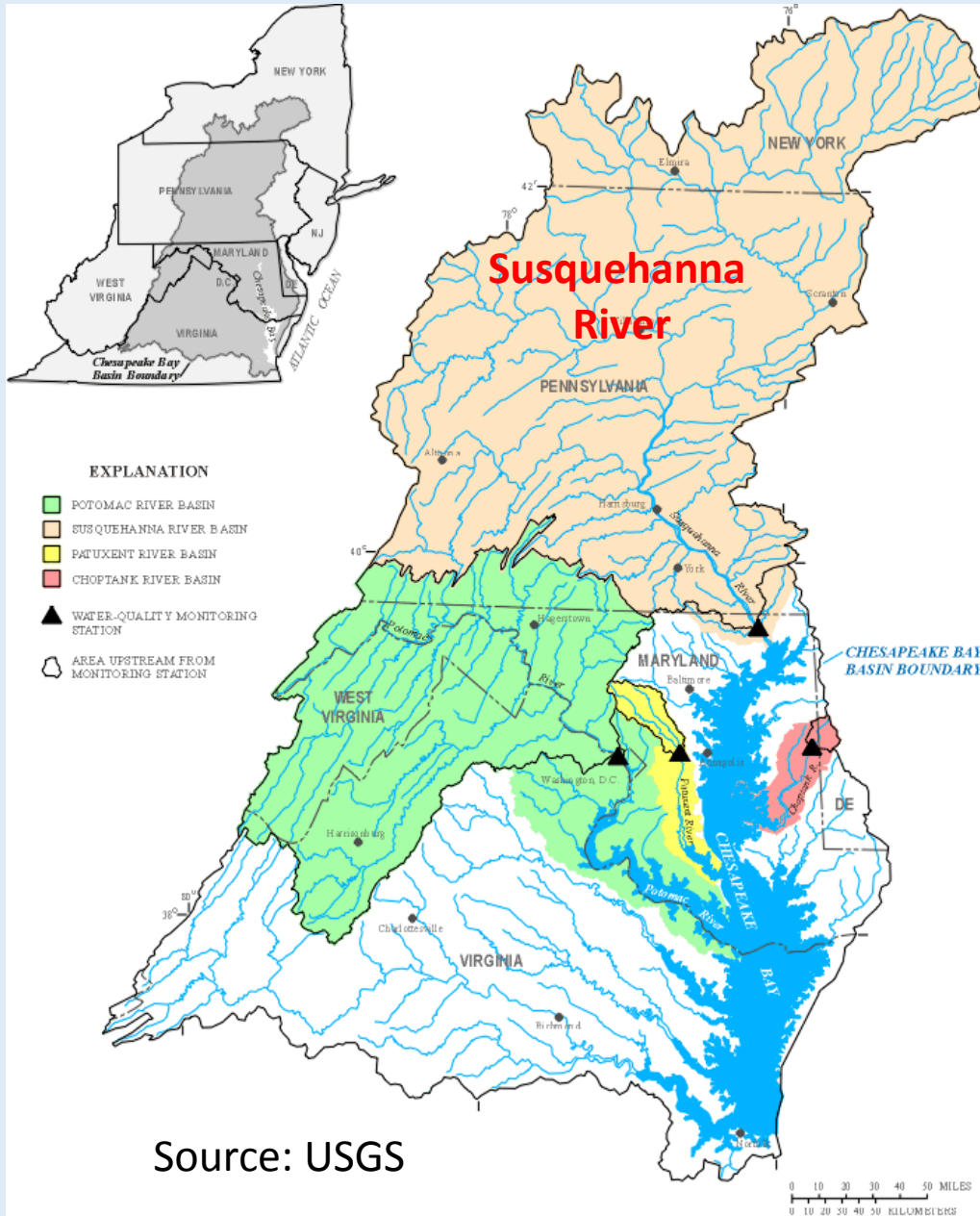
- Inter-annual comparisons of WRTDS true-condition loadings are influenced by:
 - (A) the particular history of flows occurred in a given year and
 - (B) change in the WRTDS regression surface, *i.e.*, system function.
- Developed 3 “stationary” WRTDS models that represent historical conditions of reservoir performance in 3 different years -- 1990, 2000, 2010.

Stationary-Model Analyses: Change in Storage under 3 Reservoir Conditions

Predictions of **cumulative SS net deposition** for a **Wet (2003)**, an **Average (2007)**, and a **Dry Year (2001)** by **3 scenarios of stationary surface** representing **1990, 2000, and 2010** reservoir conditions



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**

(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

- Zhang, Hirsch, Ball, **2016**, *Environ. Sci. Technol.*, 50 (4). [Link to paper](#).
- Zhang, Harman, Ball, **2016**, *Geophys. Res. Lett.*, 43. [Link to paper](#).
- Zhang, Ball, Moyer, **2016**, *Sci. Total. Environ.*, 563–564. [Link to paper](#).
- Zhang, Brady, Boynton, Ball, **2015**, *J. Am. Water. Resour. Assoc.*, 51(6). [Link to paper](#).
- Zhang, Brady, Ball, **2013**, *Sci. Total. Environ.*, 452-453. [Link to paper](#).