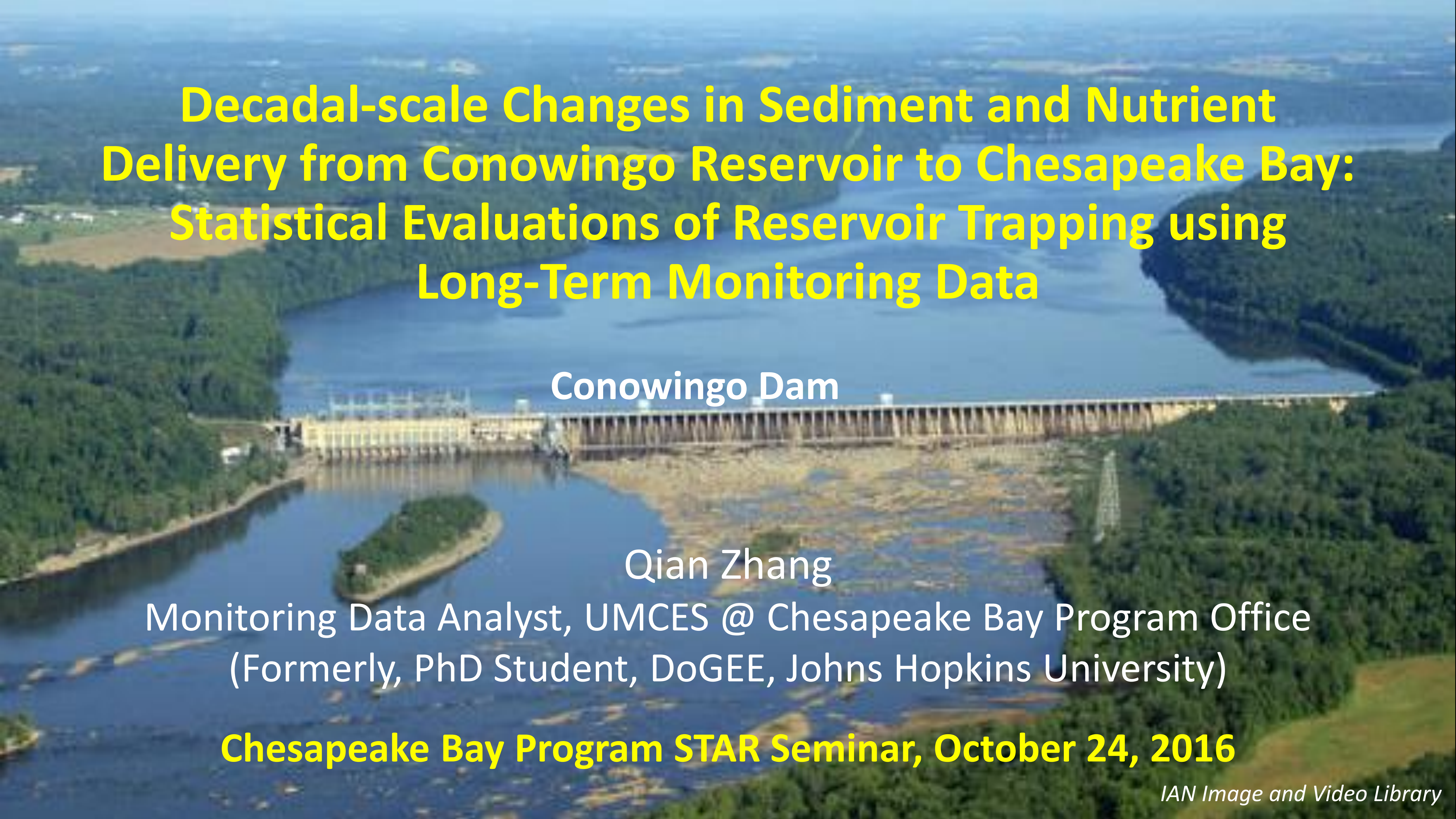
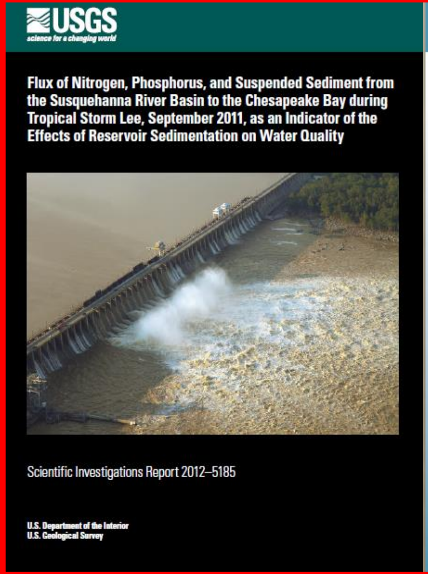
Decadal-scale Changes in Sediment and Nutrient Delivery from Conowingo Reservoir to Chesapeake Bay: Statistical Evaluations of Reservoir Trapping using Long-Term Monitoring Data

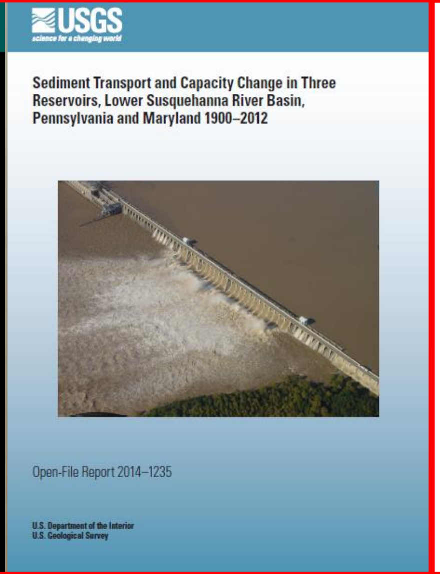


Qian Zhang
Monitoring Data Analyst, UMCES @ Chesapeake Bay Program Office
(Formerly, PhD Student, DoGEE, Johns Hopkins University)

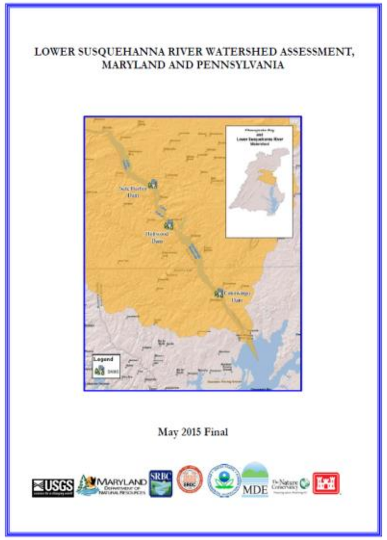
Chesapeake Bay Program STAR Seminar, October 24, 2016

USGS (2012, 2015)

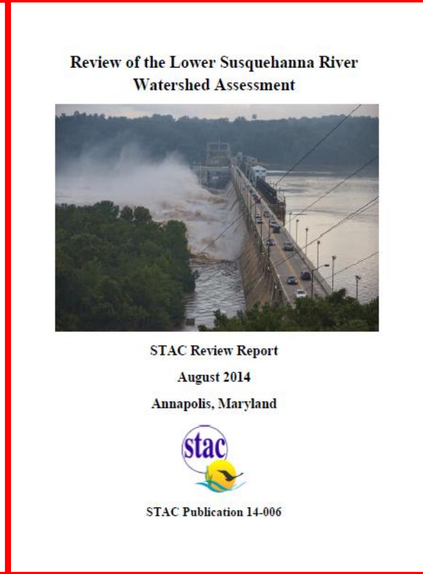




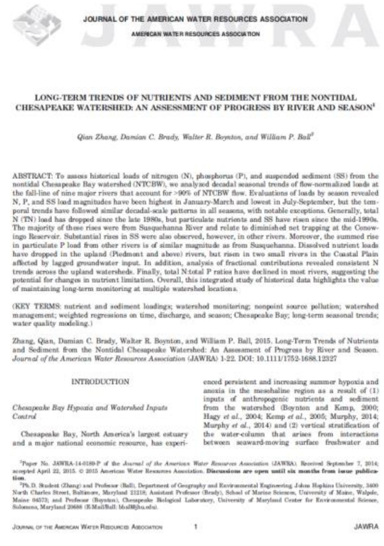
LSRWA (2015)

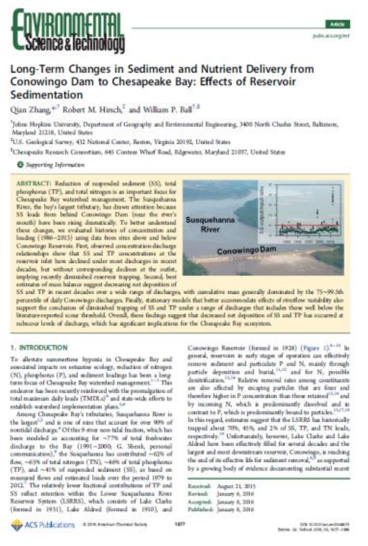


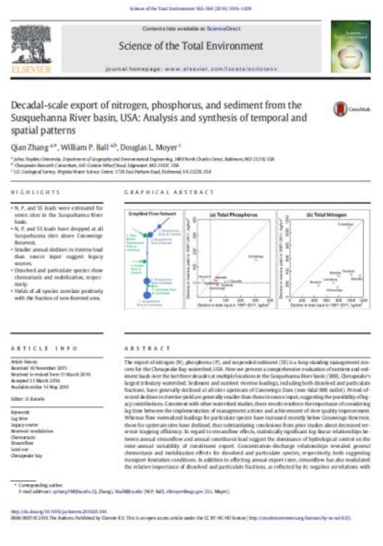
STAC (2014)



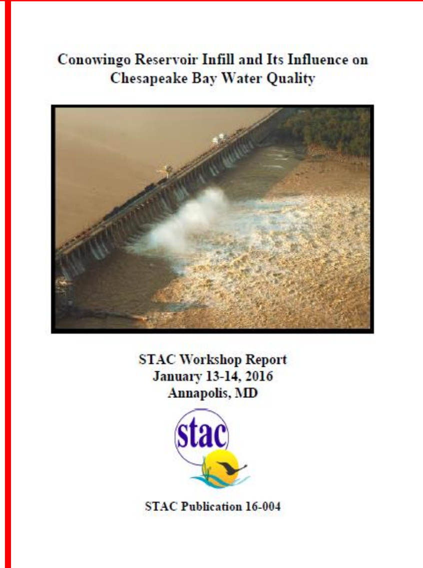
Johns Hopkins (2013, 2015, 2016)



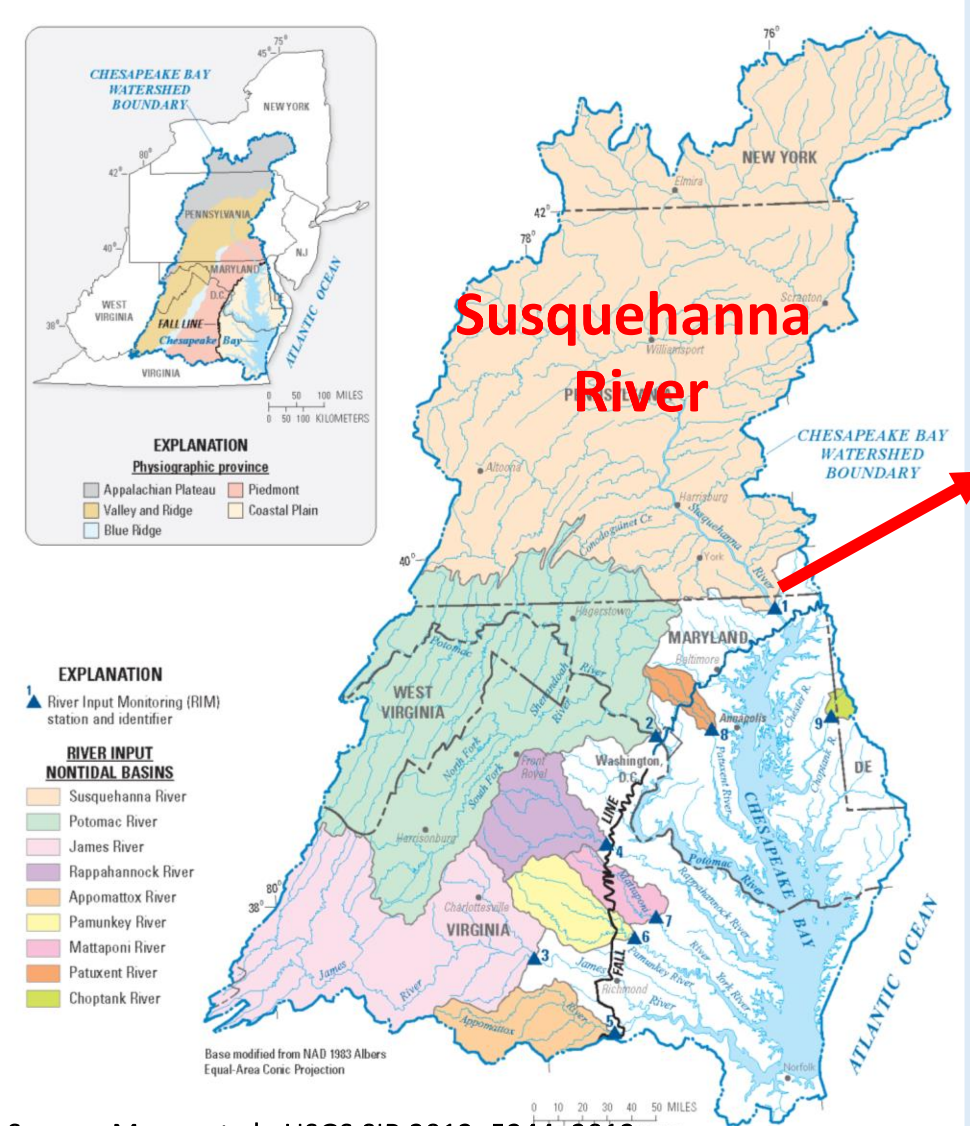




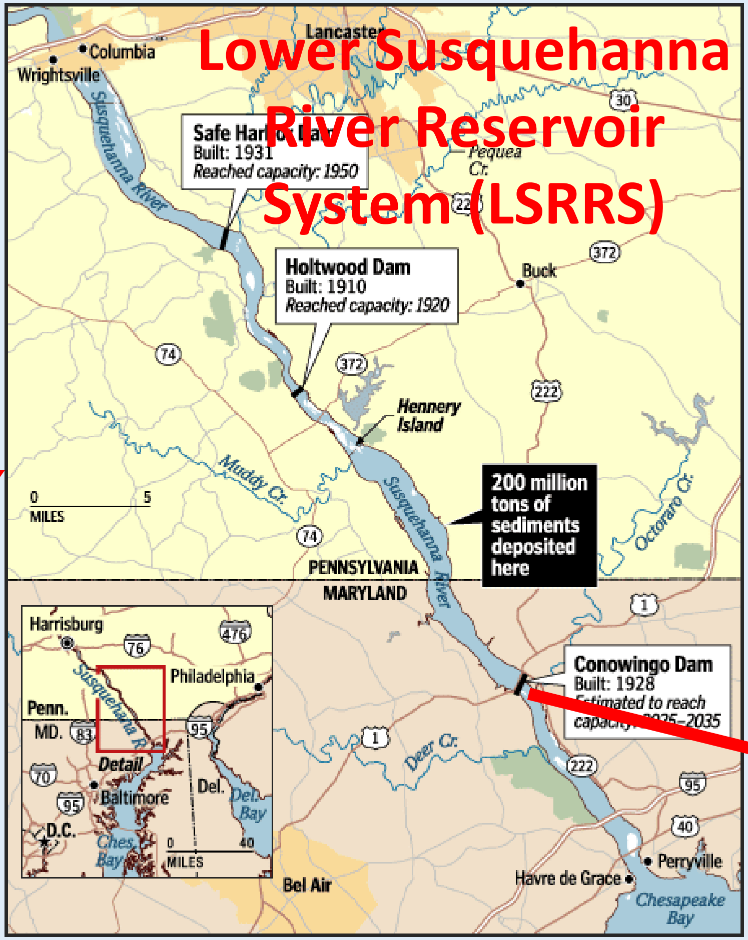
STAC (2016)



Background: LSRRS (Conowingo)



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

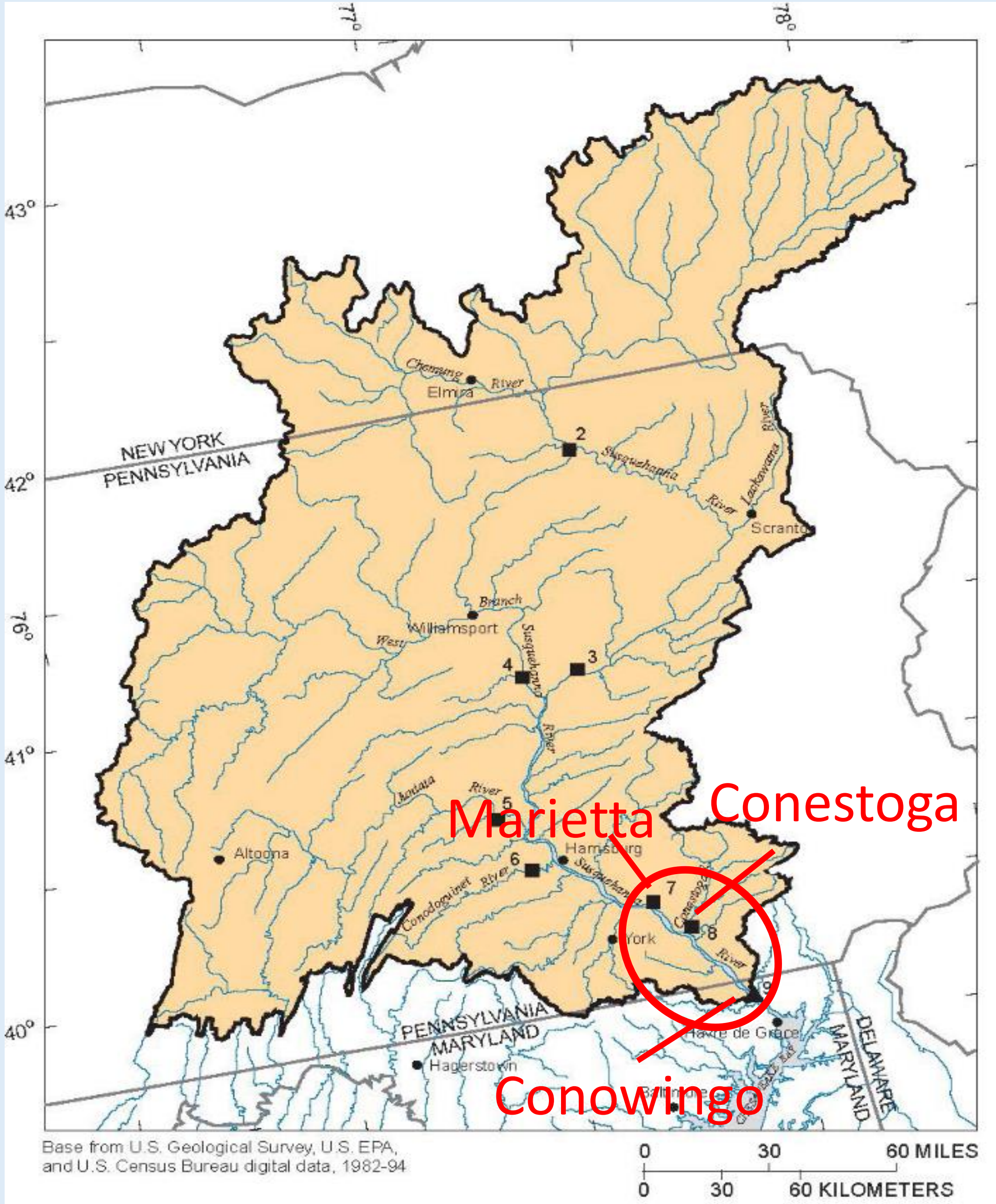


Objective

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.

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

Daily flow & sparse concentration at a sampling site

↓

WRTDS
(Hirsch *et al.*, 2010)

↓

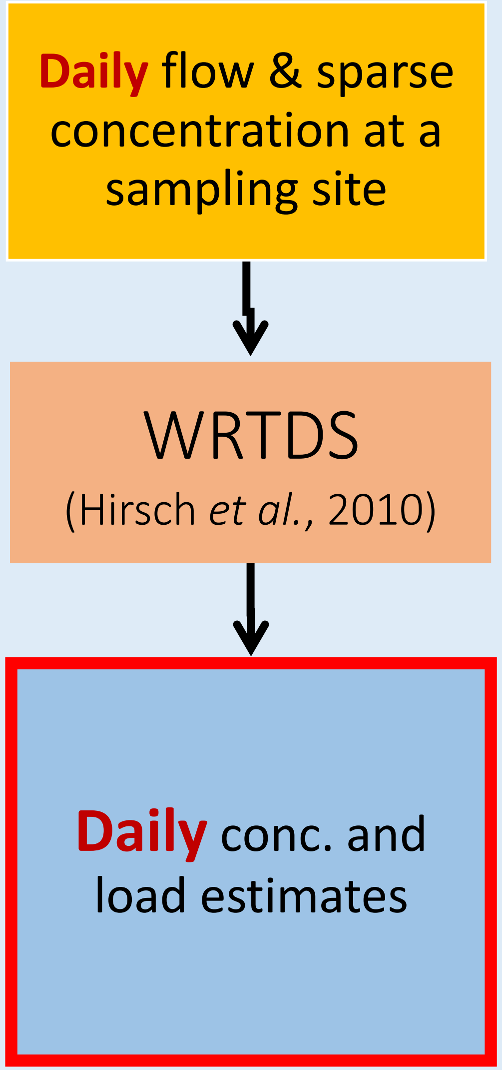
Daily conc. and load estimates

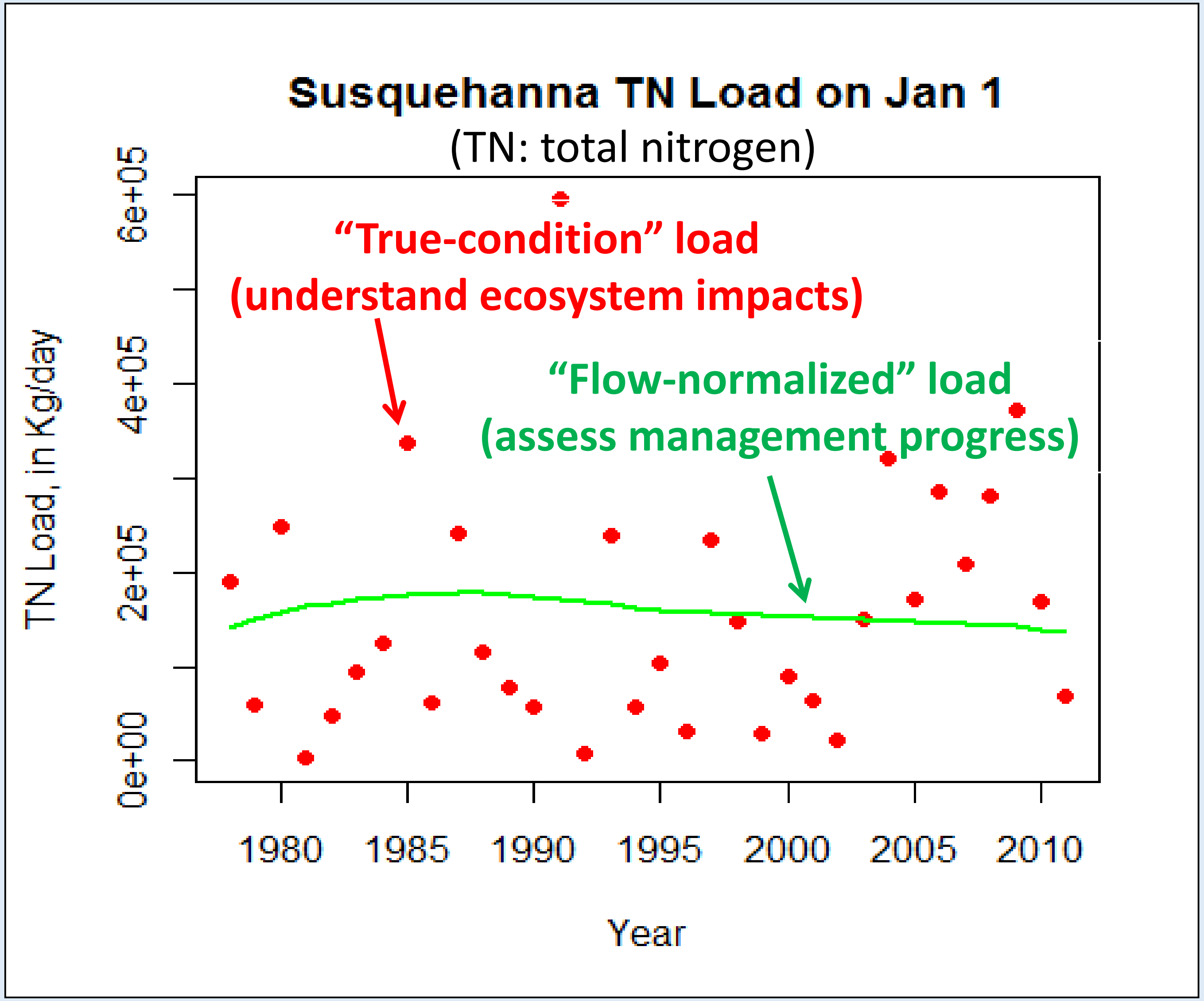
WRTDS (Hirsch *et al.*, 2010)
[Weighted Regressions on Time, Discharge, and Season]

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

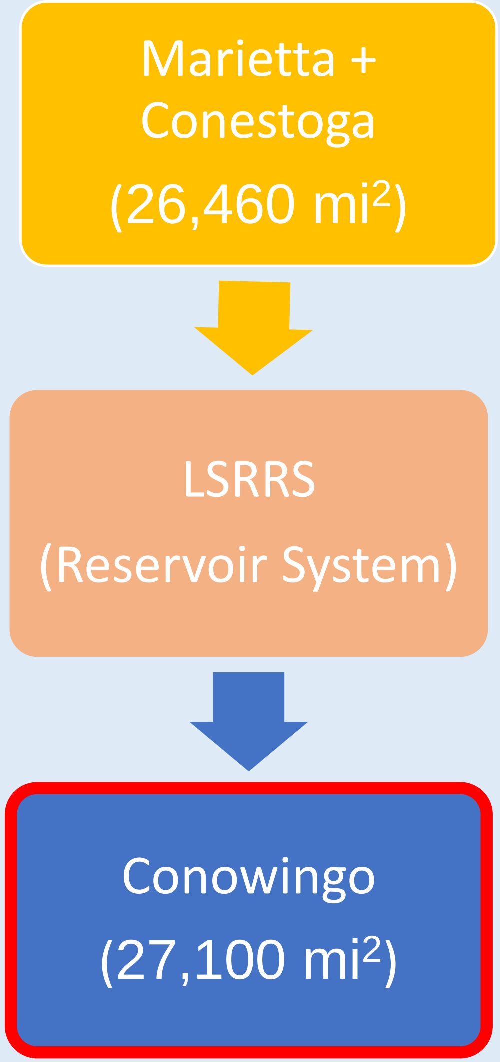
- One single model (coefficient set) for each day of estimation;
- No assumption on fixed C-Q relations over time or season;
- Better estimation performance;
- Adopted in a wide range of studies.

WRTDS Method

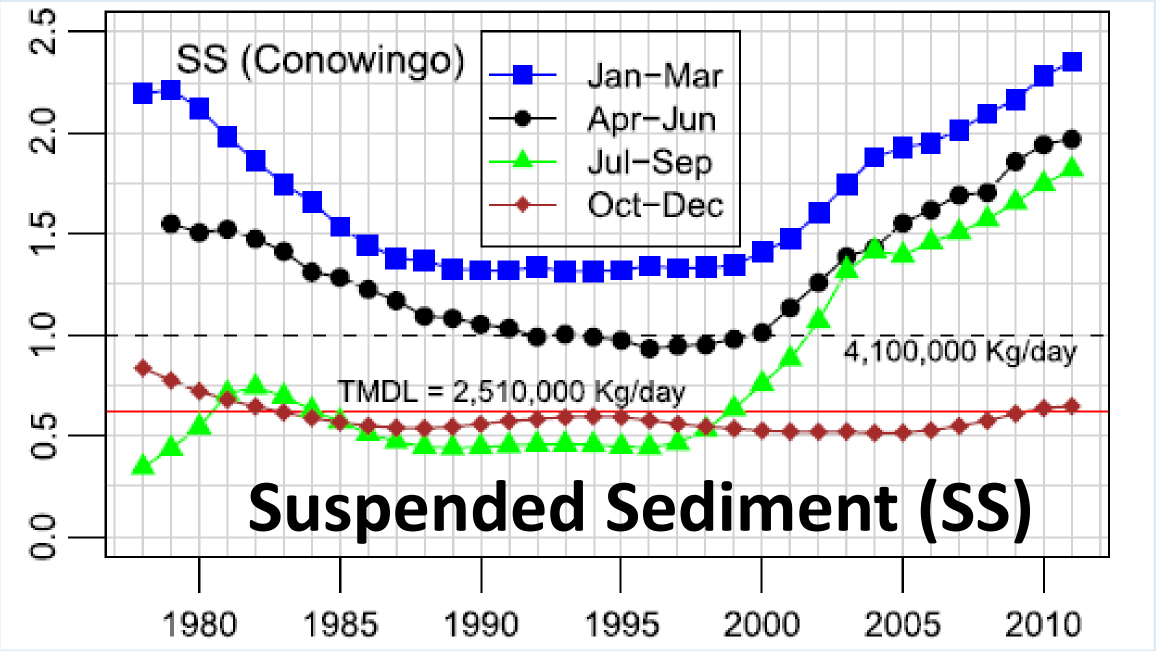


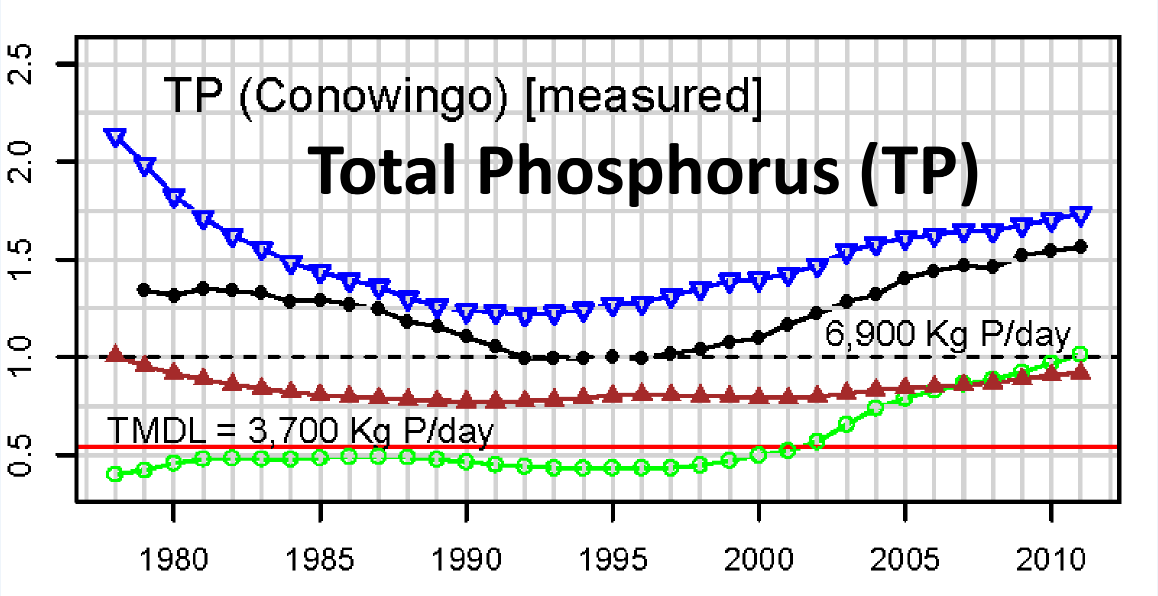


What have been the flow-normalized seasonal trends at Conowingo Dam?

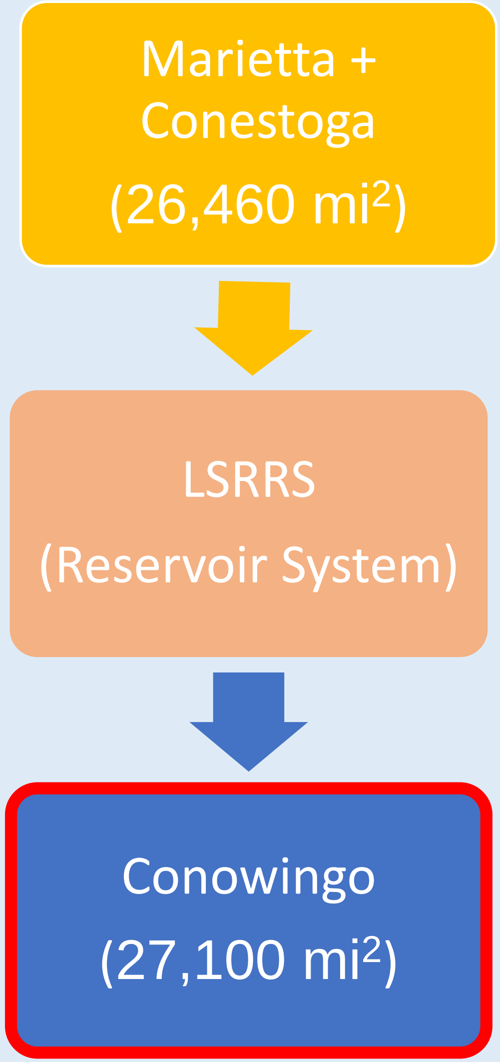


(Zhang, Brady, Ball, STOTEN, 2013)

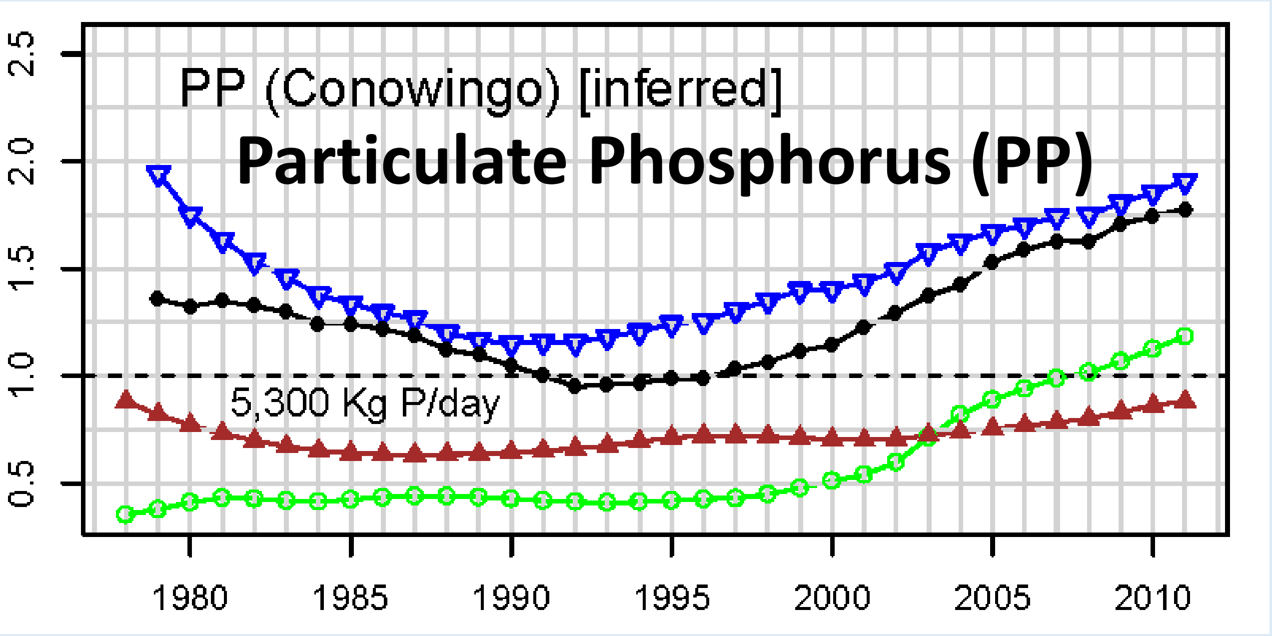


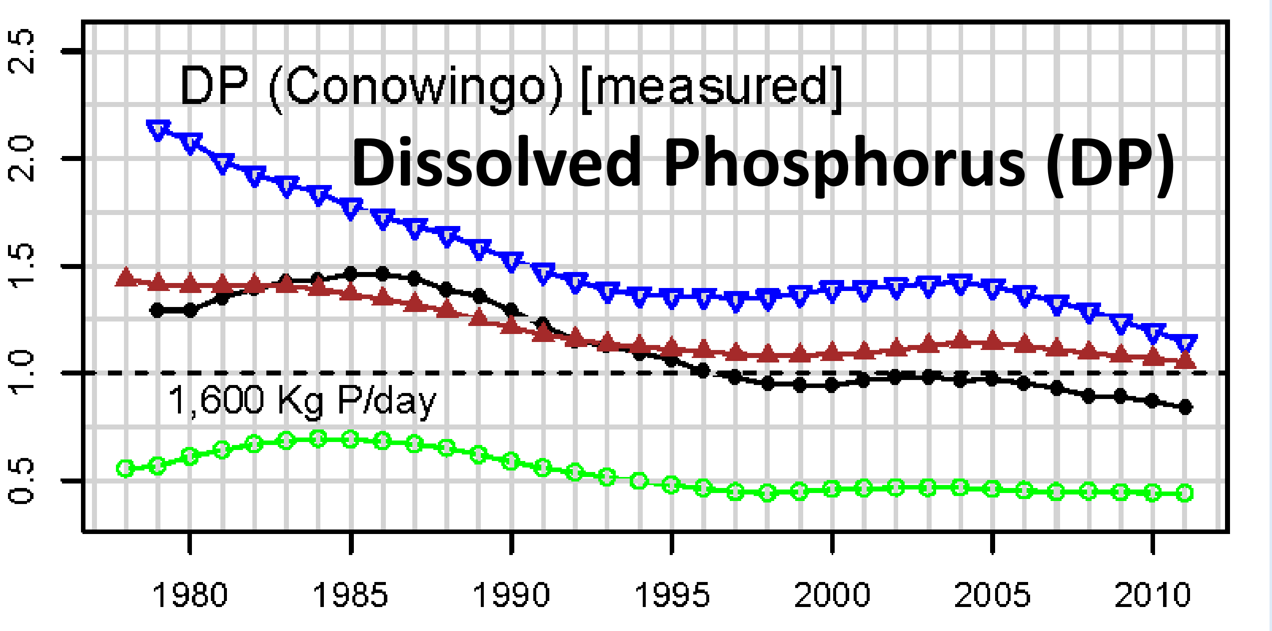


Which sub-species has driven the TP trend?

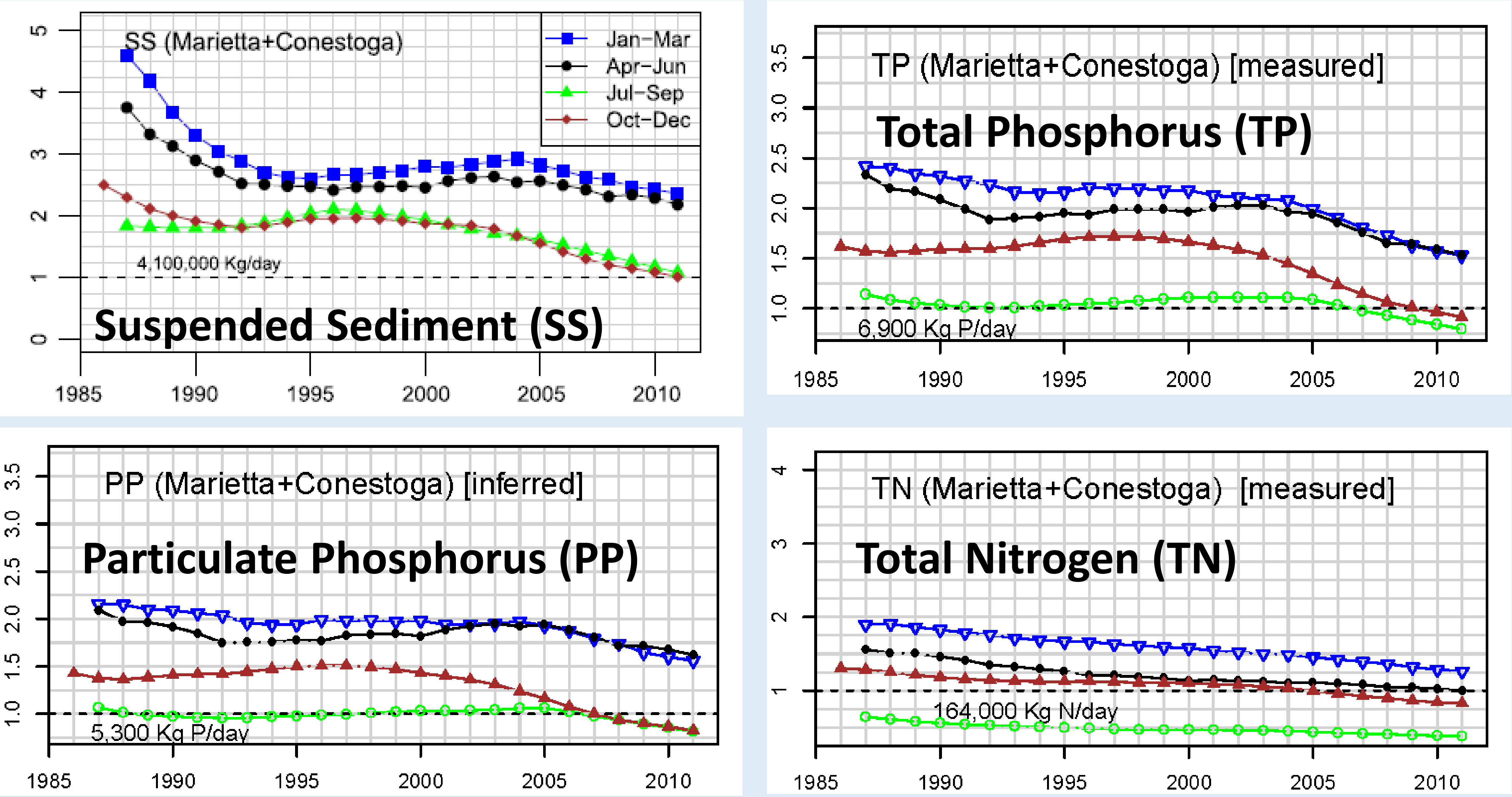


(Zhang, Brady, Ball, STOTEN, 2013)



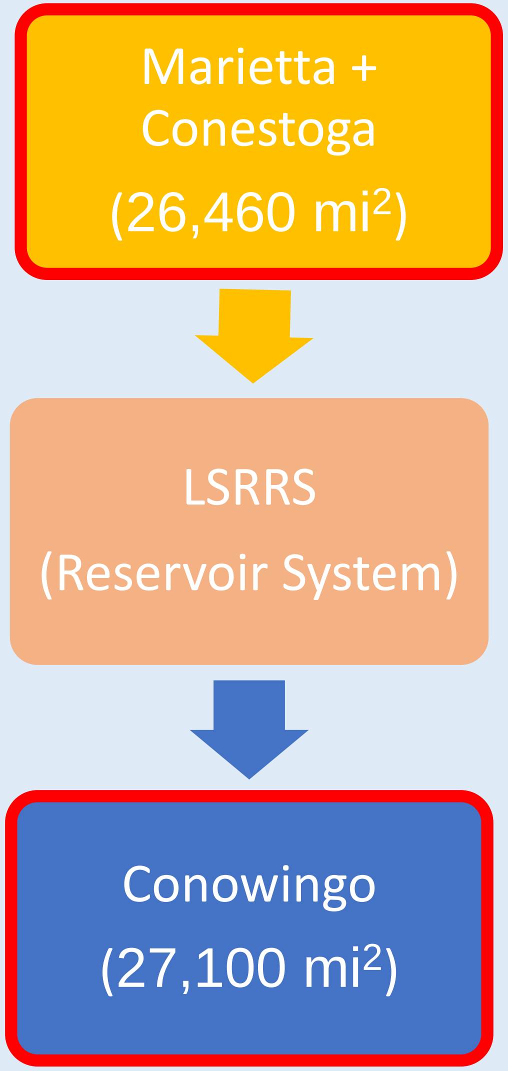


Are these trends due to changes in the upstream watershed or reservoirs?

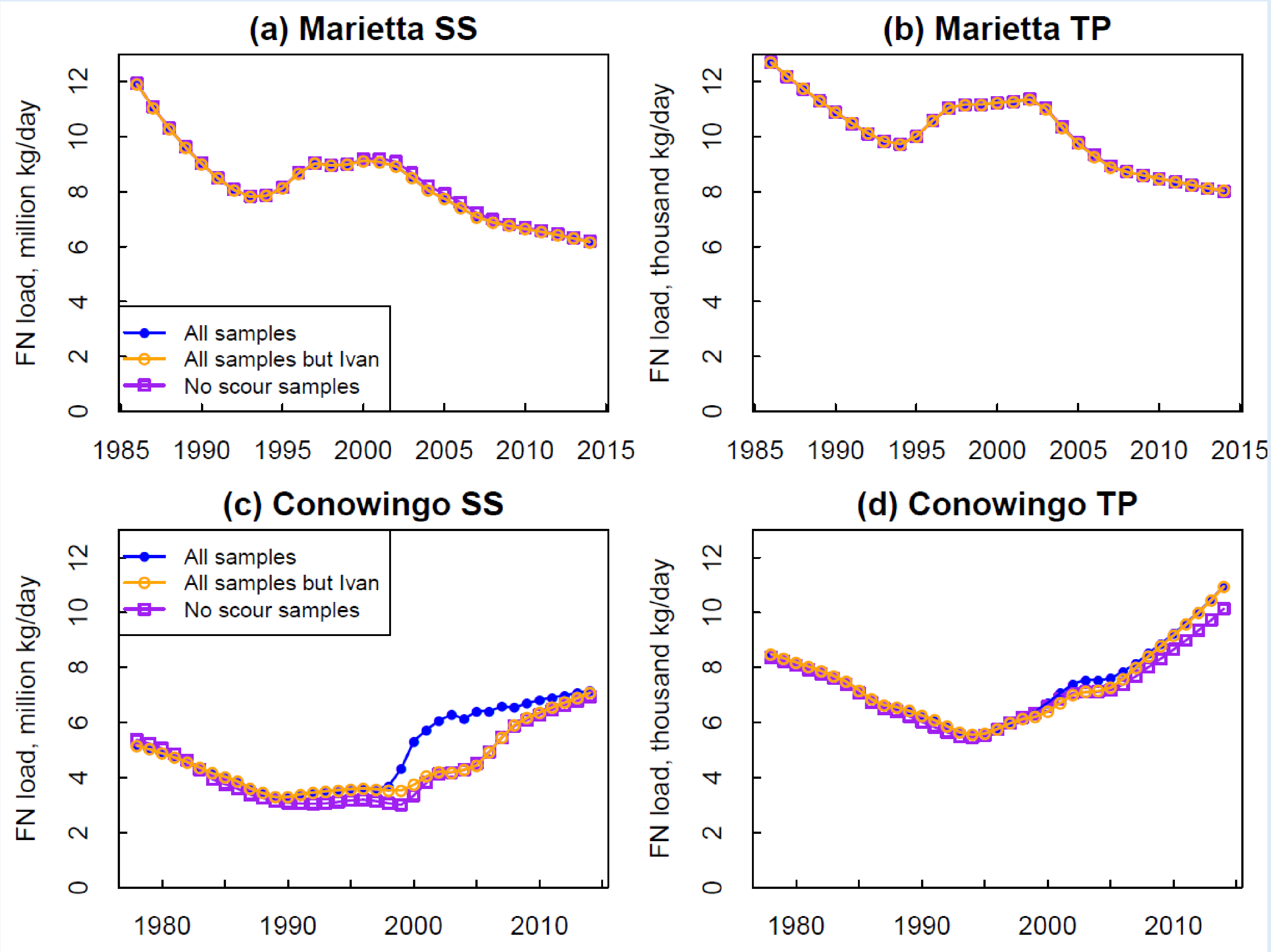


(Zhang, Brady, Ball, STOTEN, 2013)

Are these trends biased by storm-flow samples?



(Zhang and Ball, unpublished data)



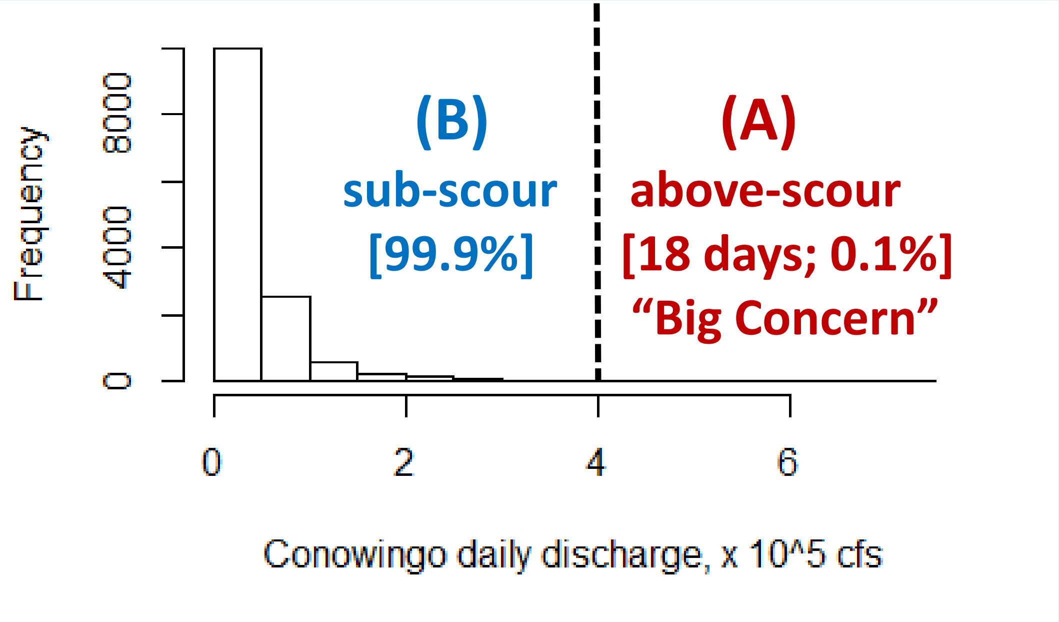
Follow-up Work by Zhang, Hirsch, and Ball (2016)

- 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).

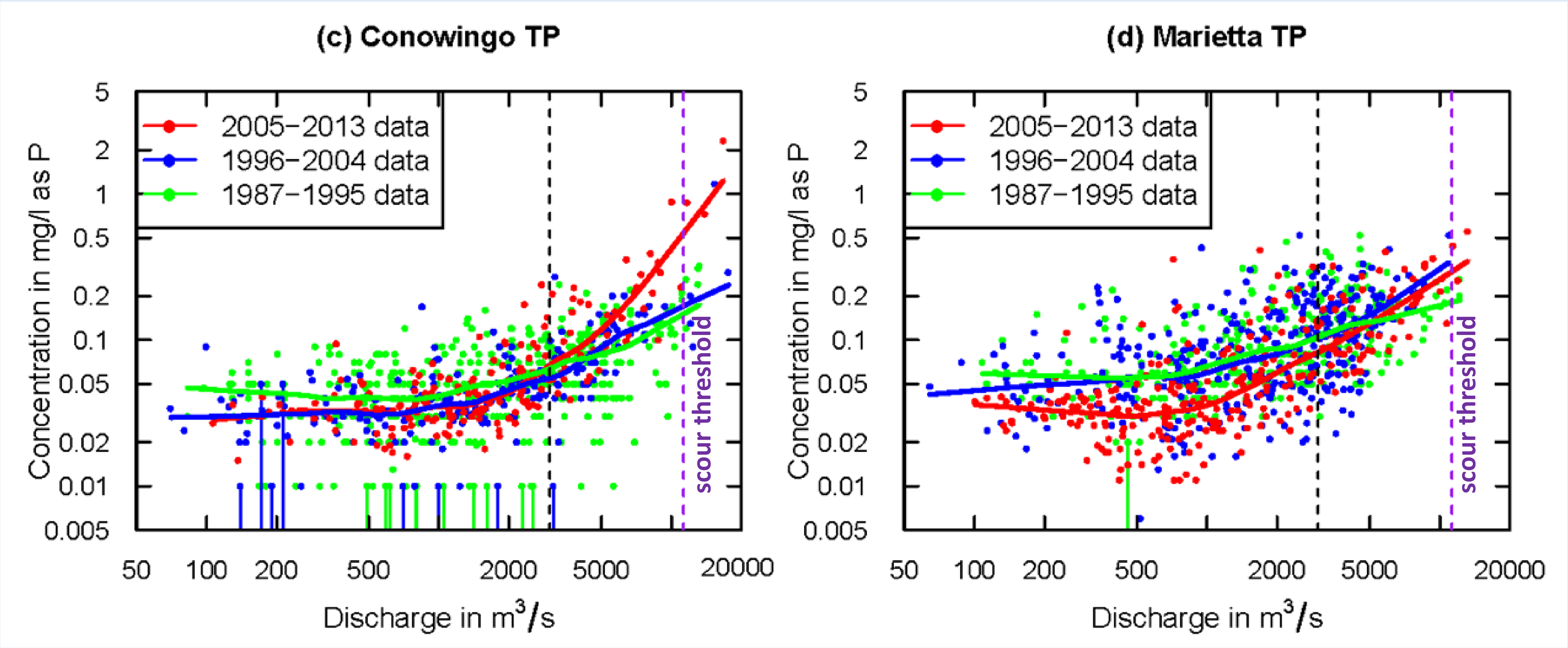
Conowingo Daily Discharge



* ***400,000*** *cfs or* ***11,300*** *m^3/s (Gross et al., 1978)*
[Major concern to managers and modelers]

Zhang, Q.; Hirsch, R. M.; Ball, W. P., Long-Term Changes in Sediment and Nutrient Delivery from Conowingo Dam to Chesapeake Bay: Effects of Reservoir Sedimentation. ***Environ. Sci. Technol.* 2016**, *50* (4), 1877-1886, doi: 10.1021/acs.est.5b04073.

Temporal Changes in C-Q Relationships: LOWESS Curves



Total Phosphorus (TP) [Results similar for SS]

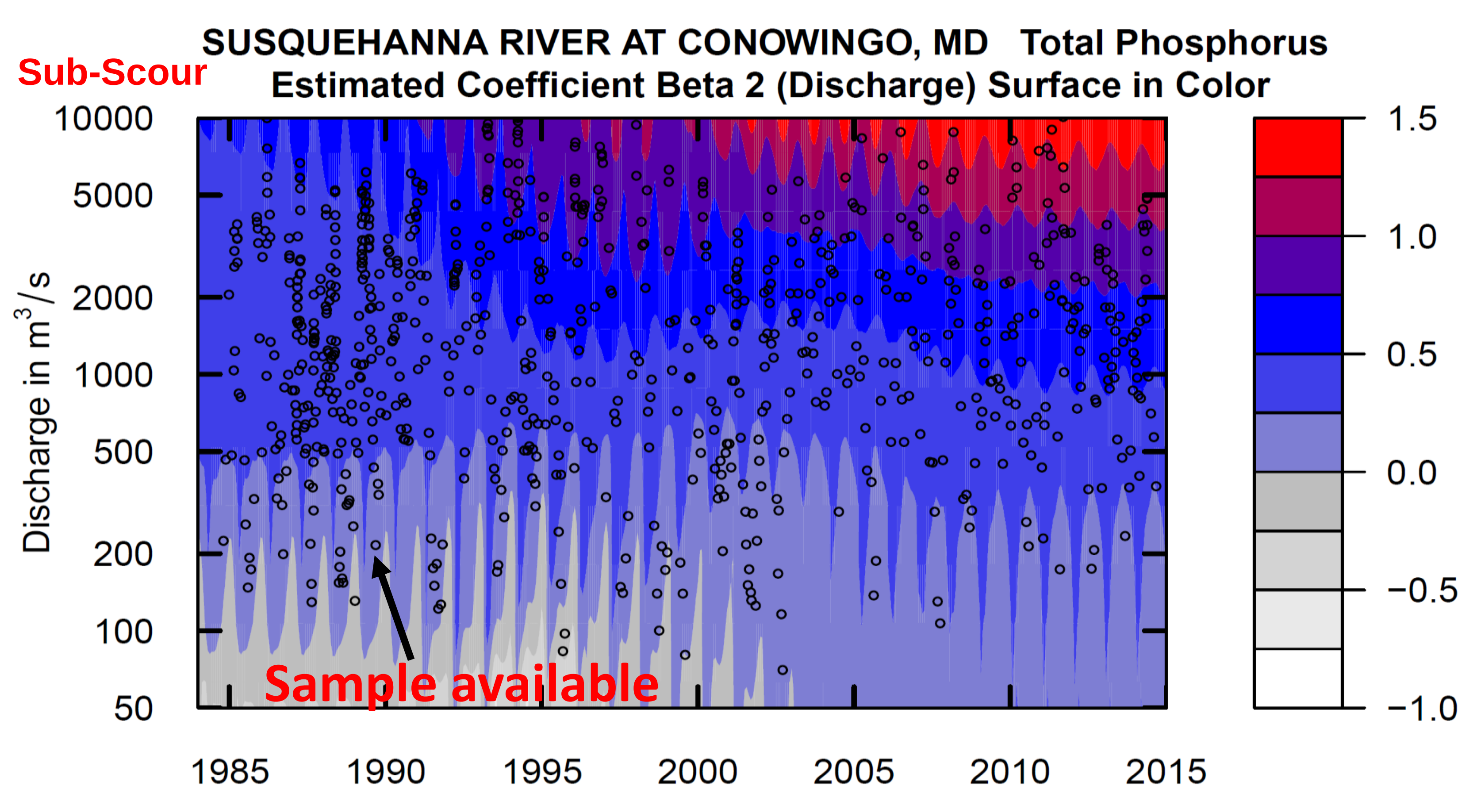
* LOWESS curves fitted to C-Q data in periods of 1987-1995, 1996-2004, and 2005-2013

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

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

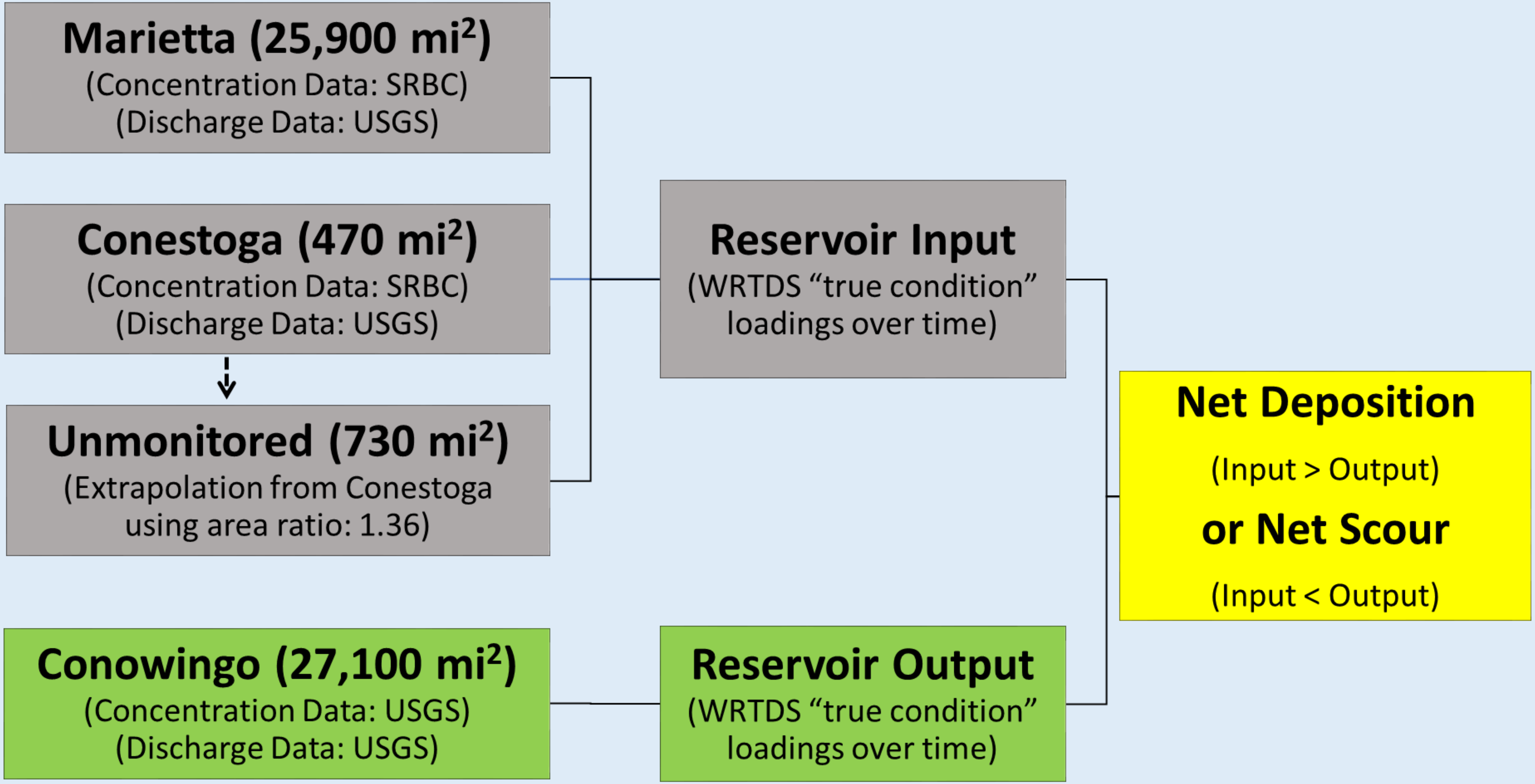
$$ln(C_i) = \beta_{0,i} + \beta_{1,i} t_i + \boldsymbol{\beta_{2,i}}\, ln(Q_i) + \beta_{3,i}\, sin(2\pi t_i) + \beta_{4,i}\, cos(2\pi t_i) + \varepsilon_i$$

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.

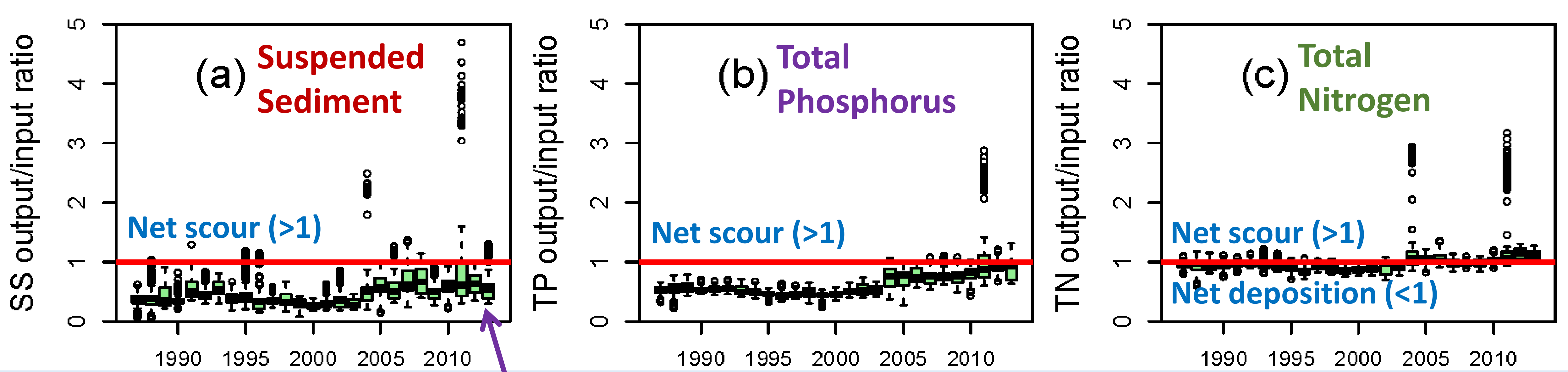
Input-Output Analyses: Net Deposition in the Reservoir



(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

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

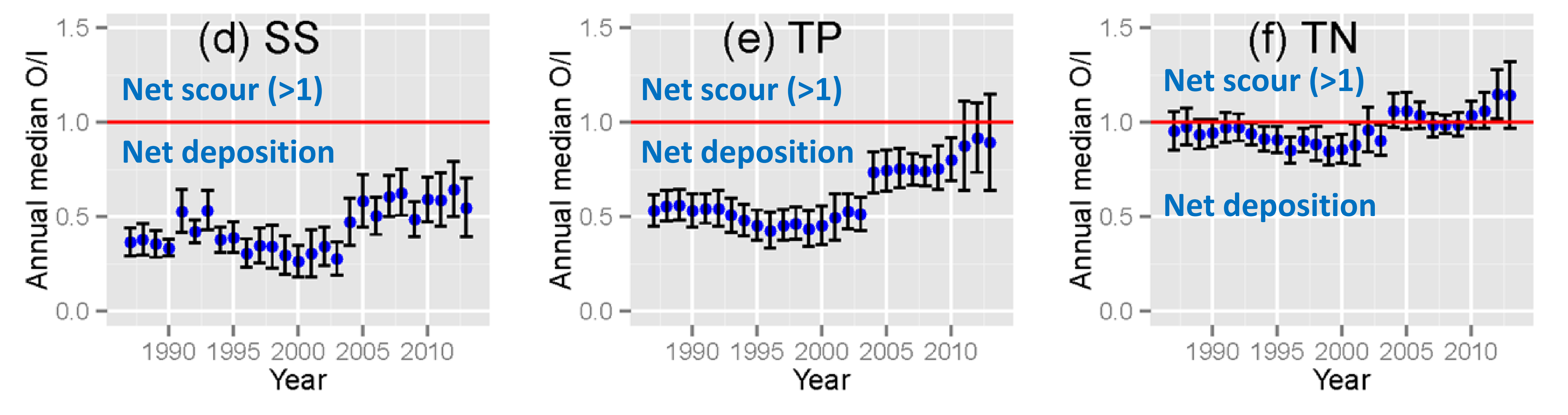
Input-Output Analyses: Uncertainty Analysis on O/I Ratio

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

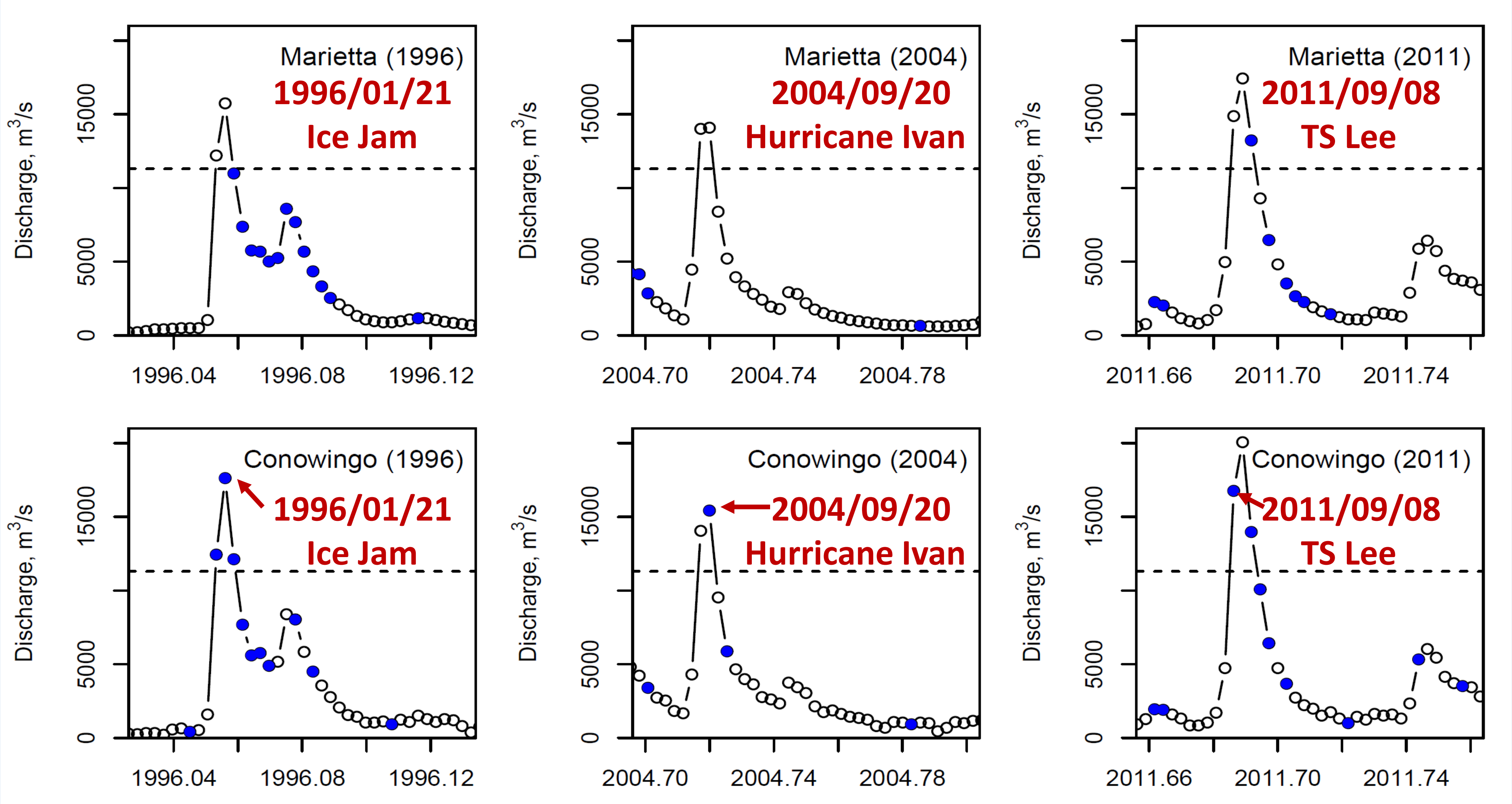
Suspended Sediment | **Total Phosphorus** | **Total Nitrogen**



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

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?

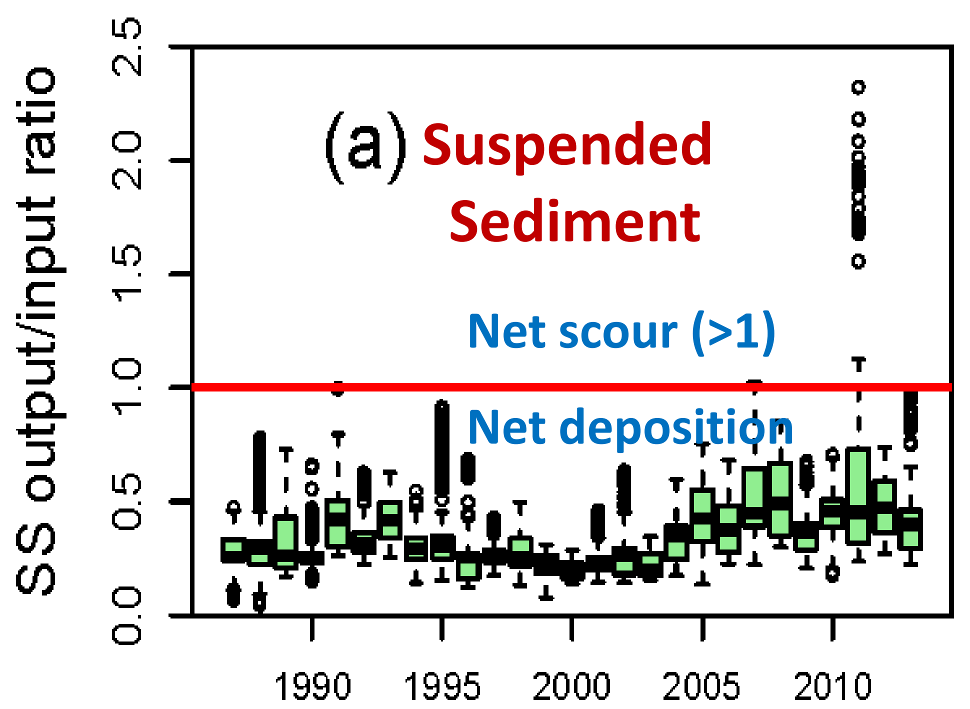


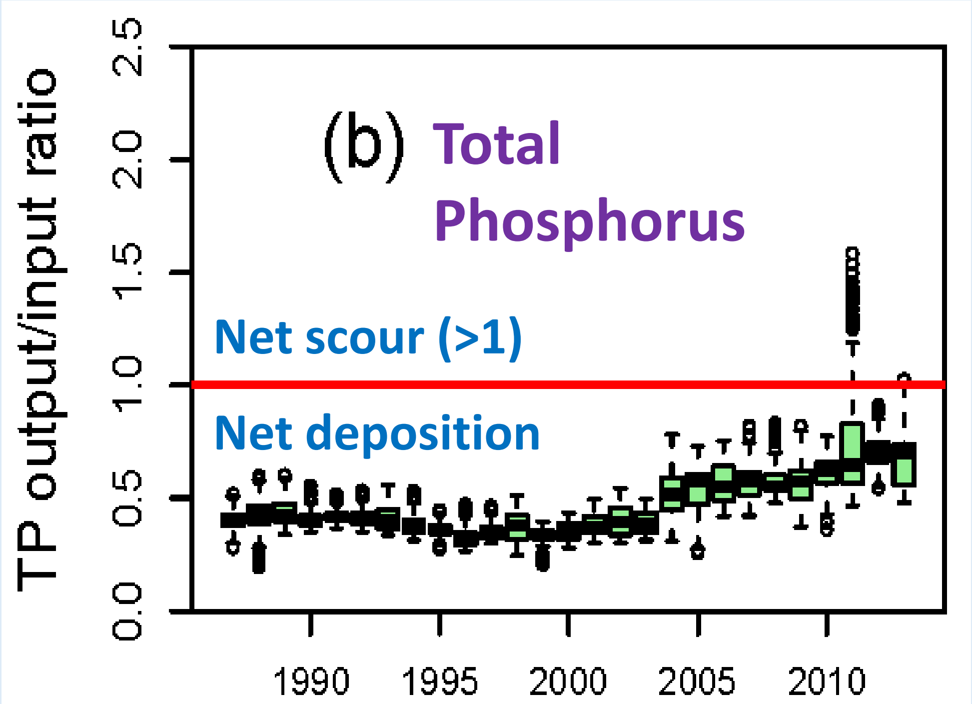
Time (years)

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?

<u>Sensitivity analysis</u> with **equally-censored samples** (**Q < 15,000 m³/s**)





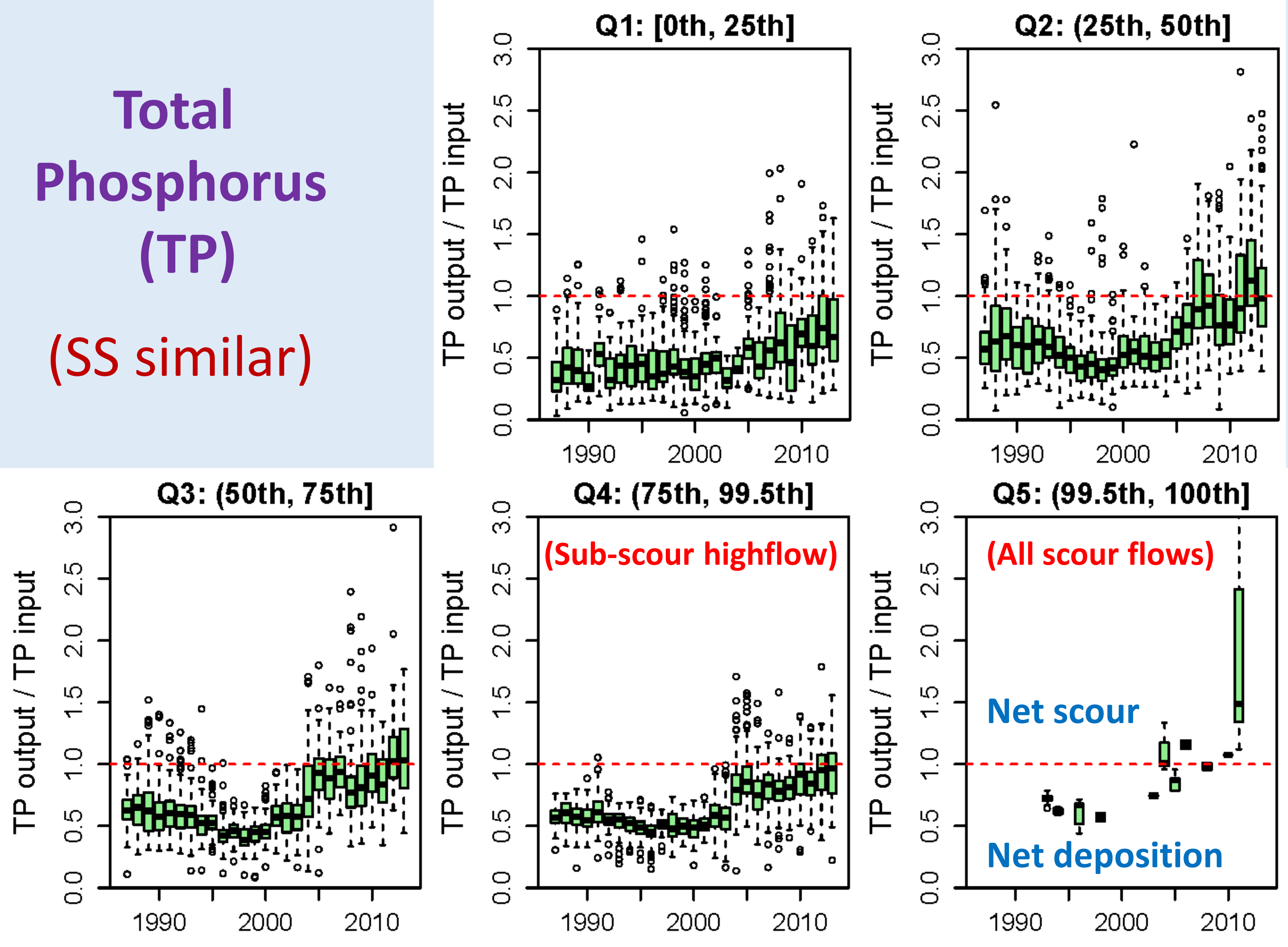
(Zhang, Hirsch, Ball, ES&T, 2016)

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

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

Total Phosphorus (TP)

(SS similar)



<u>Conowingo Flow Classes</u>

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: Contribution by Flow Class

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

<u>Conowingo Flow Classes</u>

Q_1: 25~396 m³/s;

Q_2: 399~787 m³/s;

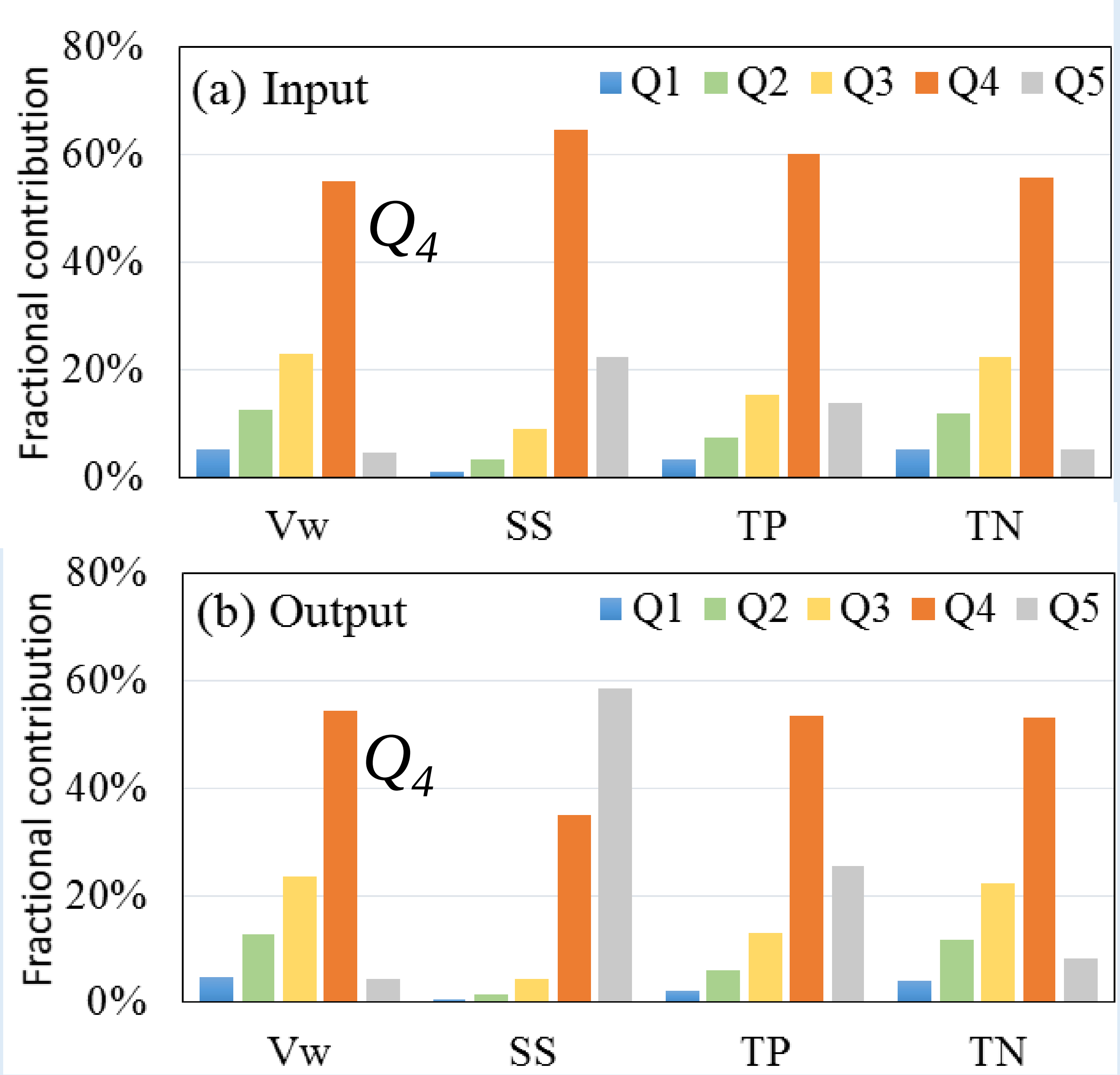
Q_3: 790~1,464 m³/s;

Q_4: 1,467~7,646 m³/s;

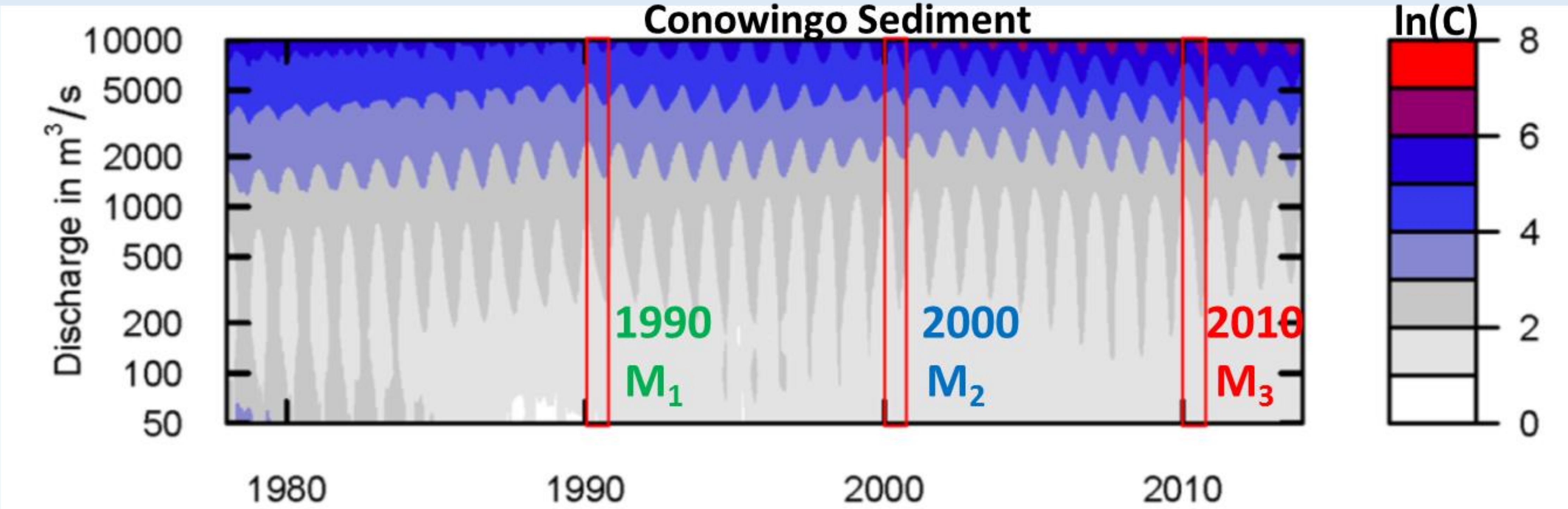
Q_5: 7,674~20,077 m³/s.

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.



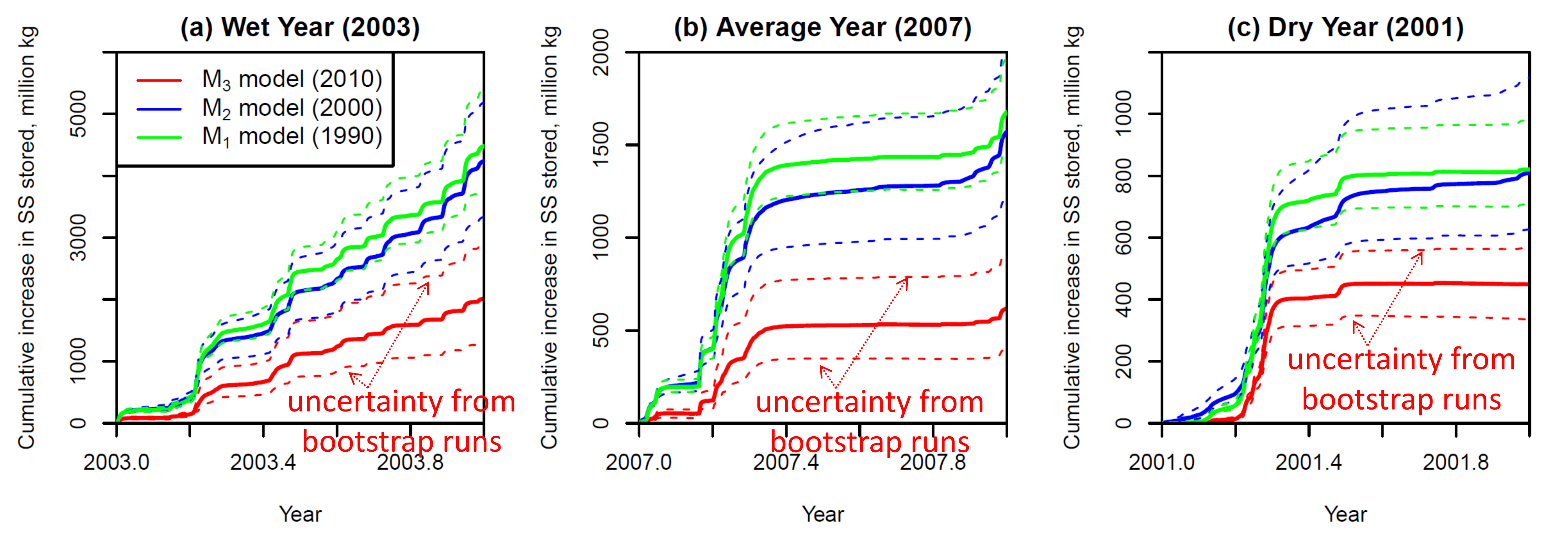
Stationary-Model Analyses: Effects of Changing $C(Q, t_{season})$ Surface



- 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**.

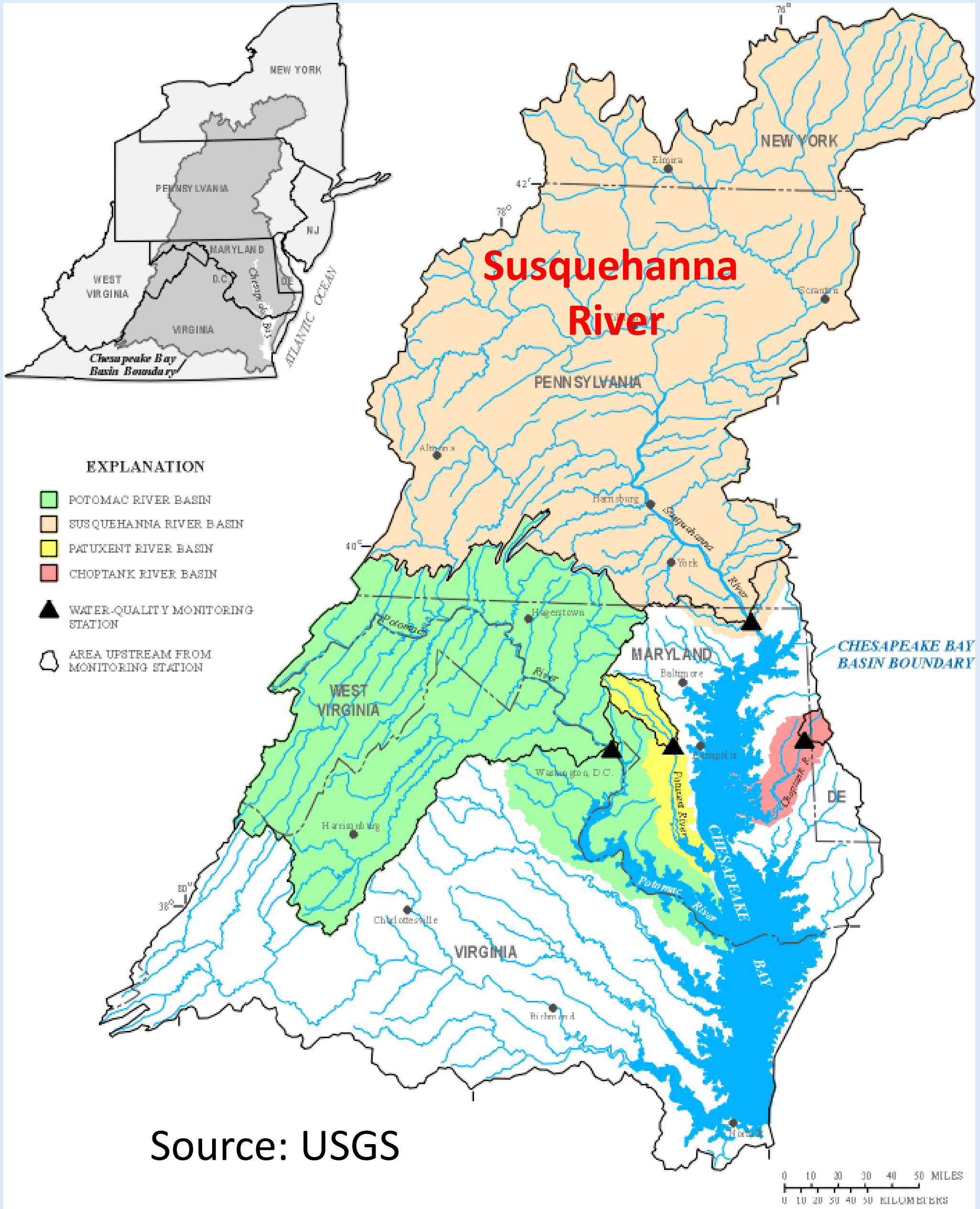
Stationary-Model Analyses: Change in Storage under 3 Reservoir Conditions

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



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

What is the significance of the Susquehanna trend in the NTCBW context?



Source: USGS

- **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.]

Acknowledgements

- Bill Ball (JHU/CRC) and Bob Hirsch (USGS) – contributions to the principle work
- Damian Brady (U. Maine), Walter Boynton (UMCES), and Doug Moyer (USGS) – contributions to related work
- Joel Blomquist (USGS), Gary Shenk (USGS), and Ken Staver (UMD) – review comments
- MD Sea Grant, USGS, NSF, and MD Water Resources Research Center – funding
- USGS and SRBC – river water-quality monitoring and data reporting

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.