# 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

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

#### **USGS**

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



Open-File Report 2014-1235

LOWER SUSQUEHANNA RIVER WATERSHED ASSESSMENT, MARYLAND AND PENNSYLVANIA



May 2015 Final







Conowingo Reservoir Sedimentation and Chesapeake Bay: State of the Science

EDIMENTATION in reservoirs is an issue of universal oncorn (liss and Morris, 1992a; Lalsula et al., 1993; Gunstlinke and Gopulakrishnan, 1999; Palmini et al., 2001; Padolak and Deyle, 2015). Reservoirs begin to fill with ediment from the moment they are constructed. Sodiment lotchkin and Huang, 1995), and even constructing additional eservoirs as upstream sediment traps (Chaudhuri, 2006). But

ceron is over Chesapeake Bay is the largest estuary in the United States, is one of many coastal seas worldwide (Diaz and Rosenberg,

(USSPA, 2019), Rudming pullates bank shows to the TMCI. In stimulated the clinical water quality reprincess, opposed to turns of standfillion dissolved suggest (COS), excesses sight to the contrast of standfillion dissolved suggest (COS), excesses sight Tac Sumplements to the legar favor into Kleengt skell. The Changelack Bay watershed and dissins portions of New York, Pinneyleasks, and Maryland. The vice employs in some unrelated material tools and Maryland. The vice employs into the unrelatement enters of Changelack Bay and provides more than ball discretization of the contrast of into the Jay. The most aphream reservoir, Luke Clarke, forms behind Safe Harbor Dam. Holtwood Dam forms Lake Aldeed, which his below Luke Clarke. The Concovings Reservoir, the largest of the three, forms behind Concovings Dam, which is situated approximately  $\delta$  km above the Chexapeake Bay head of tide.

Published March 25, 2015

Influence of Reservoir Infill on Coastal Deep Water Hypoxia

Lewis C. Linker,\* Richard A. Batiuk, Carl F. Cerco, Gary W. Shenk, Richard Tian, Ping Wang, and Guido Yactavo

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Journal of Environmental Quality

 The Conowingo Reservoir has been filling in with sediment for almost a century. It is now in a state of near-full capacity called dynamic equilibrowingo infil causes impairments to Chesapeake water

2012; Zhang et al., 2013; Langland, 2015). This study examine

because of reservoir infall, must be offset to comply with

Review of the Lower Susquehanna River Watershed Assessment



STAC Review Report August 2014 Annapolis, Maryland



STAC Publication 14-006

#### Johns Hopkins (2013, 2015, 2016)

Science of the Total Environment

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

Q. Zhang 4.8, D.C. Brady 5, W.P. Ball 6

HIGHLIGHTS

ARTICLE INFO

LONG-TERM TRENDS OF NUTRIENTS AND SEDIMENT FROM THE NONTIDAL

Qian Zhans, Damian C. Brady, Walter R. Bornton, and William P. Ball<sup>3</sup>

Zhang, Qian, Damian C. Brady, Walter R. Boynton, and William P. Ball, 2015. Long-Term Trends of Nutrient and Sediment from the Nontidal Chesapeake Watershed: An Assessment of Progress by River and Season Journal of the American Water Resources Association (JAWKa) 1-22, DOI: 10.1111/752-168812323.

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AMERICAN WATER RESOURCES ASSOCIATION

CHESAPEAKE WATERSHED: AN ASSESSMENT OF PROGRESS BY RIVER AND SEASON!

ABSTRACT. To assess historical leads of attrages (Nr., pheuphorus (Pr., and suspended sediment (SS)) from the metital Consequent Buy vasterheld (NYCHIW), we enaltyed decadal seasonal trends of the overmalized index at the follium of time and pre-tree that exceen the "Well of NYCHIW" for the Schutzinsten feals by some revealed of the present of the second present trends of the second present trends of the present trends of the present present trends have followed similar decade-seks patterns in all seasons, with notable exceptions. Generally, studied (NYC) index to the opposition of the New Schutzinsten feals by the second present trends of the New Schutzinsten feals of the New Schutzinst

\*Paper No. JAWRA-14-0180-P of the Journal of the American Water Resources Association (JAWSA). Received September 7, 2014, coupled April 22, 2015. O 2015 American Water Resources Association. Discussions are open until six months from issue publica-

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

Qian Zhang, 47 Robert M. Hirsch,2 and William P. Ball 1.8

ohn Hopkins University, Department of Geography and Environmental Engineering, 3400 North Charles Street, Baltimon, Saryland 21218, United States neuryana 22118, United States TUS. Genlegical Survey, 822 Nixtonal Center, Benton, Virginia 20192, United States <sup>8</sup>Chesapunk Research Consortium, 645 Conten Wharf Road, Edgewatts, Maryland 21037, United States

O Supporting Information

ACS Publications #20% Amount those \$1009 1809

**@AGU** PUBLICATIONS

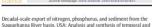
**Geophysical Research Letters** 

An improved method for interpretation of riverine concentration-discharge relationships indicates

long-term shifts in reservoir sediment trapping Qian Zhang<sup>1</sup>, Ciaran J. Harman<sup>1</sup>, and William P. Ball <sup>1,3</sup>

standing complex interactions between hydrologic and biogeochemical processes, including nutrient and sediment export dynamics (Chanar et al., 2002; Evans and Davies, 1998; Godbey et al., 2009; Meybeck and Homoton et al., 2015; House and Waterski, 1998, Richardson, 2012, C-Q initiationships laver historically been classified into three broad categories: (1) "dilution" (i.e., negative mistronship); (2) "mobilization (i.e., positive relationship); and (3) "chemostass" (i.e., Cimuniant with (3). The category of classification will vary with con-stituent and site (Godzey et al., 2009; Hendon et al., 2015; Hinch et al., 2010; Meybeck and Mootor, 2012; Statiss dand Maphy, 2014, and C G relationships may change overtime in ways that can serve as useful indi-cation of changes in him system function (Bissos and Hechtweite, 2015, But et al., 2015, Guy et al., 2015, Mohanlon, 2012, Zhang et al., 2016b). These changes may in turn reflect with repoperic activities such as land disturbance and watenihed management, particularly if the stochastic properties of river discharge how remained roughly unchanged over time.

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Science of the Total Environment

spatial patterns Qian Zhang 48, William P. Ball 46, Douglas L. Moyer

ARTICLE INFO

\* Communiting outlier:

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Conowingo Reservoir Infill and Its Influence on Chesapeake Bay Water Quality



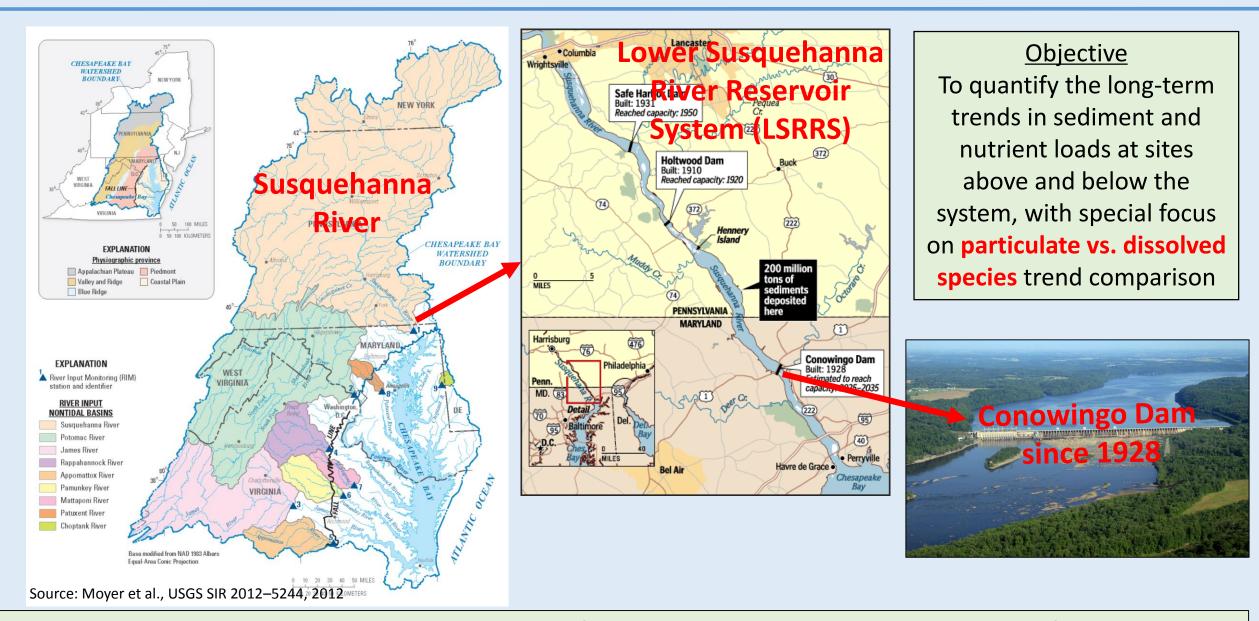
STAC Workshop Report January 13-14, 2016 Annapolis, MD



STAC Publication 16-004

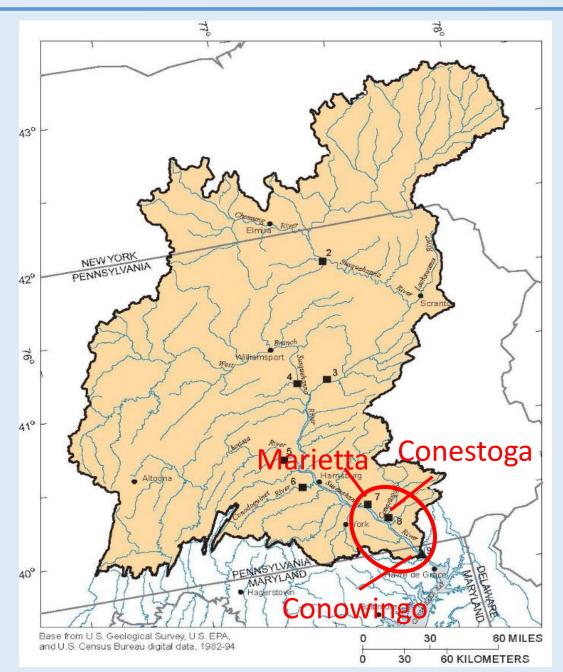
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#### **Background: LSRRS (Conowingo)**



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)

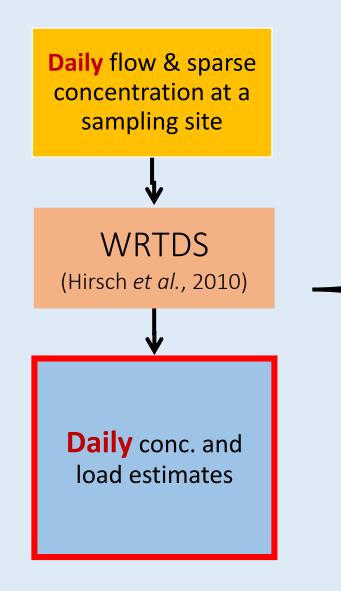
#### **Monitoring Data:**

- 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**

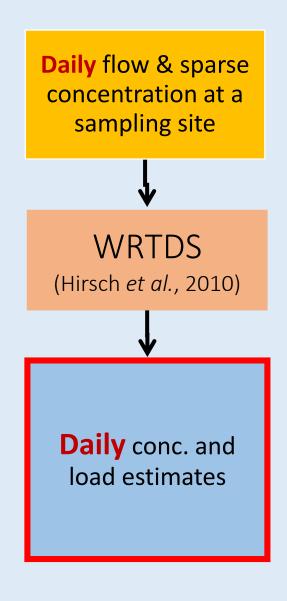


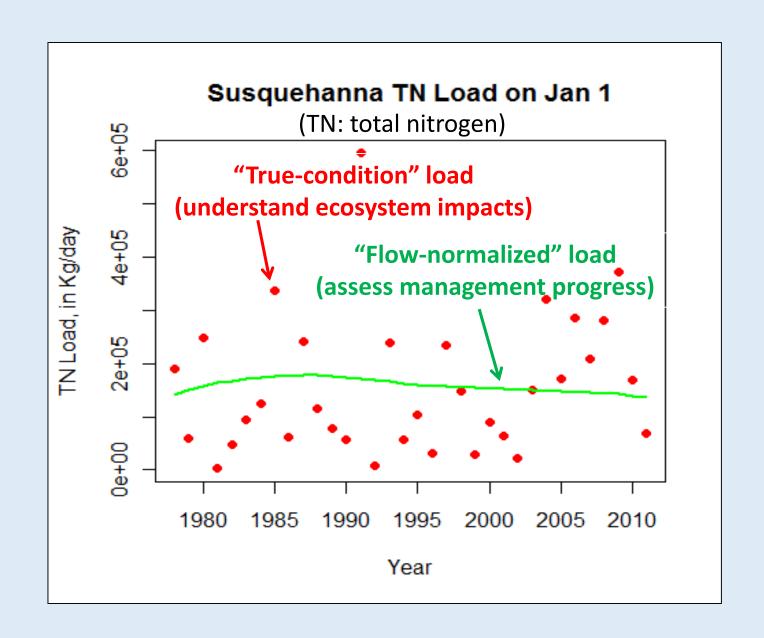
WRTDS (Hirsch *et al.*, 2010) [Weighted Regressions on Time, Discharge, and Season]

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

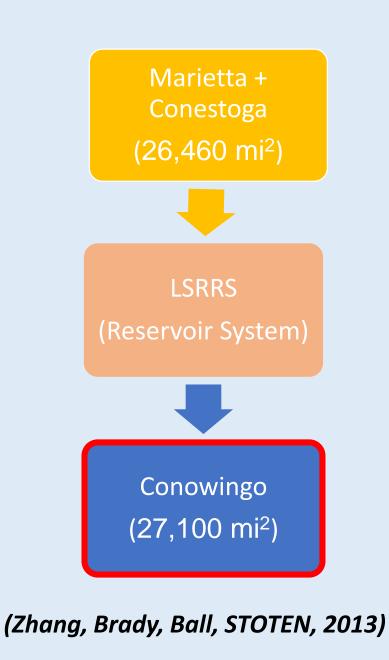
- One single model (coefficient set) for each day of estimation;
- No assumption on fixed C-Q relations over time or season;
- Better estimation performance;
- Adopted in a wide range of studies.

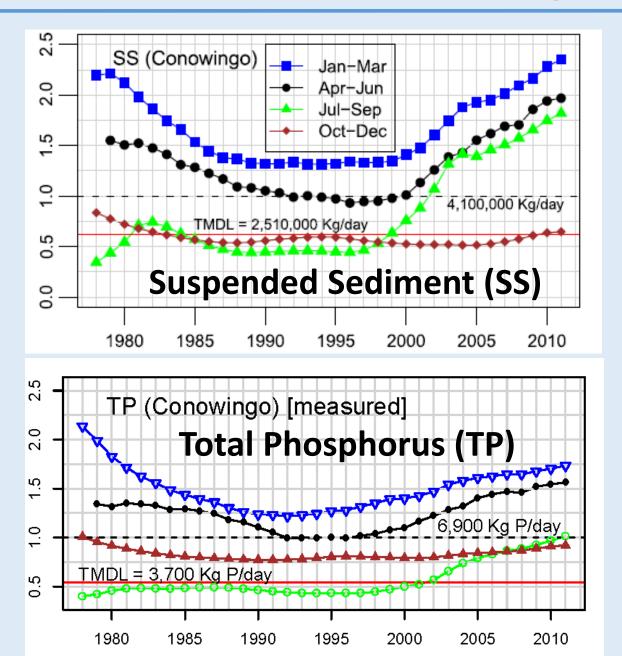
#### **WRTDS Method**



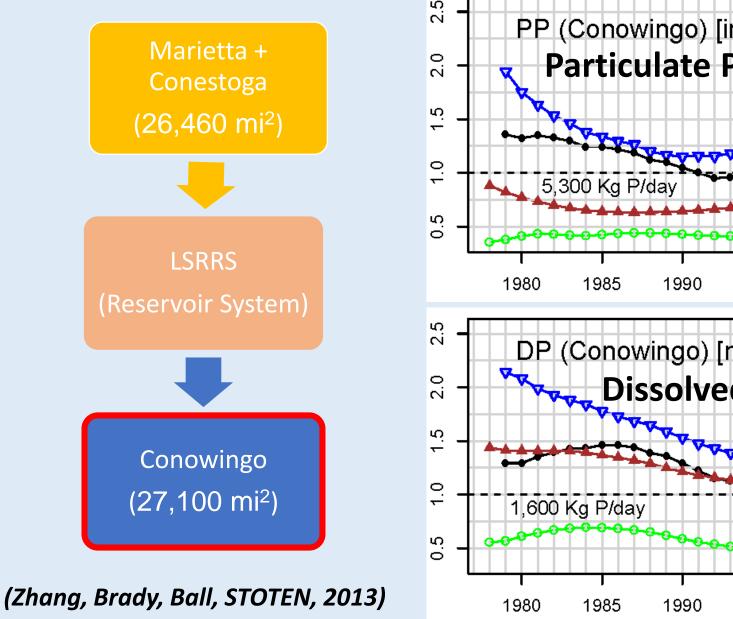


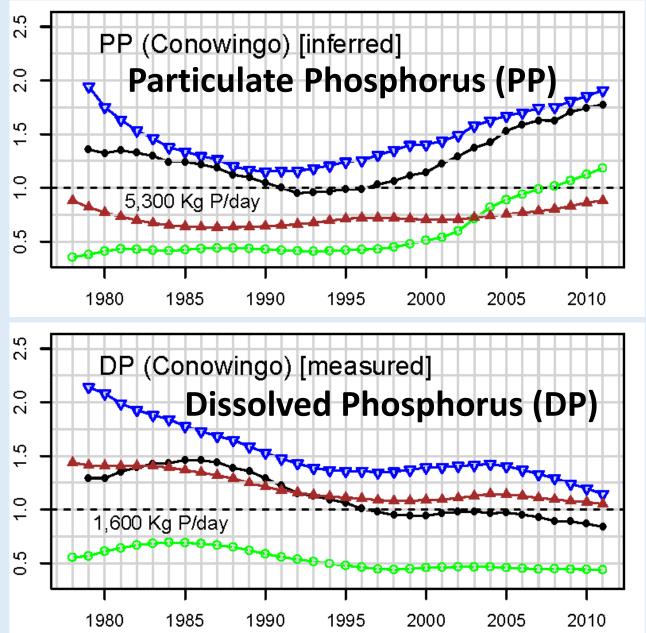
#### What have been the flow-normalized seasonal trends at Conowingo Dam?



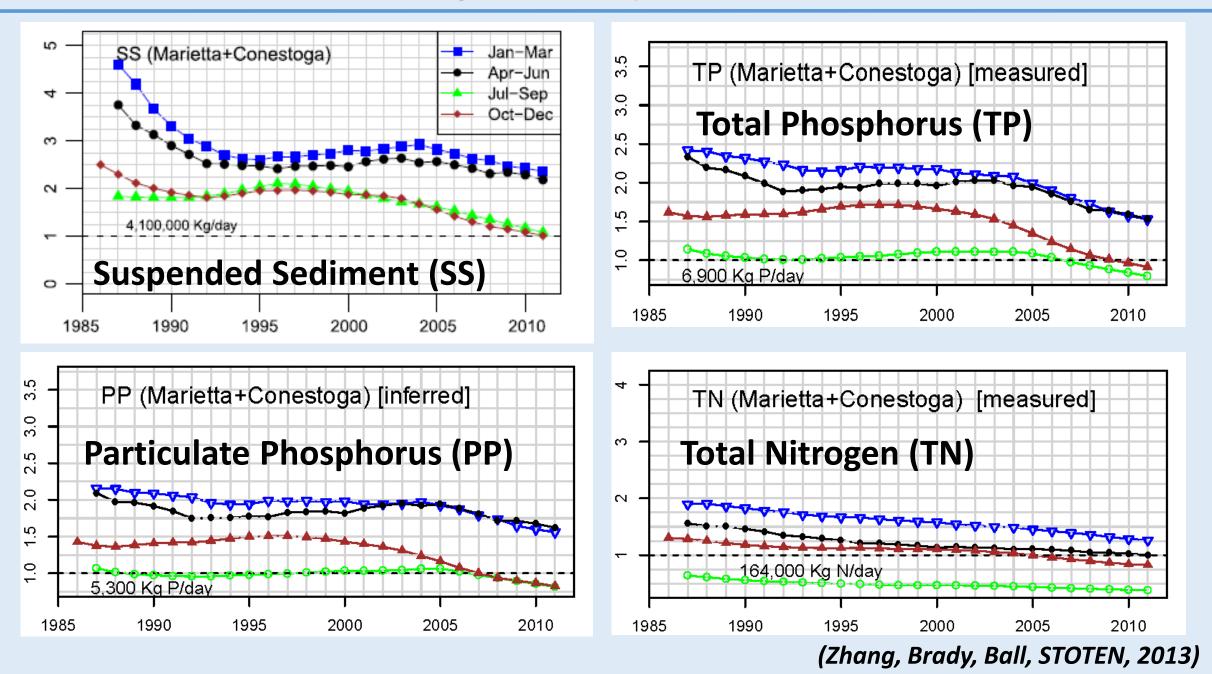


#### Which sub-species has driven the TP trend?





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



#### Are these trends biased by storm-flow samples?

Marietta + Conestoga (26,460 mi<sup>2</sup>)

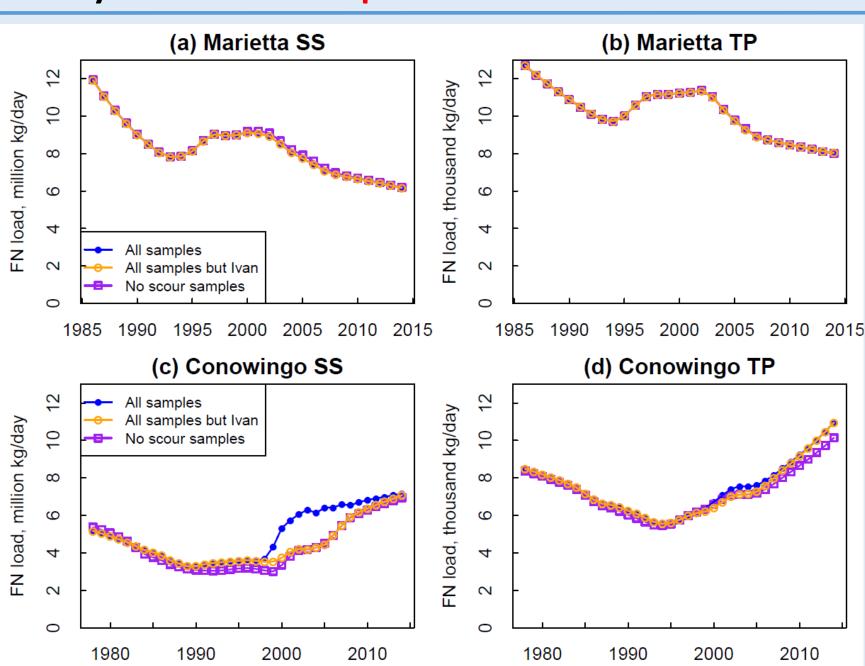


LSRRS (Reservoir System)



Conowingo (27,100 mi<sup>2</sup>)

(Zhang and Ball, unpublished data)

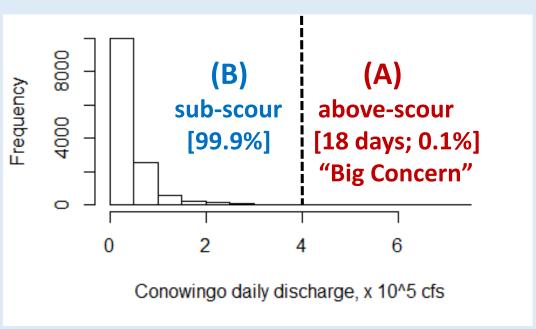


#### Follow-up Work by Zhang, Hirsch, and Ball (2016)

- 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).

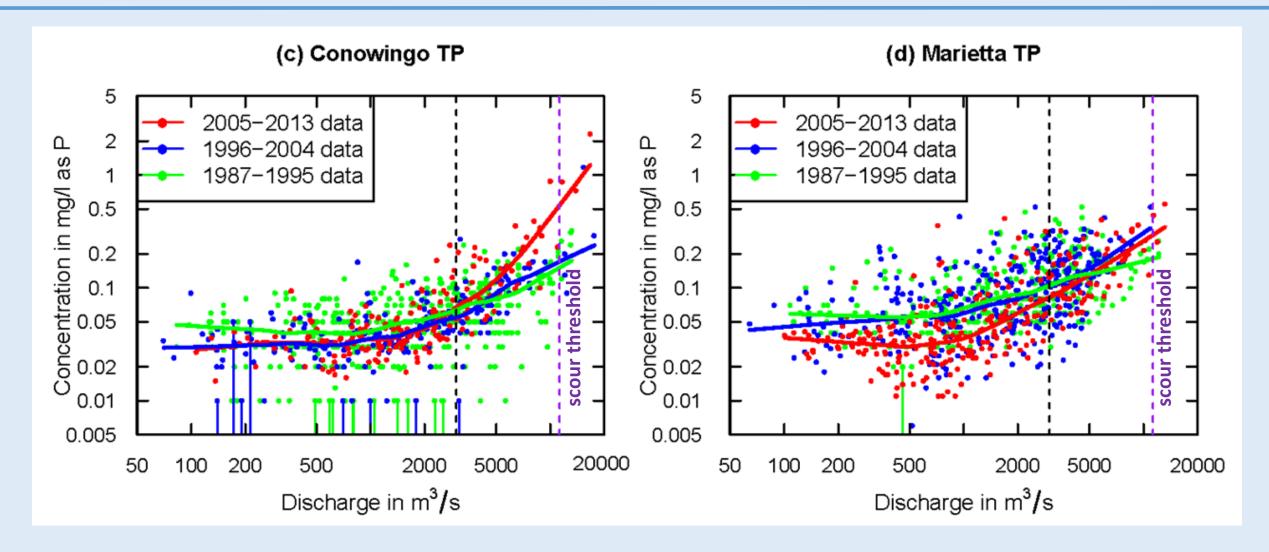
\* **400,000** cfs or **11,300** m<sup>3</sup>/s (Gross et al., 1978) [Major concern to managers and modelers]

#### **Conowingo Daily Discharge**



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

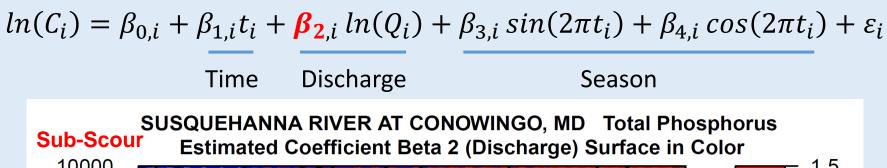


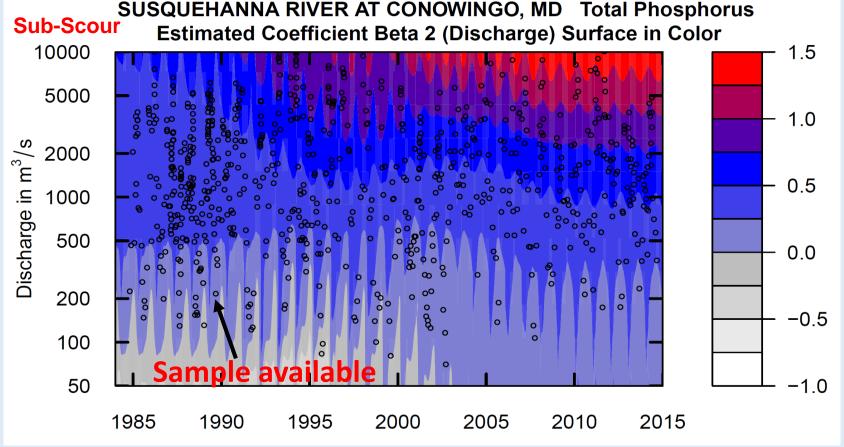
**Total Phosphorus (TP)** [Results similar for SS]

\* 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 $\beta_2$ Coefficients





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

### Marietta (25,900 mi²)

(Concentration Data: SRBC) (Discharge Data: USGS)

#### Conestoga (470 mi<sup>2</sup>)

(Concentration Data: SRBC) (Discharge Data: USGS)

#### Unmonitored (730 mi<sup>2</sup>)

(Extrapolation from Conestoga using area ratio: 1.36)

#### Conowingo (27,100 mi<sup>2</sup>)

(Concentration Data: USGS) (Discharge Data: USGS)

#### **Reservoir Input**

(WRTDS "true condition" loadings over time)

#### **Net Deposition**

(Input > Output)

or Net Scour

(Input < Output)

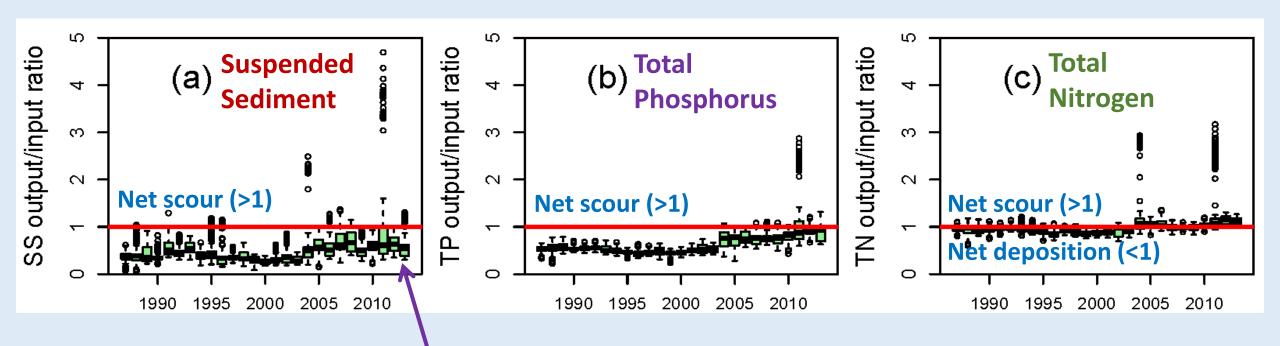
#### **Reservoir Output**

(WRTDS "true condition" loadings over time)

(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 <u>true-condition</u> O/I ratios in each year from 1987 to 2013

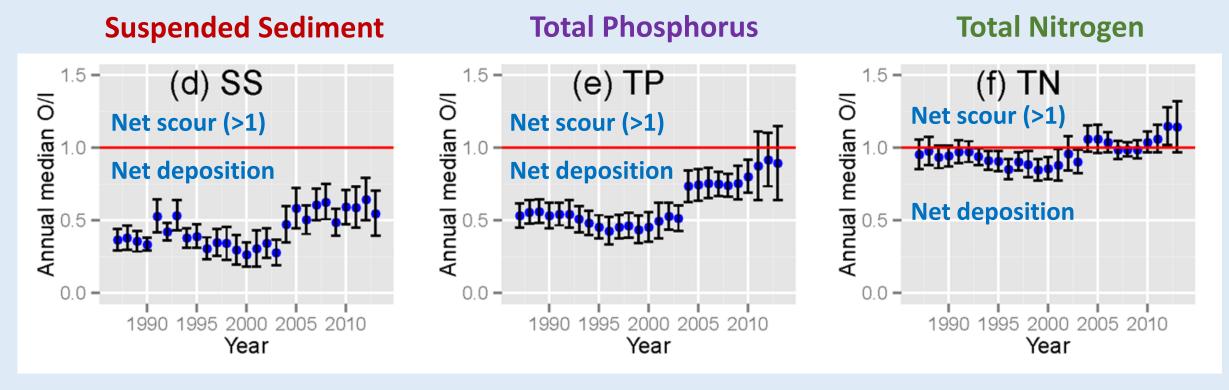
(Zhang, Hirsch, Ball, ES&T, 2016)

#### 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

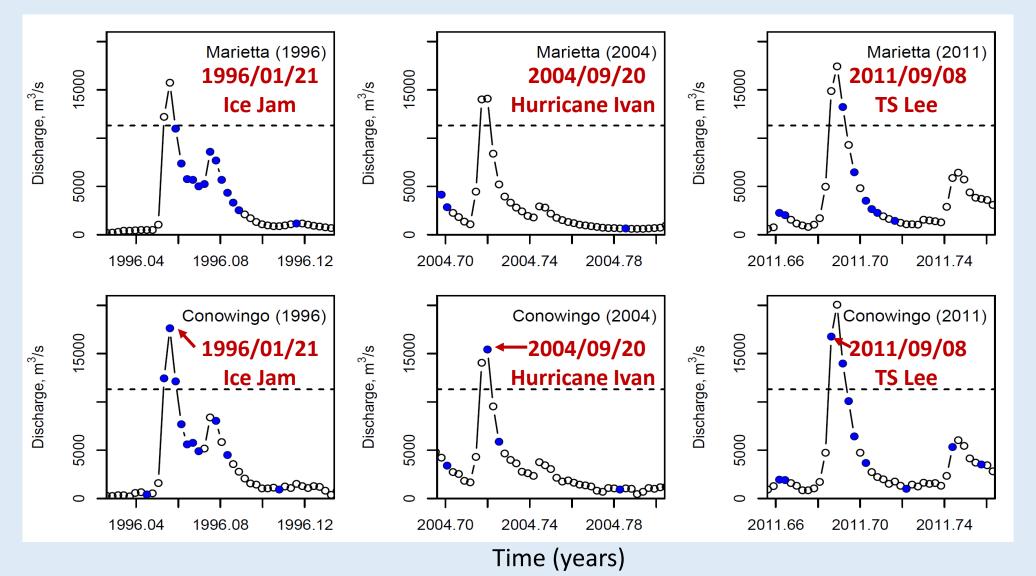
→ 100 "centerlines" (annual medians) → Mean & the 95% CI



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

#### Input-Output Analyses: Sensitivity to Differential Highflow Sampling

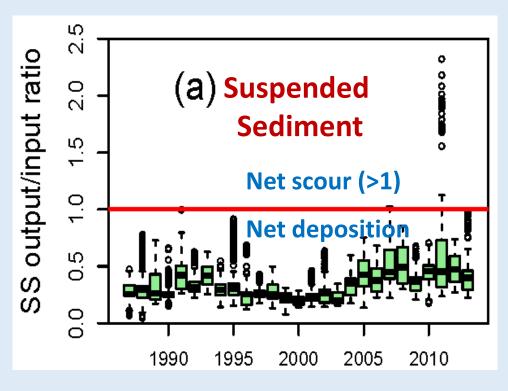
## Q: Are trends in O/I ratio biased by the differential highflow sampling at Marietta and Conowingo?

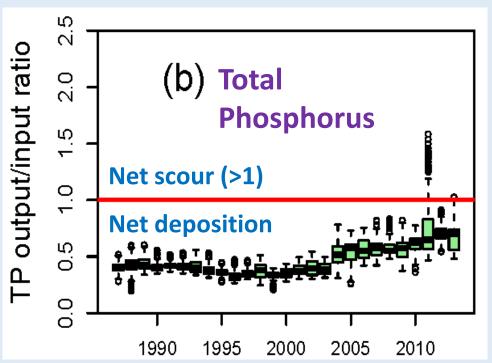


#### **Input-Output Analyses: Sensitivity to Differential Highflow Sampling**

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<sup>3</sup>/s)





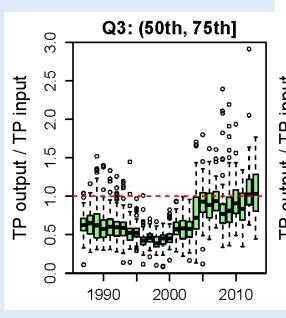
(Zhang, Hirsch, Ball, ES&T, 2016)

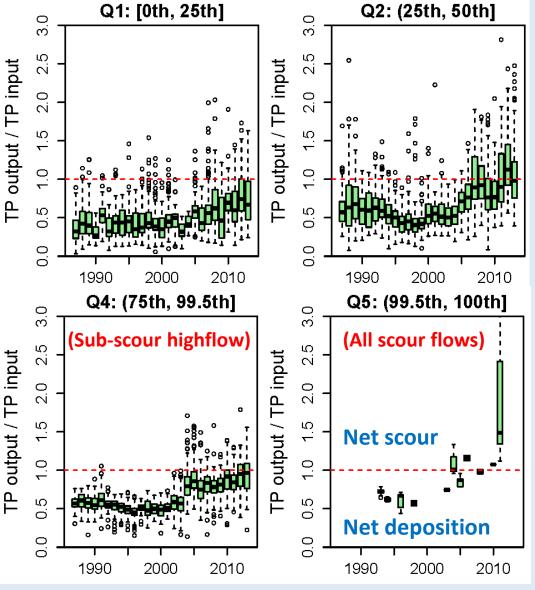
#### Input-Output Analyses: O/I Ratio by Flow Class

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

Total
Phosphorus
(TP)

(SS similar)





#### **Conowingo Flow Classes**

 $Q_1$ : 25~396 m<sup>3</sup>/s;

Q<sub>2</sub>: 399~787 m<sup>3</sup>/s;

 $Q_3$ : 790~1,464 m<sup>3</sup>/s;

Q<sub>4</sub>: 1,467~7,646 m<sup>3</sup>/s;

 $Q_5$ : 7,674~20,077 m<sup>3</sup>/s.

 $Q_{scour}$ : ~ 11,000 m<sup>3</sup>/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/

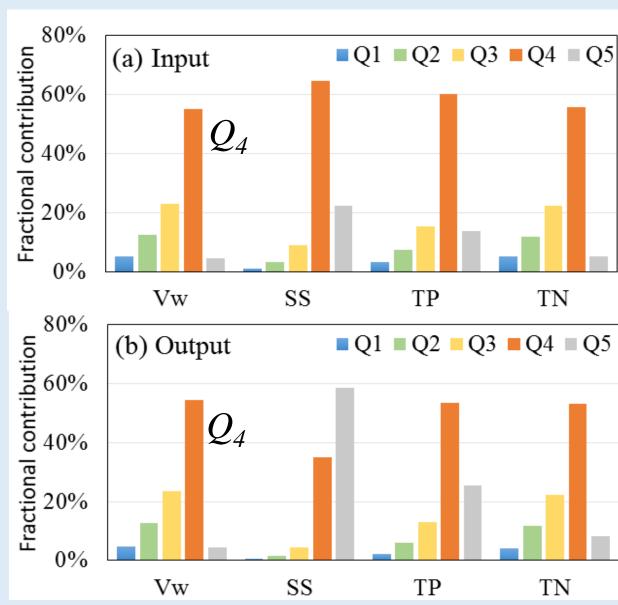
(Zhang, Hirsch, Ball, ES&T, 2016)

#### **Input-Output Analyses: Contribution by Flow Class**

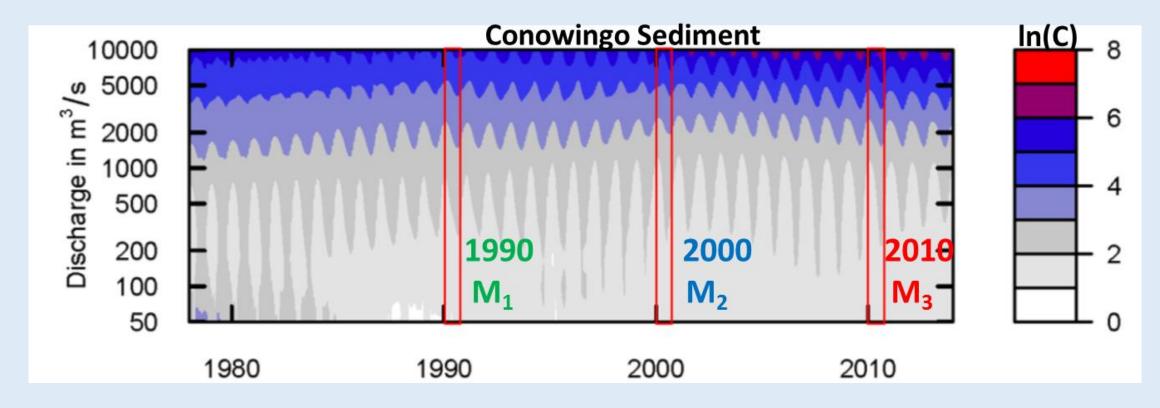
#### Q: Which flow class has contributed the most to mass delivery?

Conowingo Flow Classes
Q<sub>1</sub>: 25~396 m<sup>3</sup>/s;
Q<sub>2</sub>: 399~787 m<sup>3</sup>/s;
Q<sub>3</sub>: 790~1,464 m<sup>3</sup>/s;
Q<sub>4</sub>: 1,467~7,646 m<sup>3</sup>/s;
Q<sub>5</sub>: 7,674~20,077 m<sup>3</sup>/s.
Q<sub>5</sub>: 0,674~20,077 m<sup>3</sup>/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.



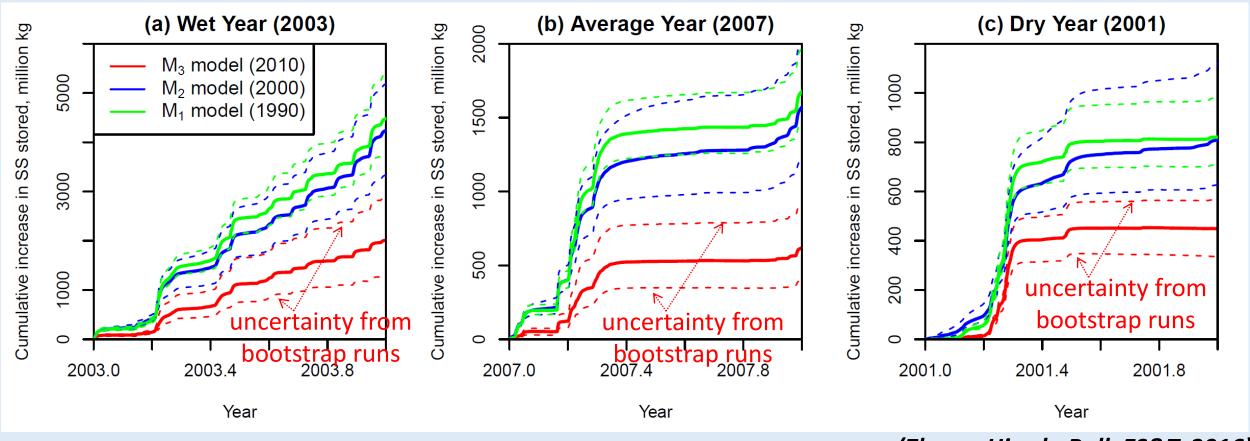
#### Stationary-Model Analyses: Effects of Changing $C(Q, t_{season})$ Surface



- Inter-annual comparisons of WRTDS <u>true-condition</u> 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.

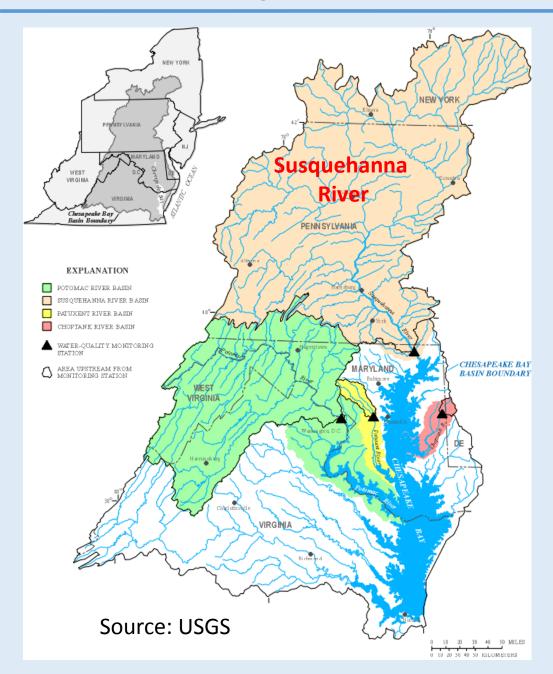
#### Stationary-Model Analyses: Change in Storage under 3 Reservoir Conditions

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?



- 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. <u>Link to paper</u>.
- 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.