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

Photo of Conowingo Dam from www.chesapeakeboating.net

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Acknowledgements

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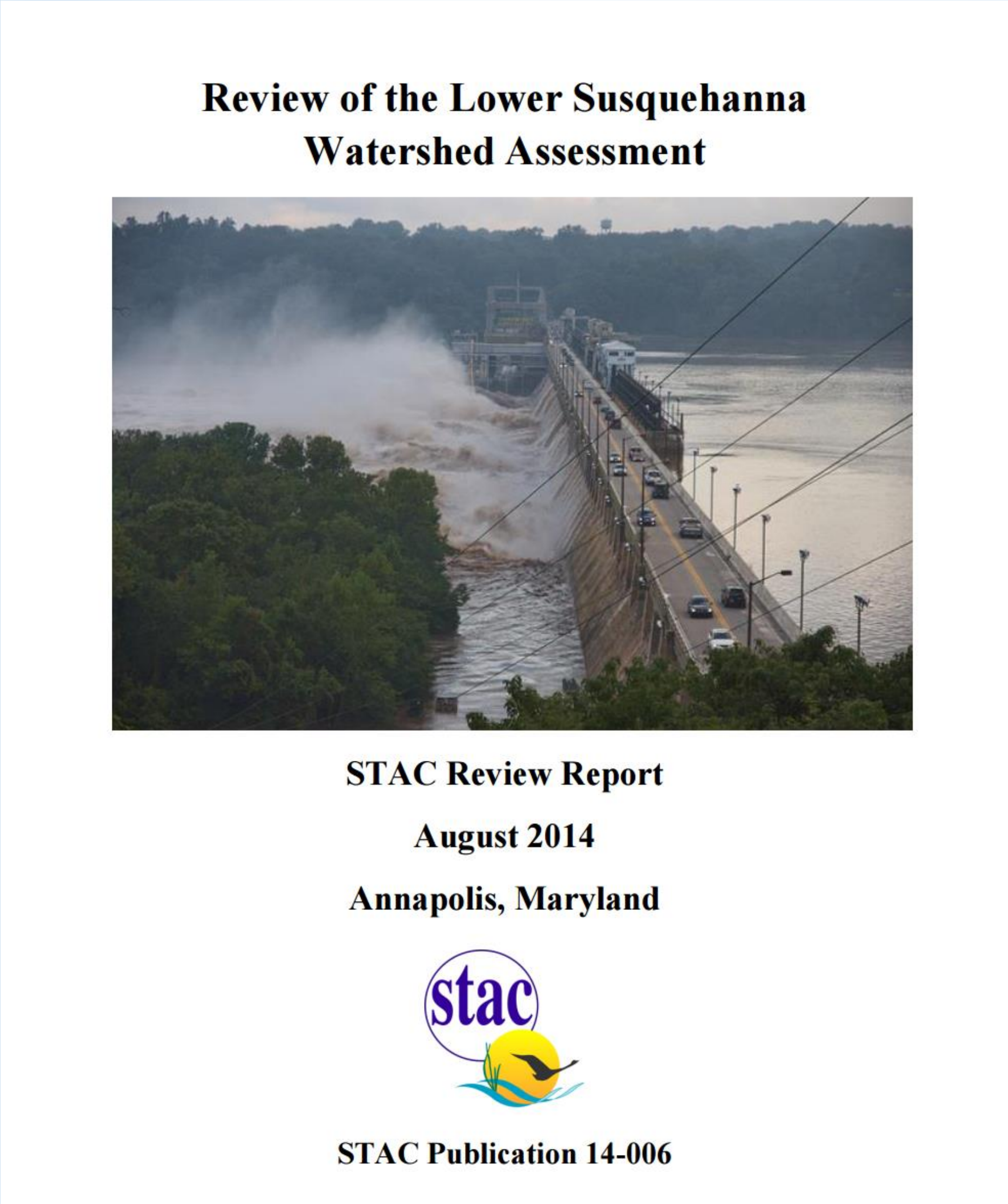
US Geological Survey
MD Water Resources Research Center

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
  - Near end of effective life for **SS** removal (USGS reports: Hirsch, 2012; Langland, 2015).
  - Previously (1978) reported sediment scour threshold: 11,300 m^3/s (400,000 cfs).

Background


Review of the Lower Susquehanna Watershed Assessment

STAC Review Report

August 2014

Annapolis, Maryland

stac

STAC Publication 14-006

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****."*

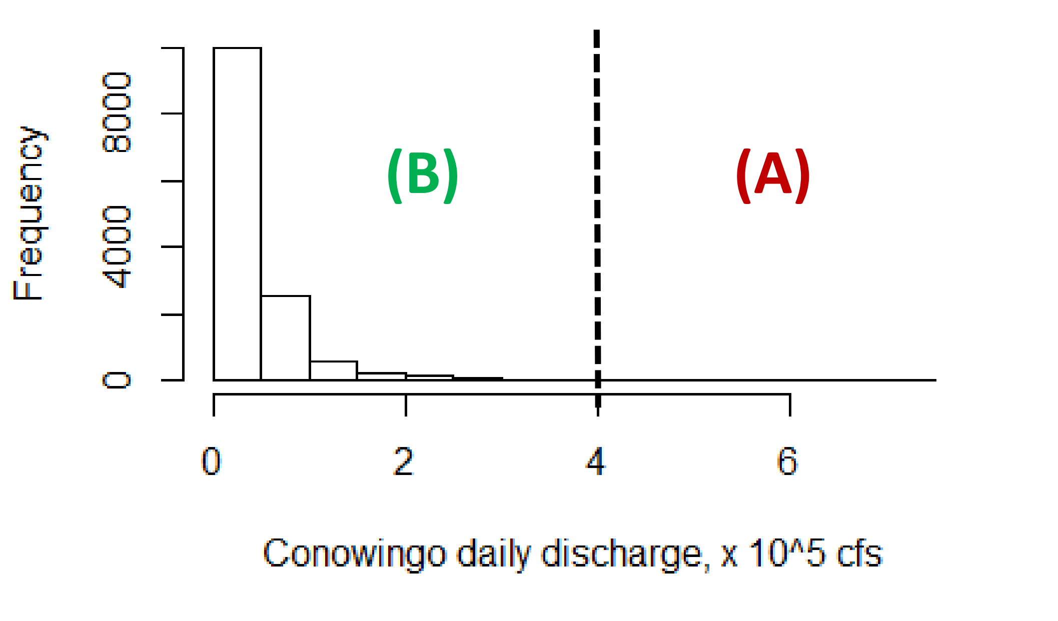
Background

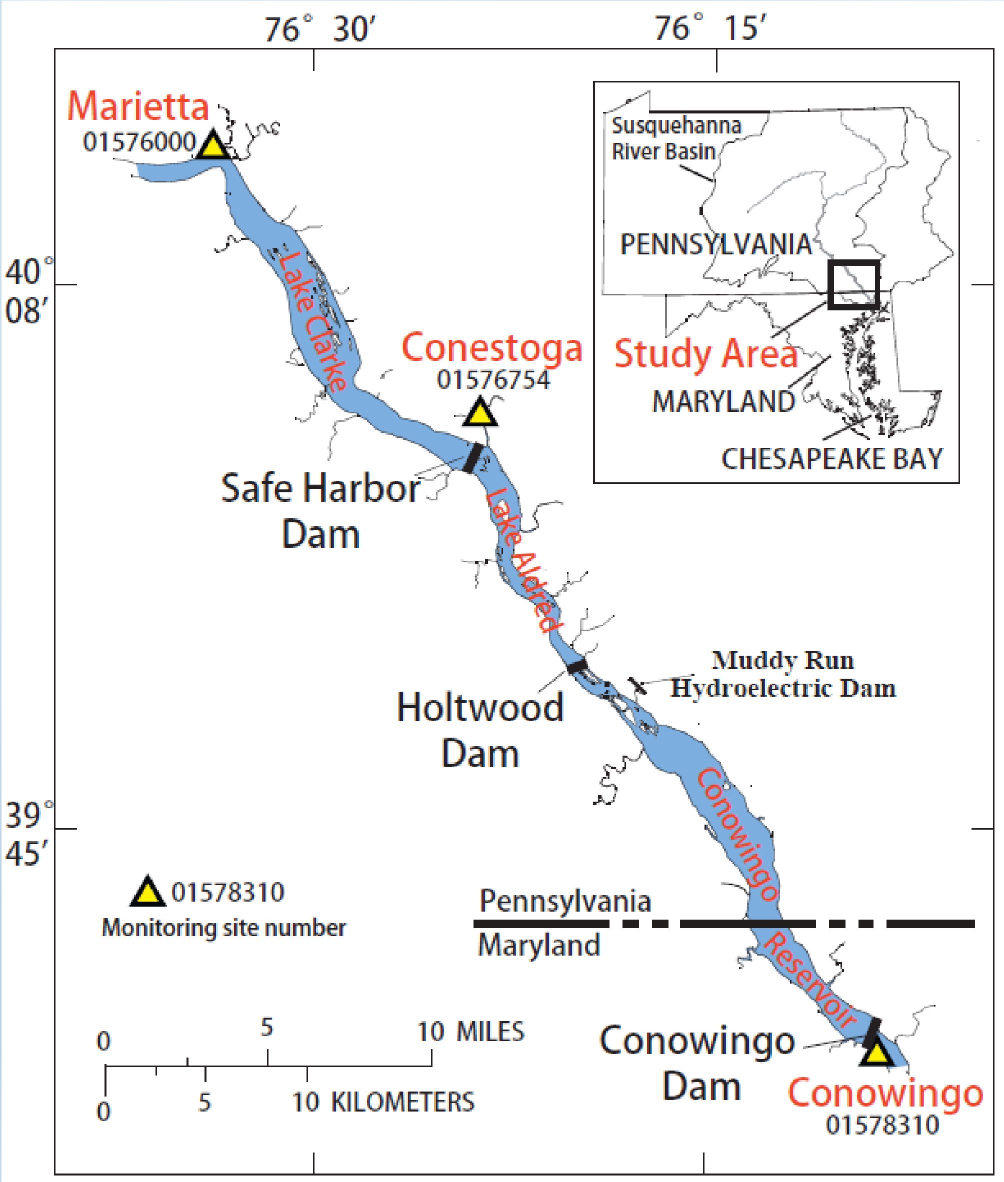
- Need to quantify the broad declines in reservoir performance in the last three decades.

- 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 dis





LSRRS Map

Objectives

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

1
- Identify temporal change in system function (C *vs* Q 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 [$C(Q, t_{season})$]
  Application of "stationary" *C(Q, t) surfaces* on the same long-term flow data

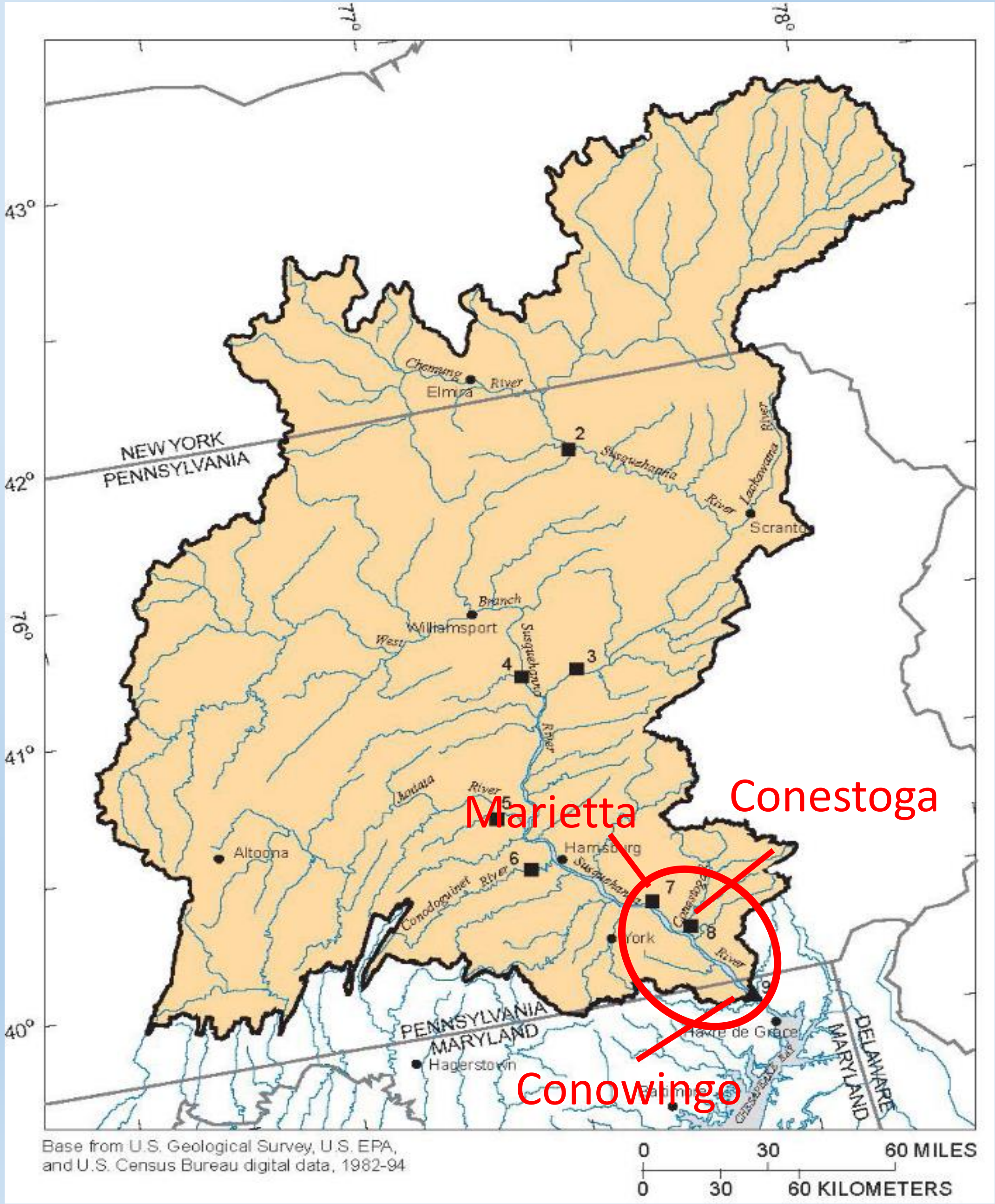
Study Sites and Data

Monitoring sites:

- Above LSRRS:
  Marietta + Conestoga
  (~97% of SRB drainage area)
- Below LSRRS:
  Conowingo
  (99% of SRB drainage area)

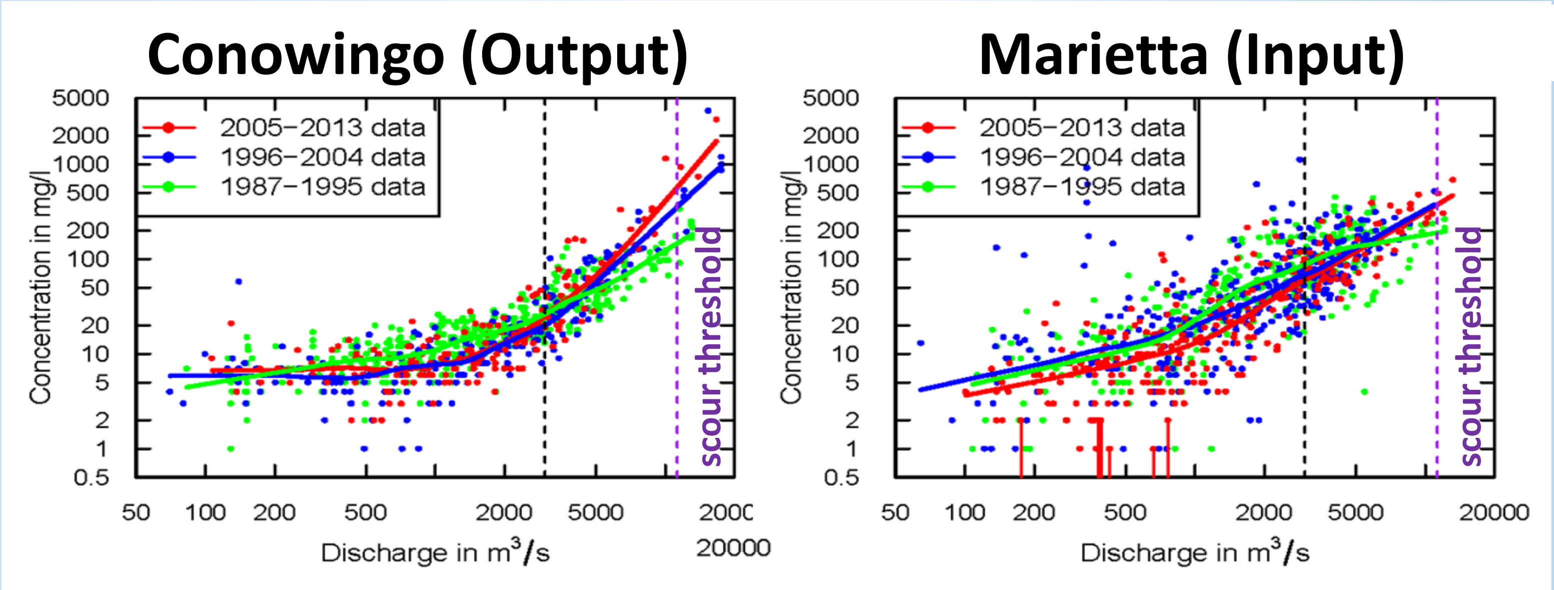
Available Data (all sites):

- Discharge data (daily);
- **SS**, **P**, and **N** data(25-40 sampled days per year)

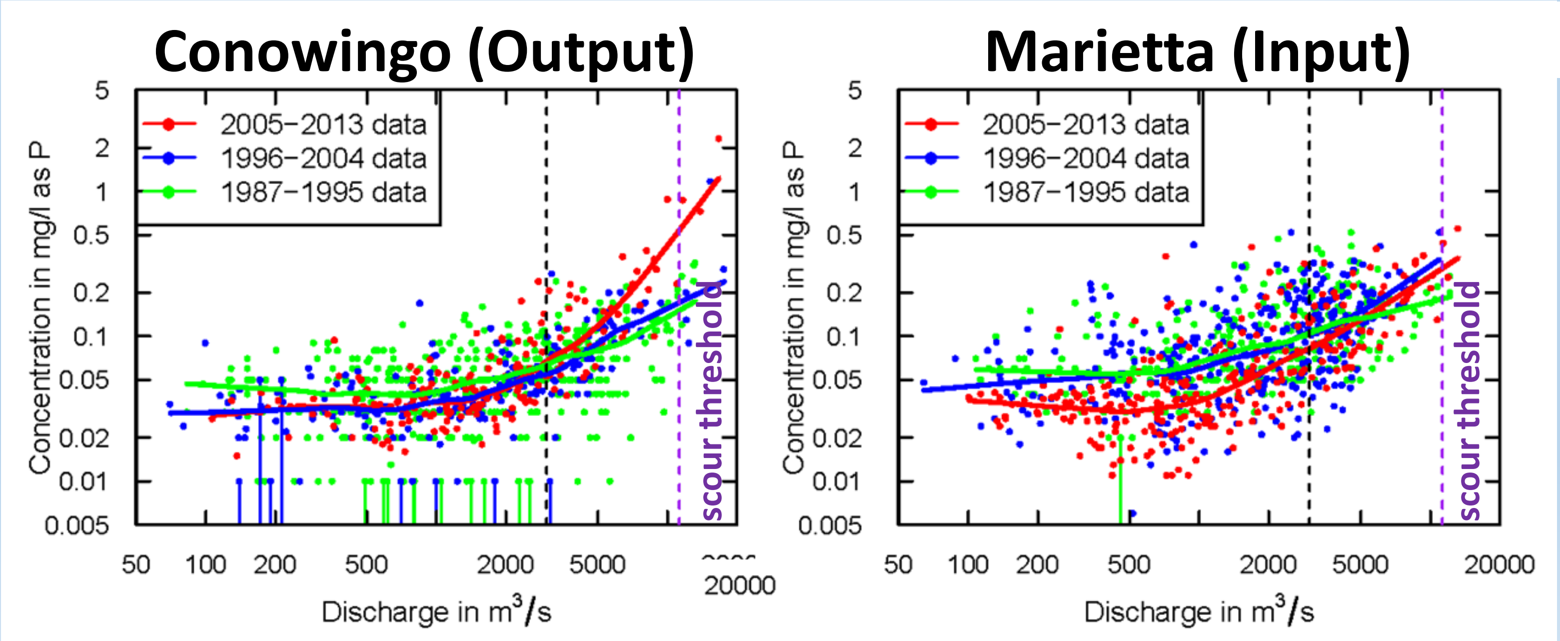


1. Temporal changes in *C-Q* relationships above & below LSRRS

Suspended Sediment (SS)



Total Phosphorus (TP)



2. Flow-normalized trends in particulate loadings above & below LSRRS

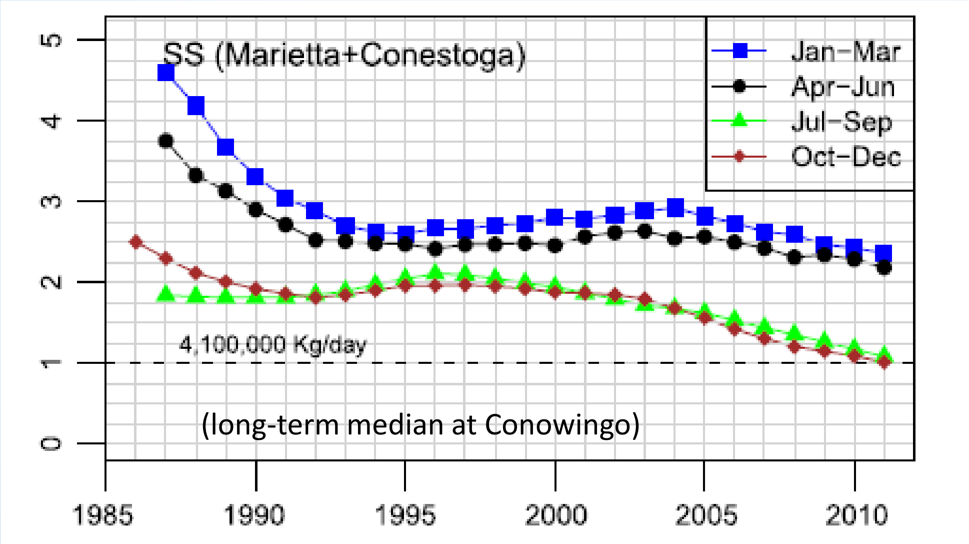
Marietta + Conestoga
(26,460 mi^2)

LSRRS

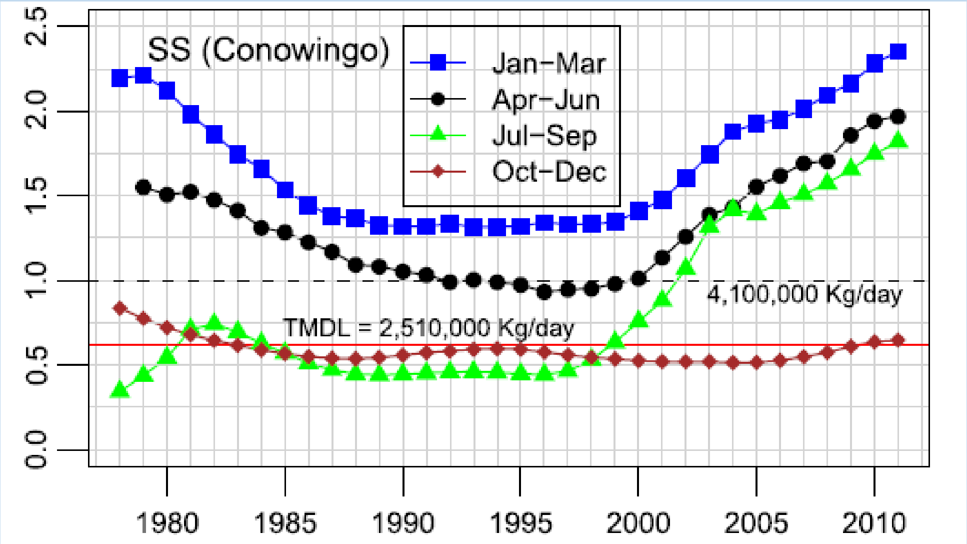
Conowingo
(27,100 mi^2)

Suspended Sediment (SS) loadings

"Flow-Normalized" Estimates by Season of Year



Upstream



Downstream

(Zhang *et al.*, *STOTEN*, 2013)

2. (cont'd) **Flow-normalized trends in particulate loadings above & below LSRRS**

Marietta + Conestoga

(26,460 mi²)

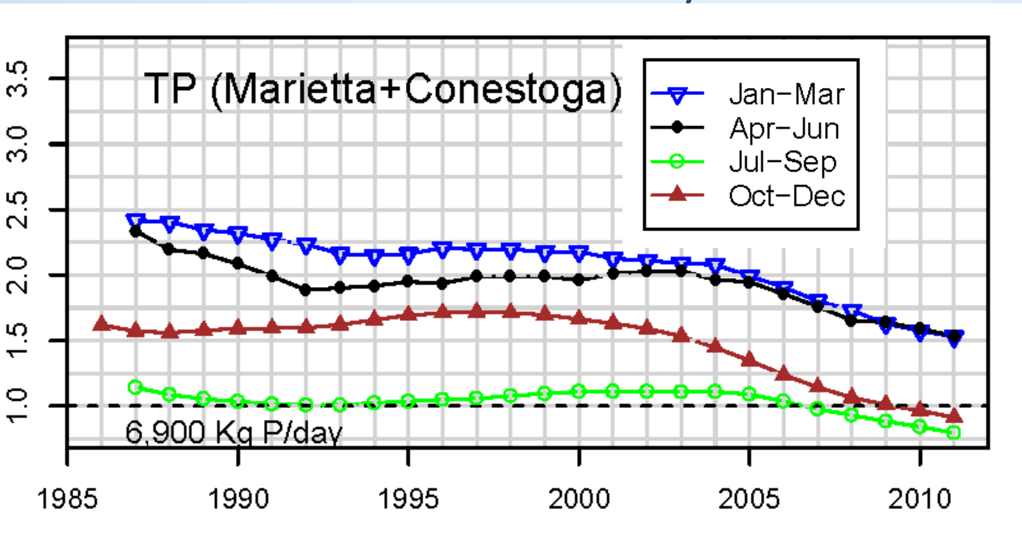
LSRRS

Conowingo

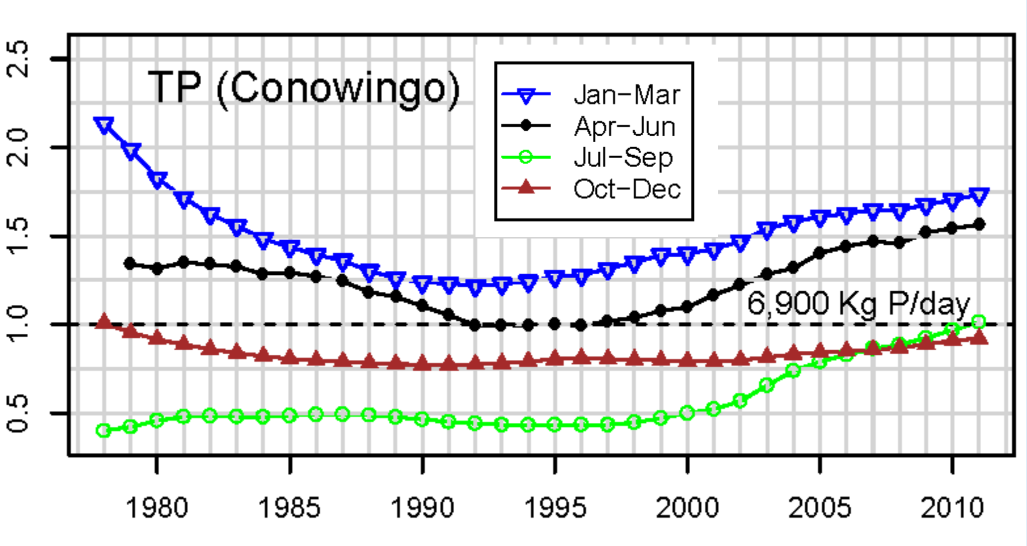
(27,100 mi²)

Total Phosphorus (TP) loadings

"Flow-Normalized" Estimates by Season of Year



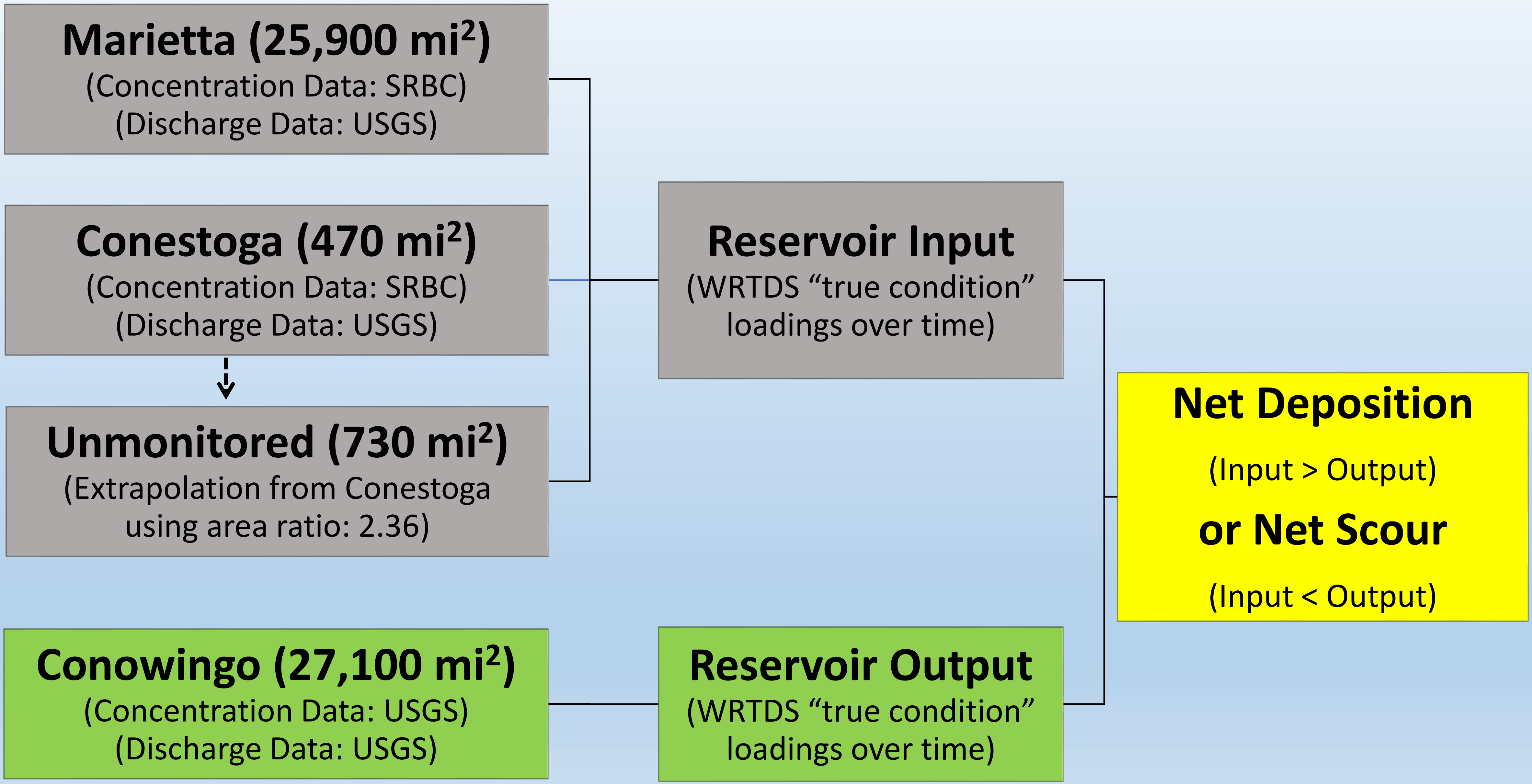
Upstream



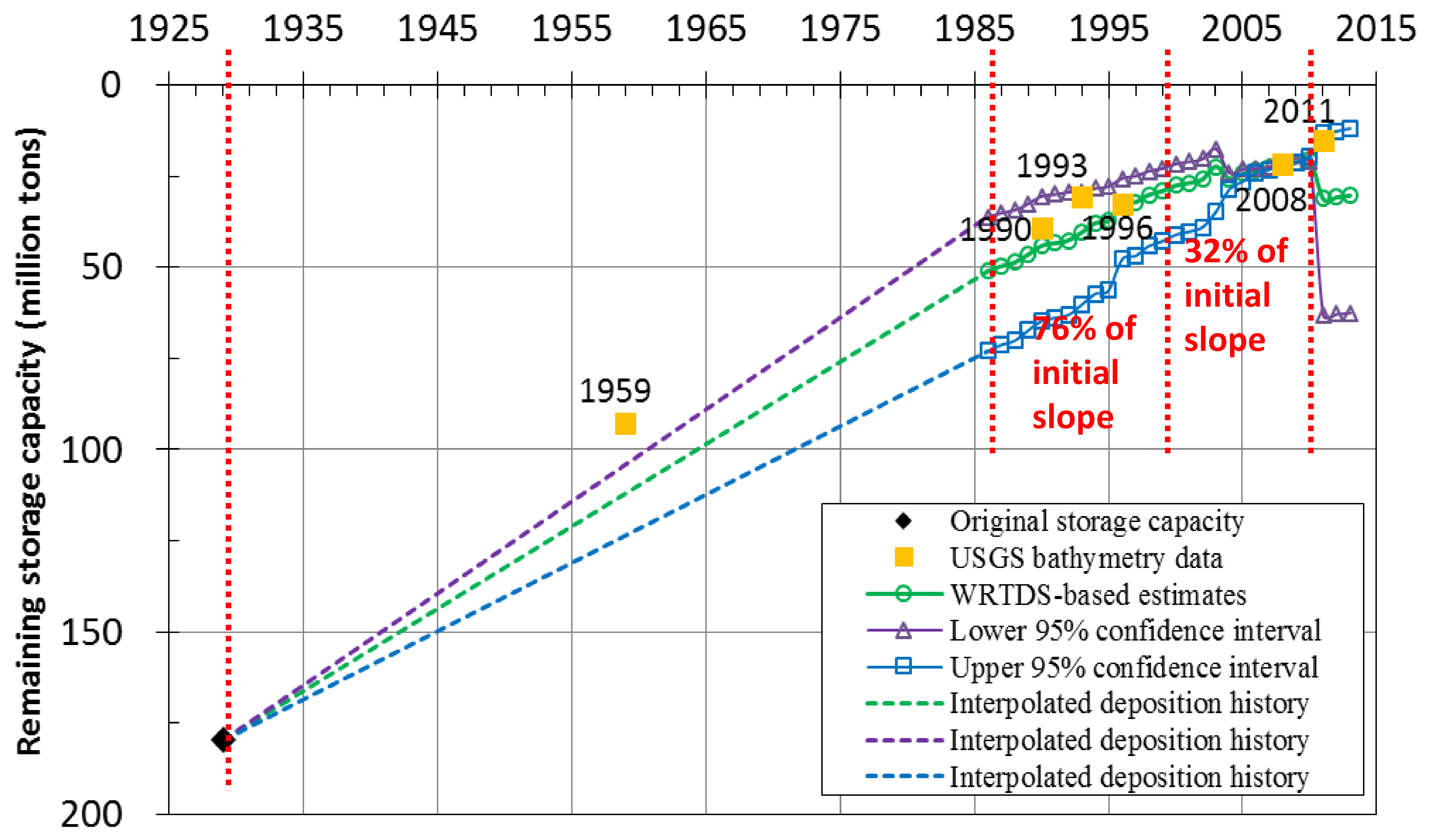
Downstream

(Zhang *et al.*, *STOTEN*, 2013)

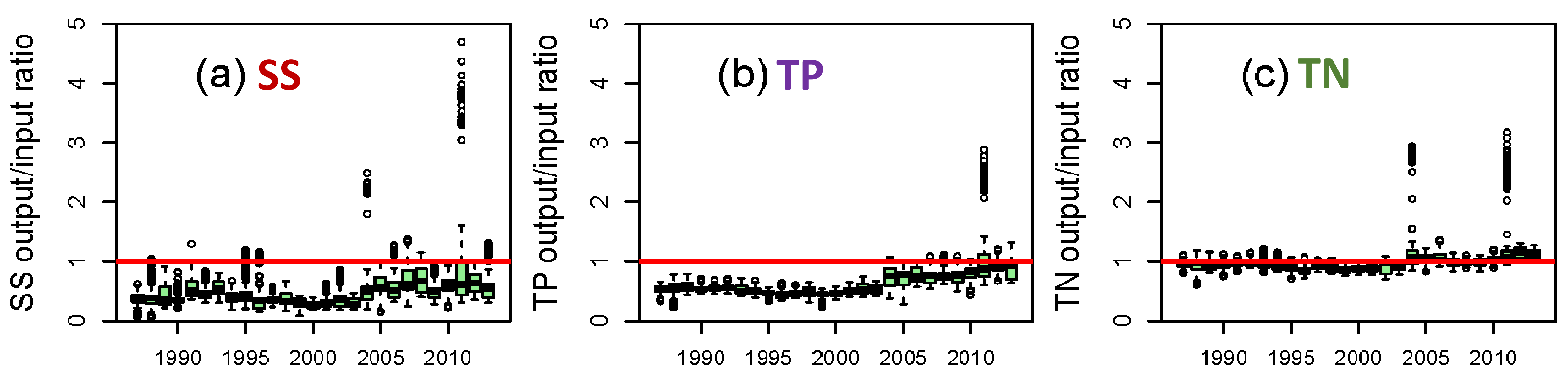
3. Input-output analyses: net deposition in the reservoirs over time



3. (cont'd) **Input-output analyses: sediment storage from mass balance**



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.

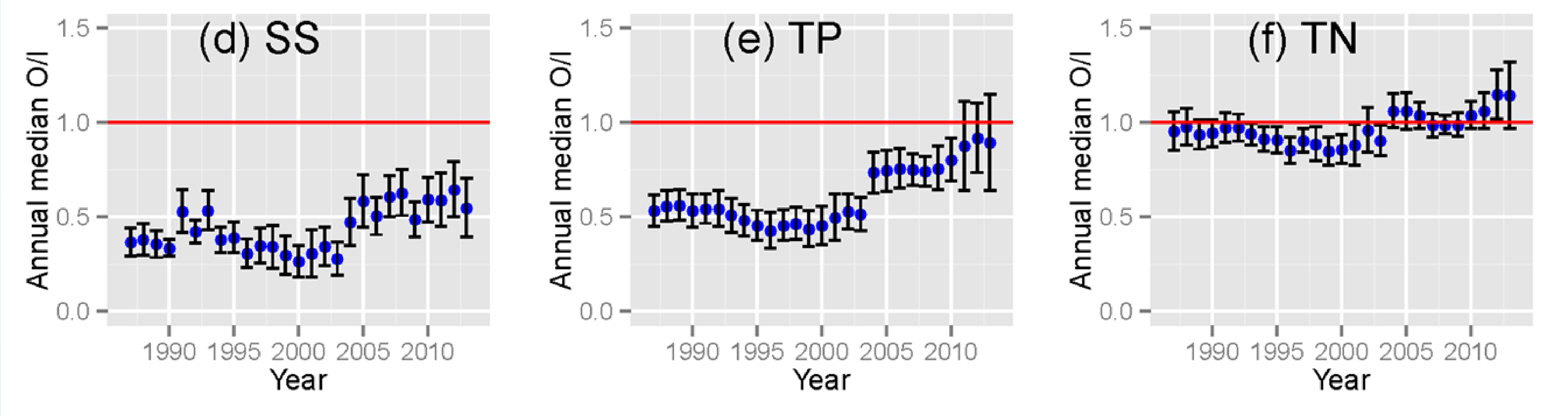
Notes:

- **TP** loads are dominated by **PP**
- **TN** loads are dominated by **DN**

3. (cont'd) Input-output analyses: uncertainty analysis on O/I ratio

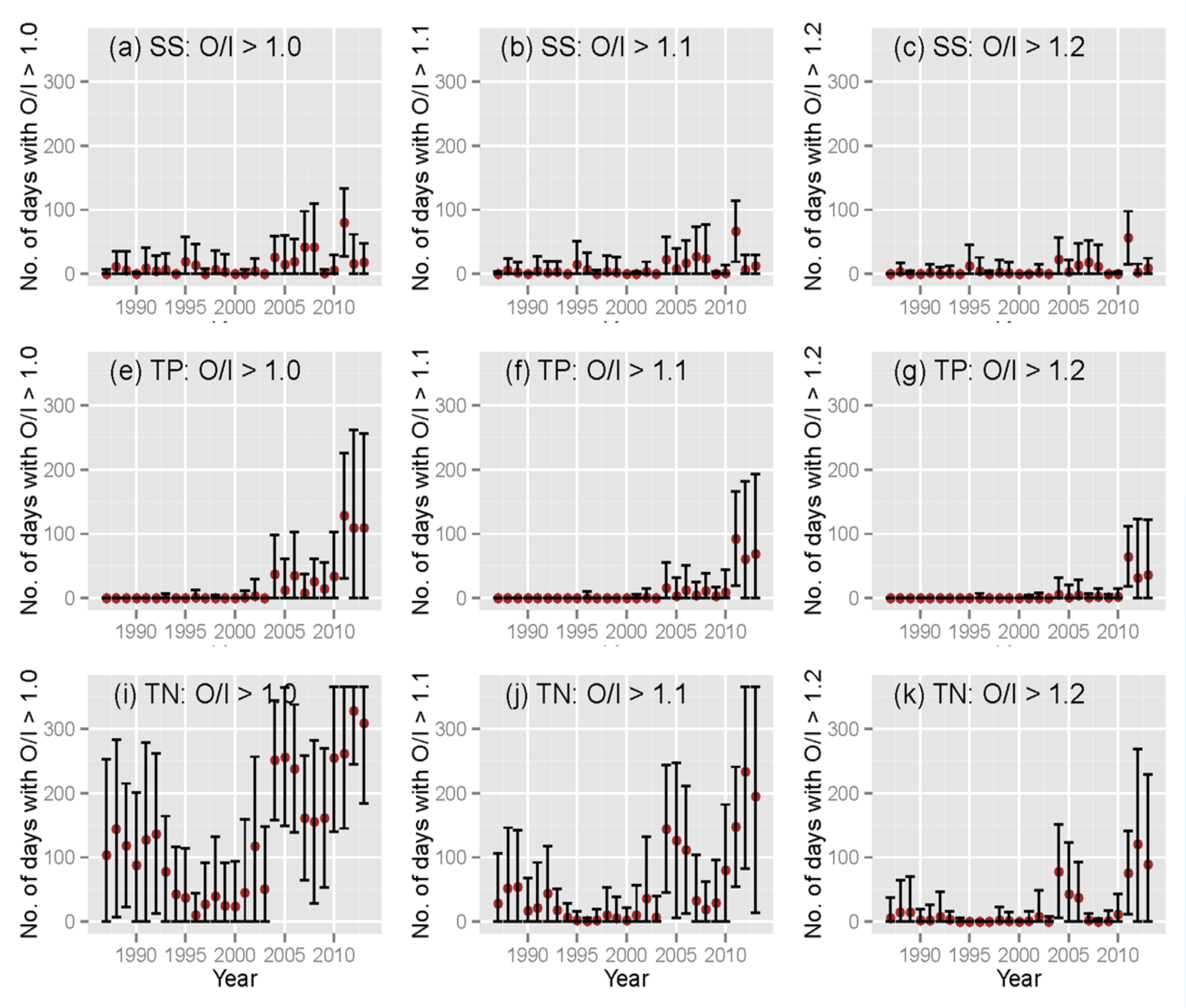
Annual median values of O/I ratio

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.

3. (cont'd) **Input-output analyses: uncertainty analysis on O/I ratio**



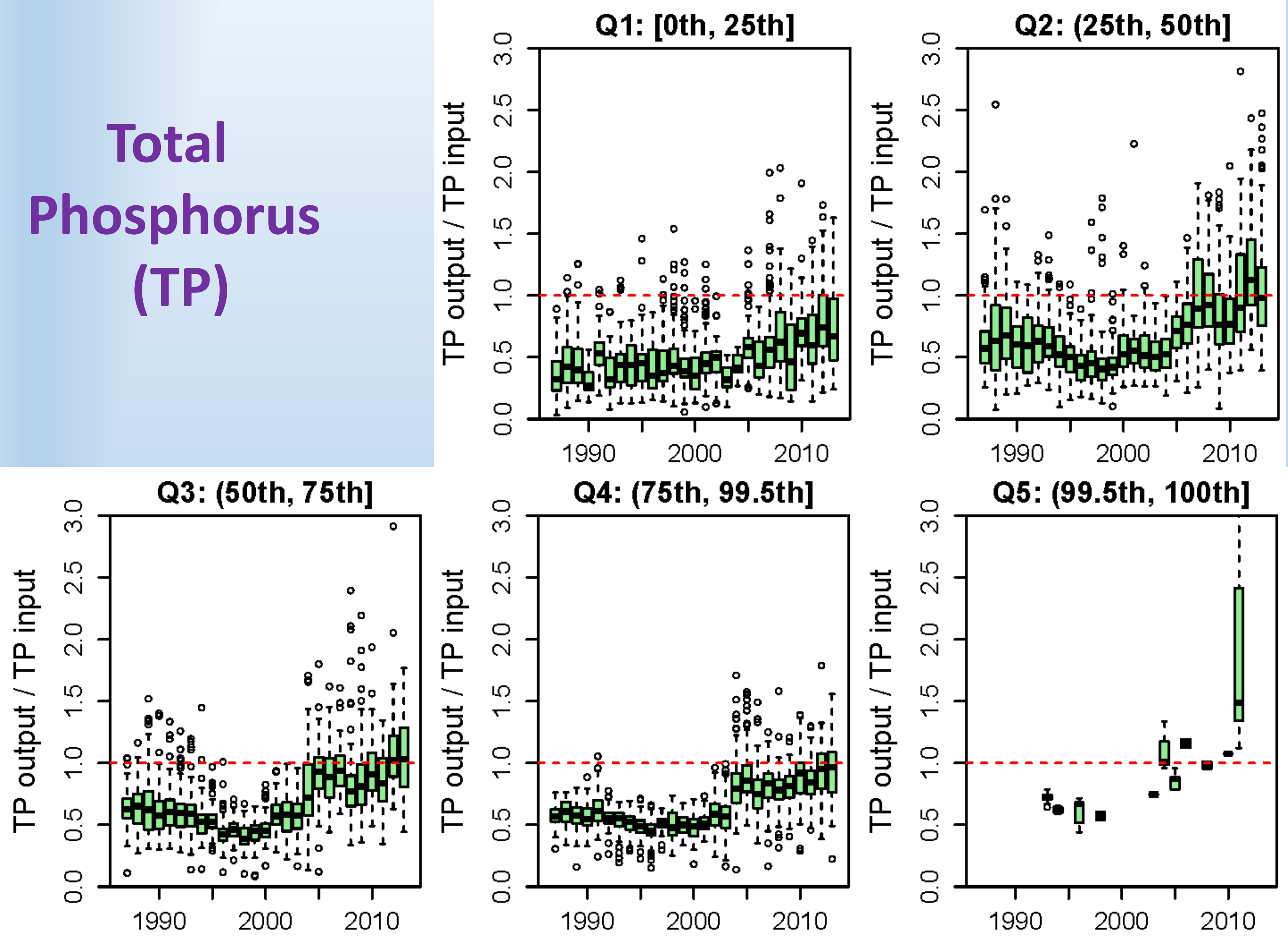
<u>Annual No. of excursions for O/I ratio for different cut-off thresholds</u>

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

Total Phosphorus (TP)



<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/

3. (cont'd) Input-output analyses: % contributions of loads by flow classes

<u>Conowingo Flow Classes</u>

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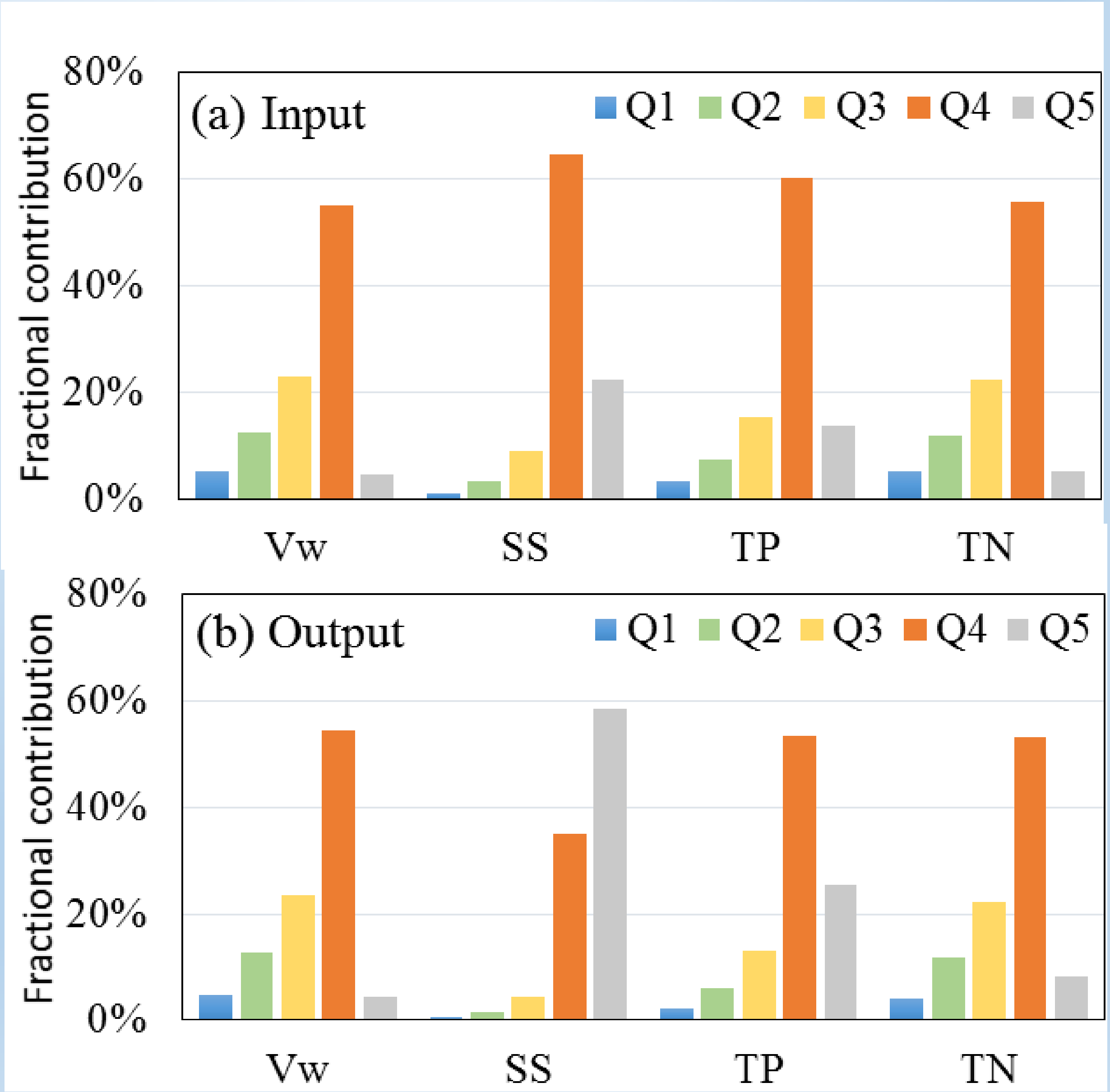
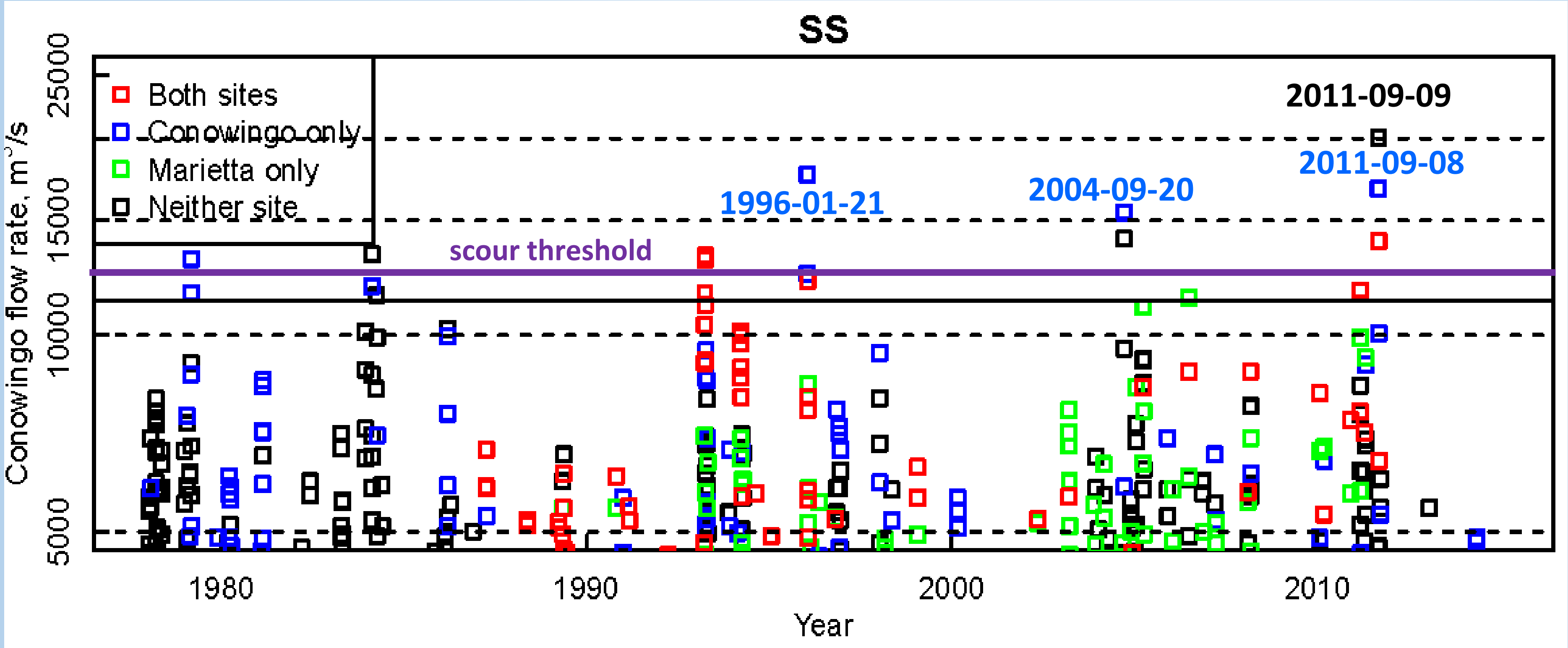
Q_4: 1,467~7,646 m^3/s;
Q_5: 7,674~20,077 m^3/s.
Q_{scour}: ~ 11,000 m^3/s

- 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.



3. (cont'd) **Input-output analyses: sensitivity to differential highflow samplings**

Q: Are these results biased by differential highflow samplings at Marietta and Conowingo?

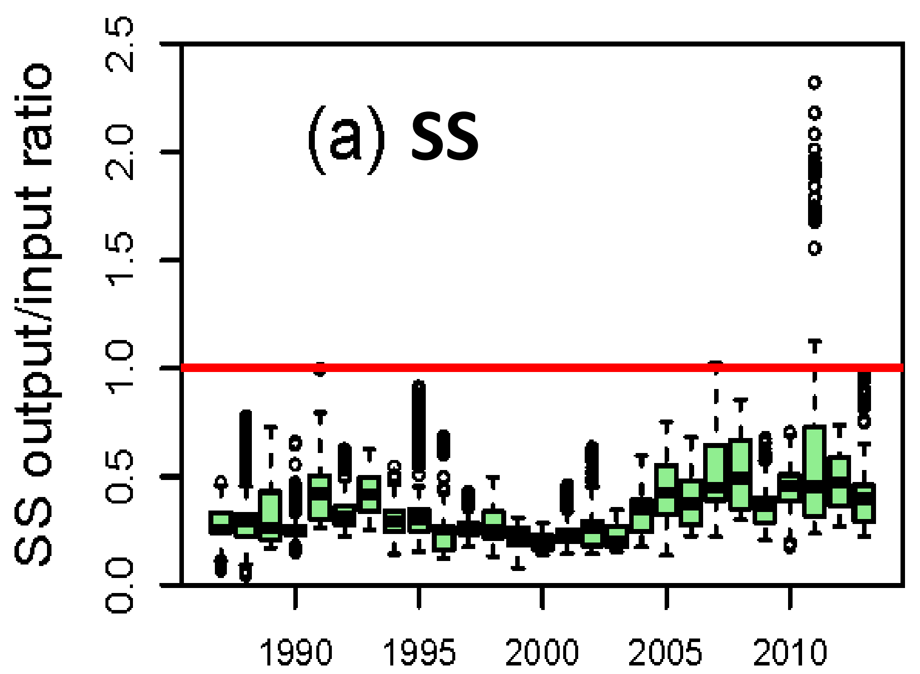


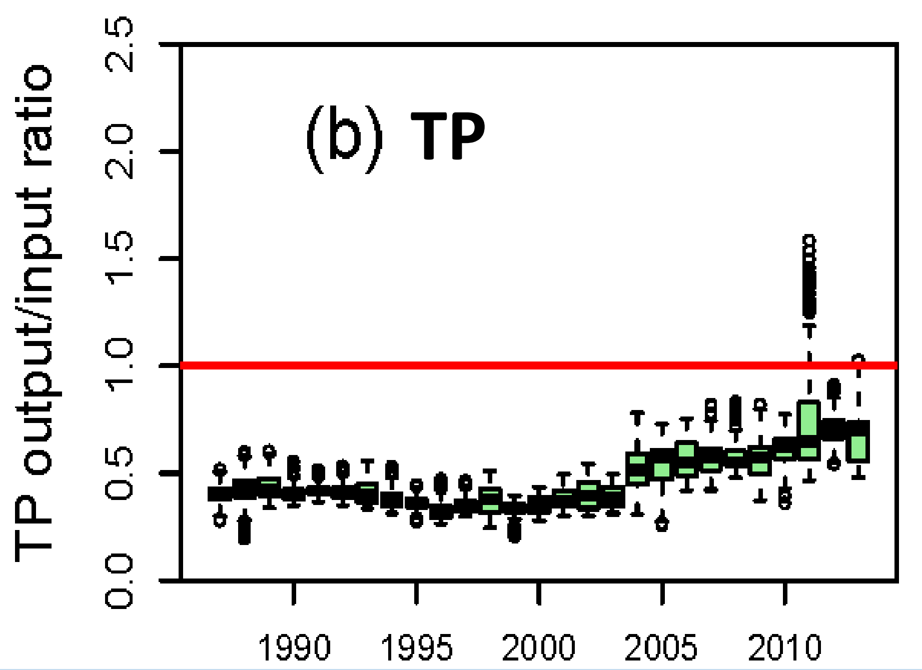
- The major distinction on highflow sampling lies in **15000-20000 m^3/s**, for which 3 dates were sampled at Conowingo (*i.e.*, ***1996/01/21, 2004/09/20, and 2011/09/08***) but not Marietta.

3. (cont'd) **Input-output analyses: sensitivity to differential highflow samplings**

Sensitivity analysis

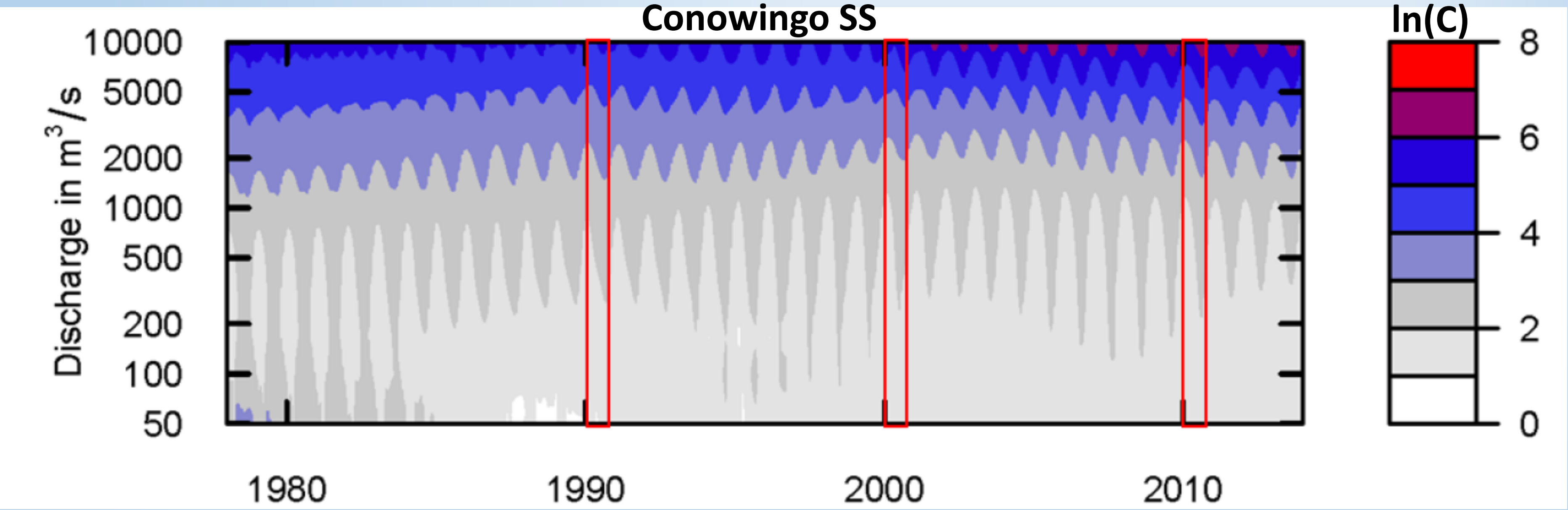
- We have re-run WRTDS model on Marietta and Conowingo by using only those samples with Q < 15000 m^3/s.
- Results are consistent with those based on all samples – SS and TP output/input ratio has been rising since the early 2000s.





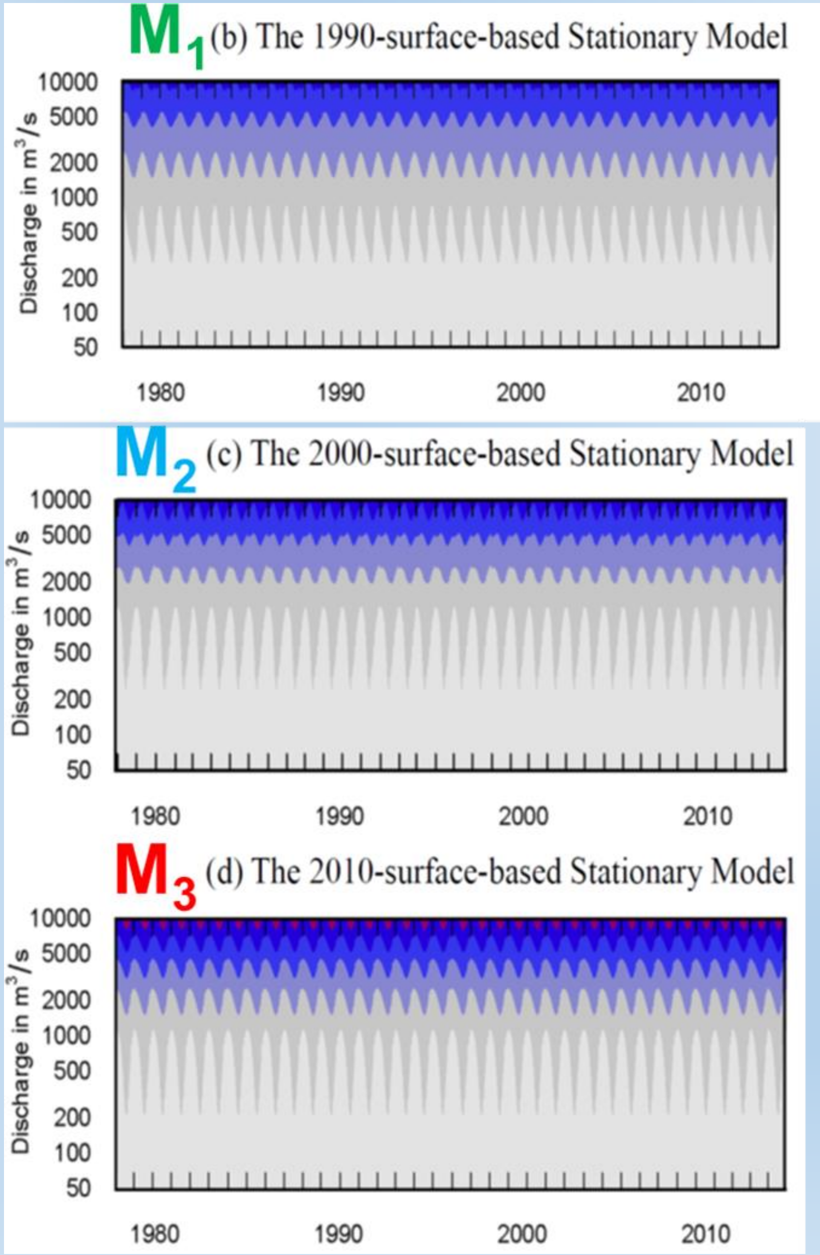
4. Stationary-model analyses: effects of changing $C(Q, t_{season})$ surface

- 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

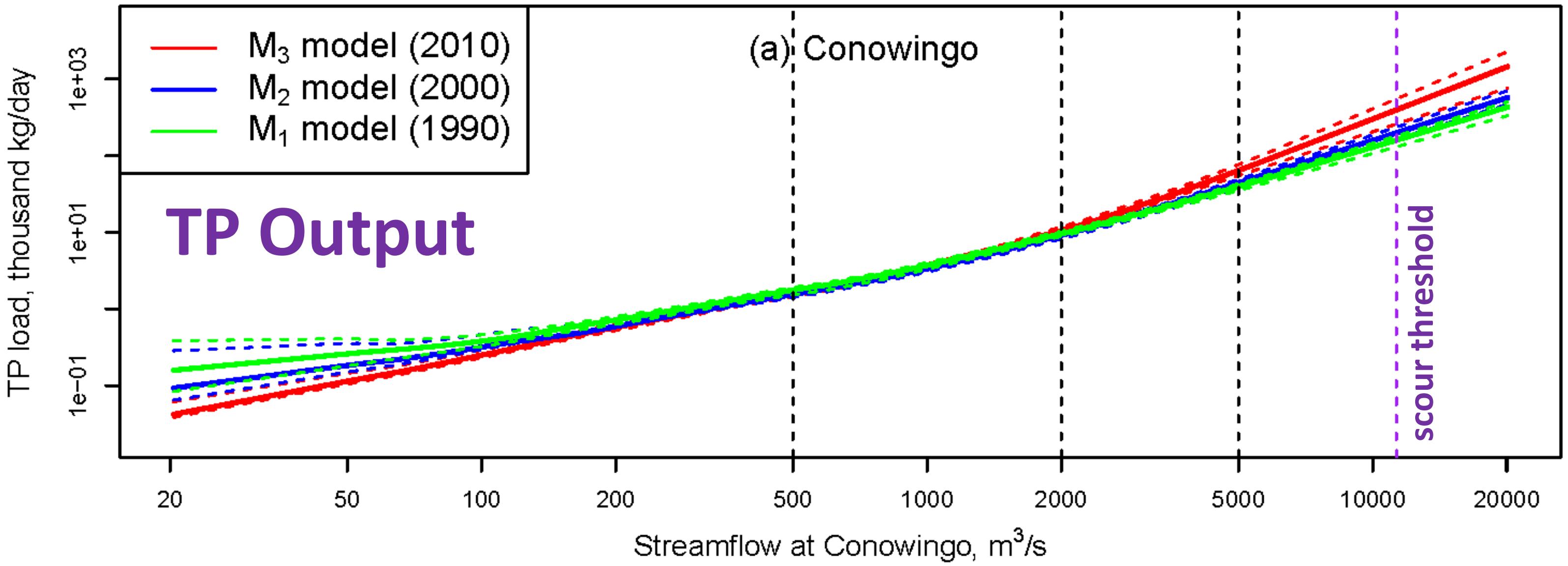


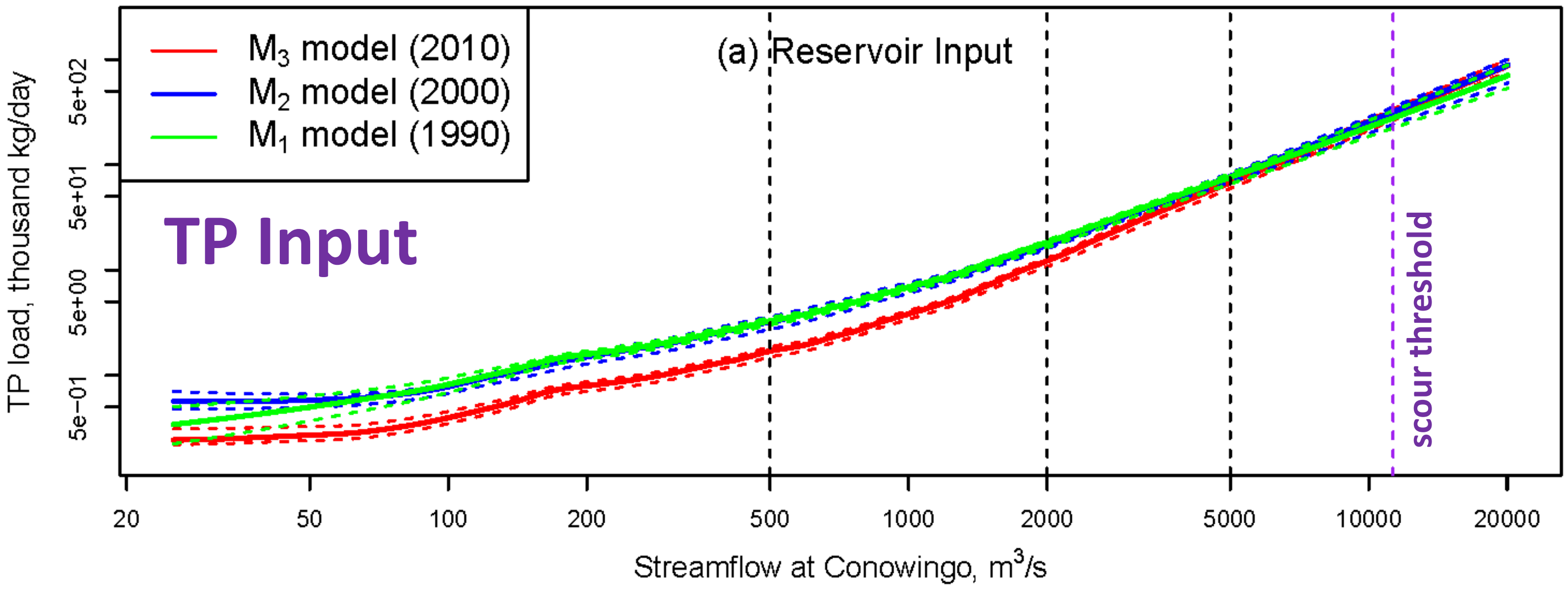
- **Step 3:** Separately repeat each of these 1-year surfaces over the full record to produce three "stationary" surfaces for the full period of record.
- **Step 4:** Apply each surface to the same full period of record (of daily Q) to estimate daily C and loads.
- **Step 5:** Conduct mass-balance analyses 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

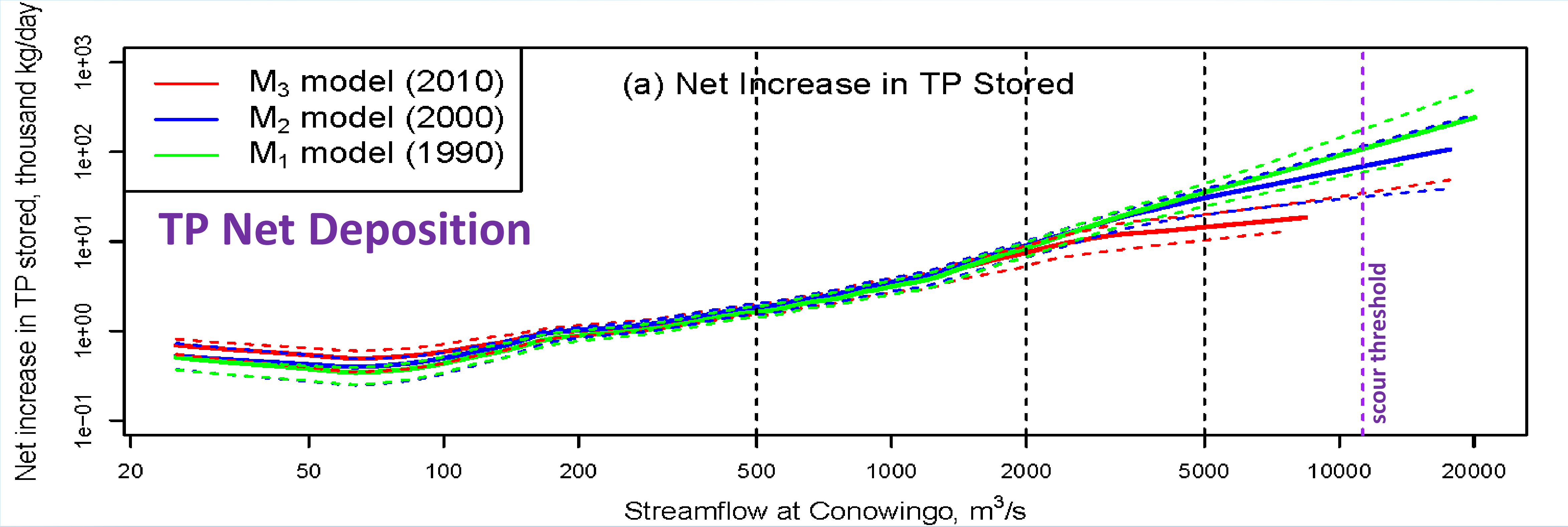
Differences in TP loading vs flow (Q) among three scenarios of stationary regression surface representing 1990, 2000, and 2010 reservoir conditions





4. (cont'd) Stationary-model analyses: load vs. Q under 3 reservoir conditions

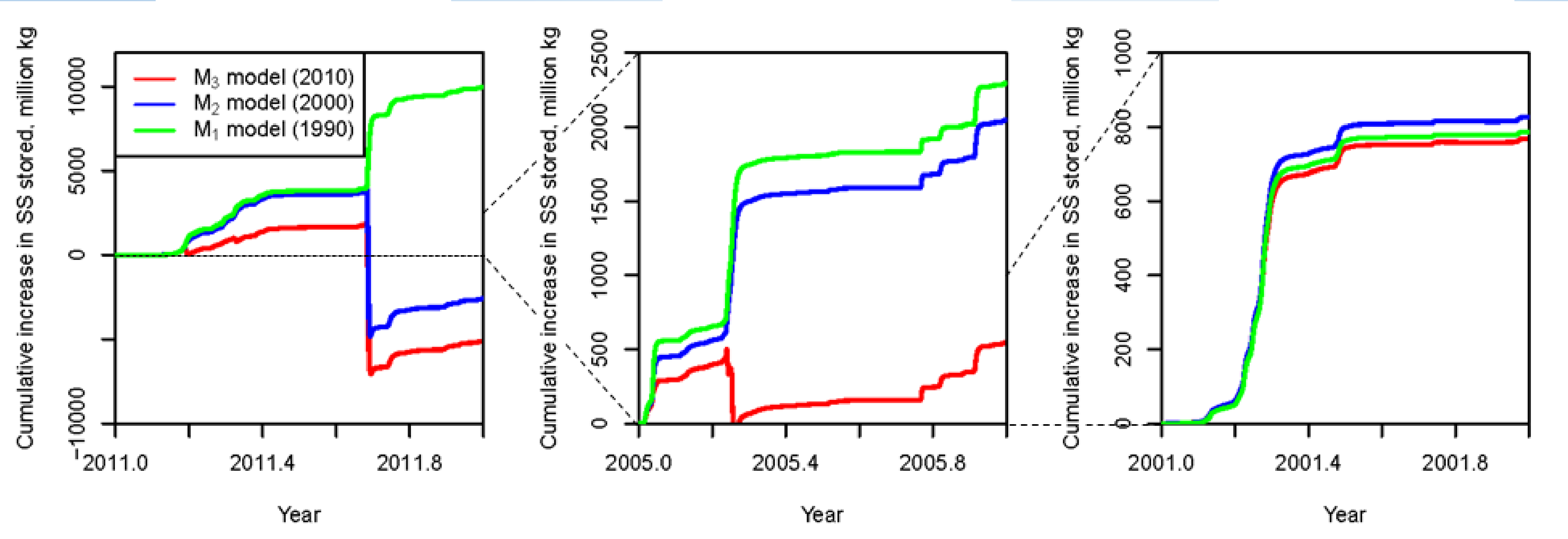
Differences in *net deposition rate vs flow* among three scenarios of stationary regression surface representing 1990, 2000, and 2010 reservoir conditions



- 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.

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

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***



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

5. Summary

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 75^{th}~99.5^{th} 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.

5. (cont'd) Summary

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.

Acknowledgements

Co-authors:

Qian Zhang (doctoral student, JHU)

Bob Hirsch (research hydrologist, USGS)

Funding:

- Maryland Sea Grant (NOAA)
- US Geological Survey
- Maryland Water Resources Research Center

Documents in **mySTAC WorkZone**:

- Zhang, Hirsch, Ball, 2016, *Environ. Sci. Technol.*, in press, doi: 10.1021/acs.est.5b04073.
- Zhang, Brady, Ball, 2013, *Sci. Total. Environ.*, 452-453, 208-221, doi: 10.1016/j.scitotenv.2013.02.012.

QUESTIONS?

Statistical Method (WRTDS)

Hirsch *et al.*, *JAWRA* (2010); Zhang *et al.*, *SOTE* (2013)

Daily flow & semi-monthly concentration at sampling sites → **WRTDS** (Hirsch et al. 2010） → Daily estimates of concentration and load

Two types of output:

A: “true-condition”

B: “flow-normalized”

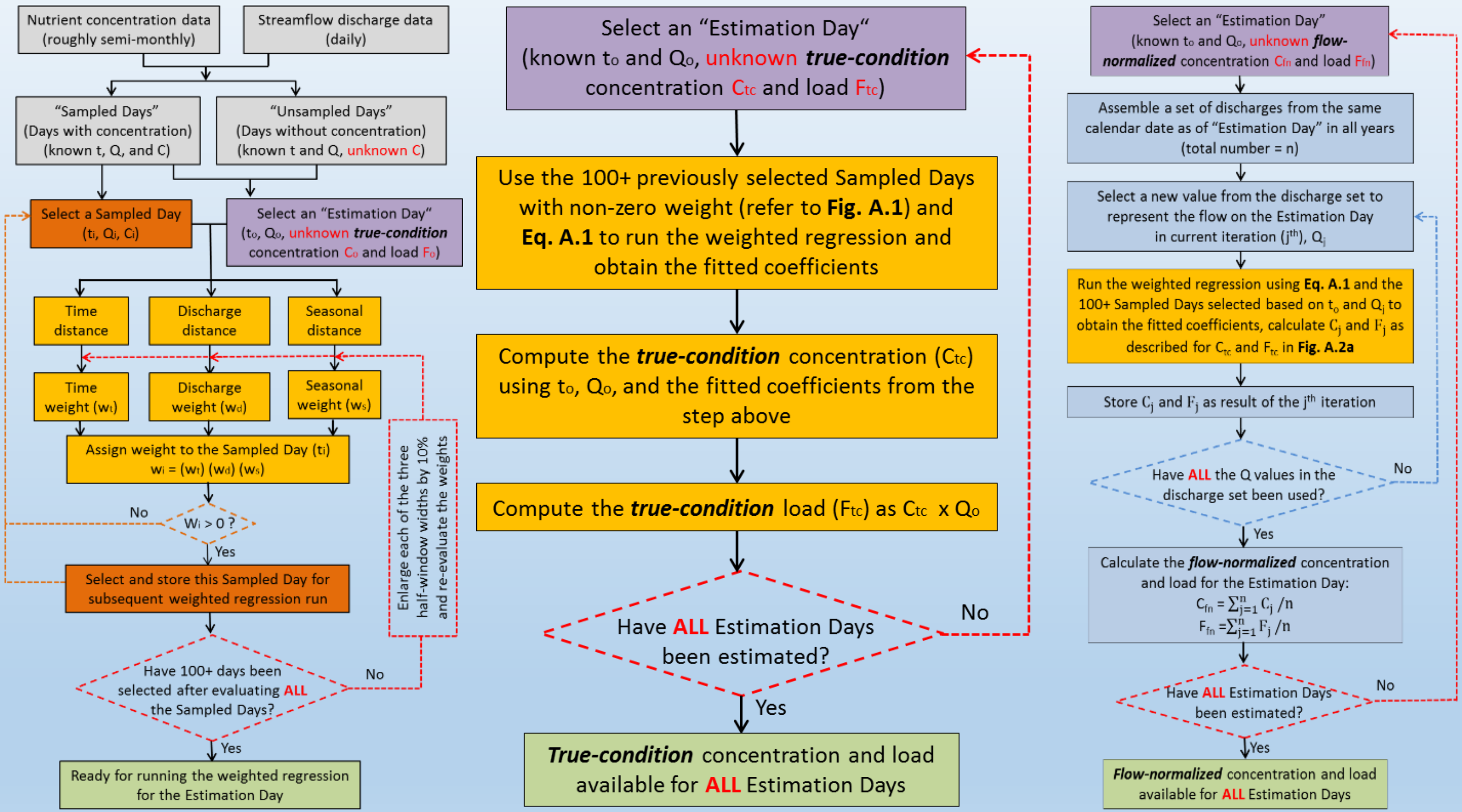
Output A: “true-condition” daily concentration and load

- 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)

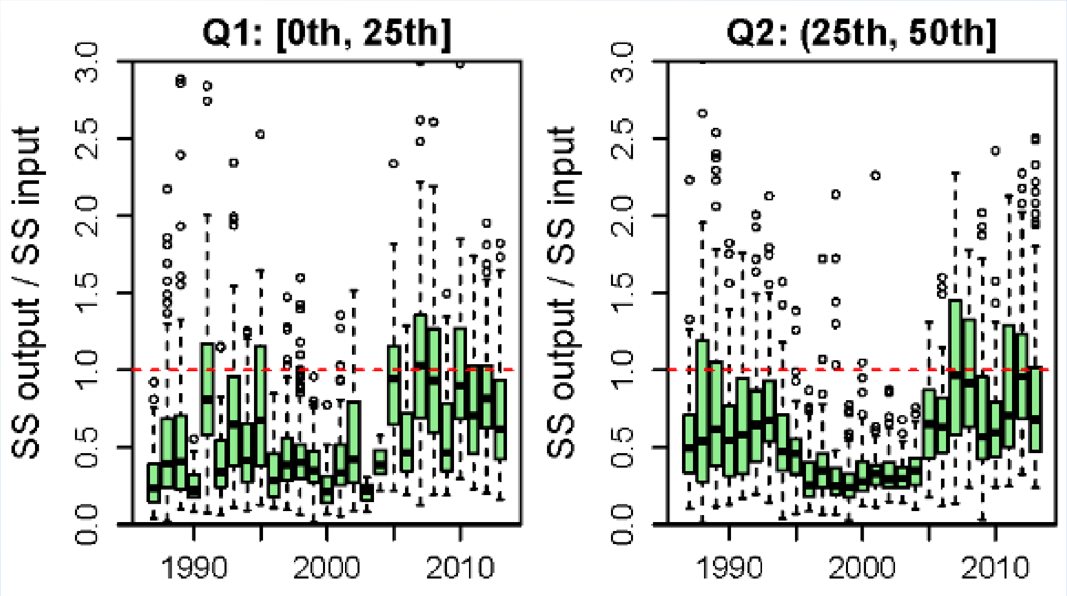
The WRTDS Model

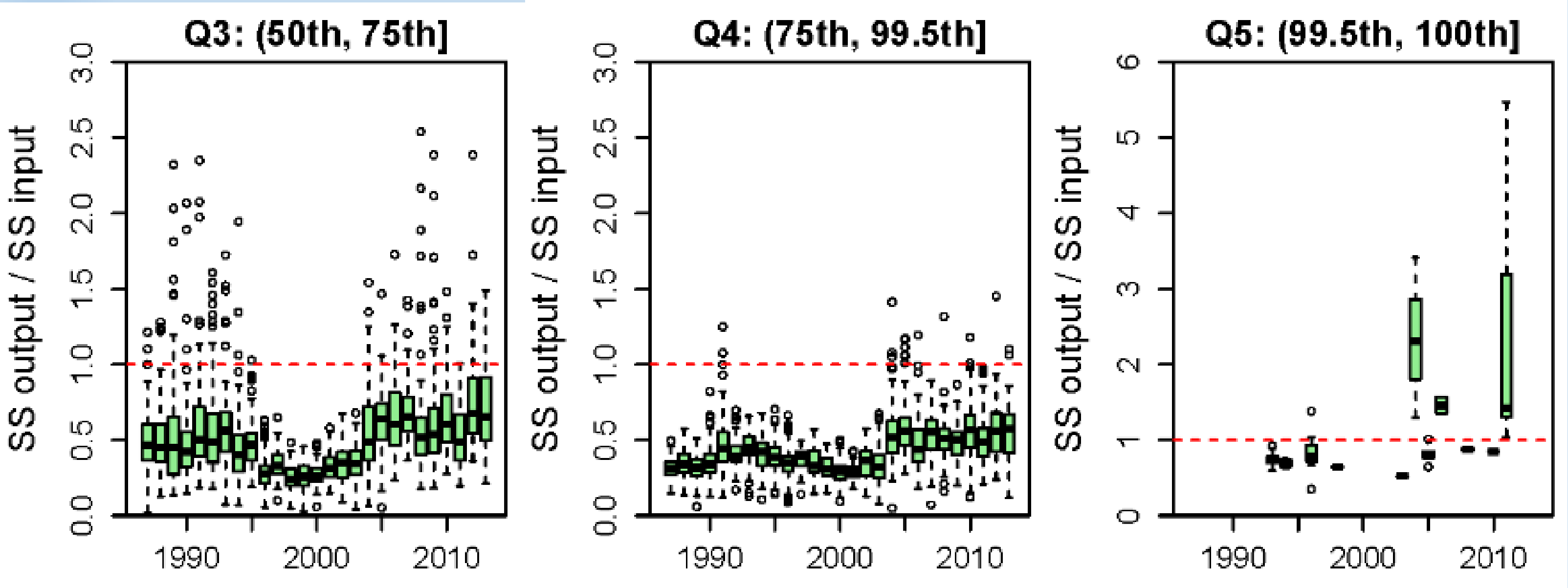


Reproduced from Zhang *et al.* (2013)

3. (cont'd) **Input-output analyses: O/I ratios by flow class**

Suspended Sediments (SS)





<u>Conowingo Flow Classes</u>

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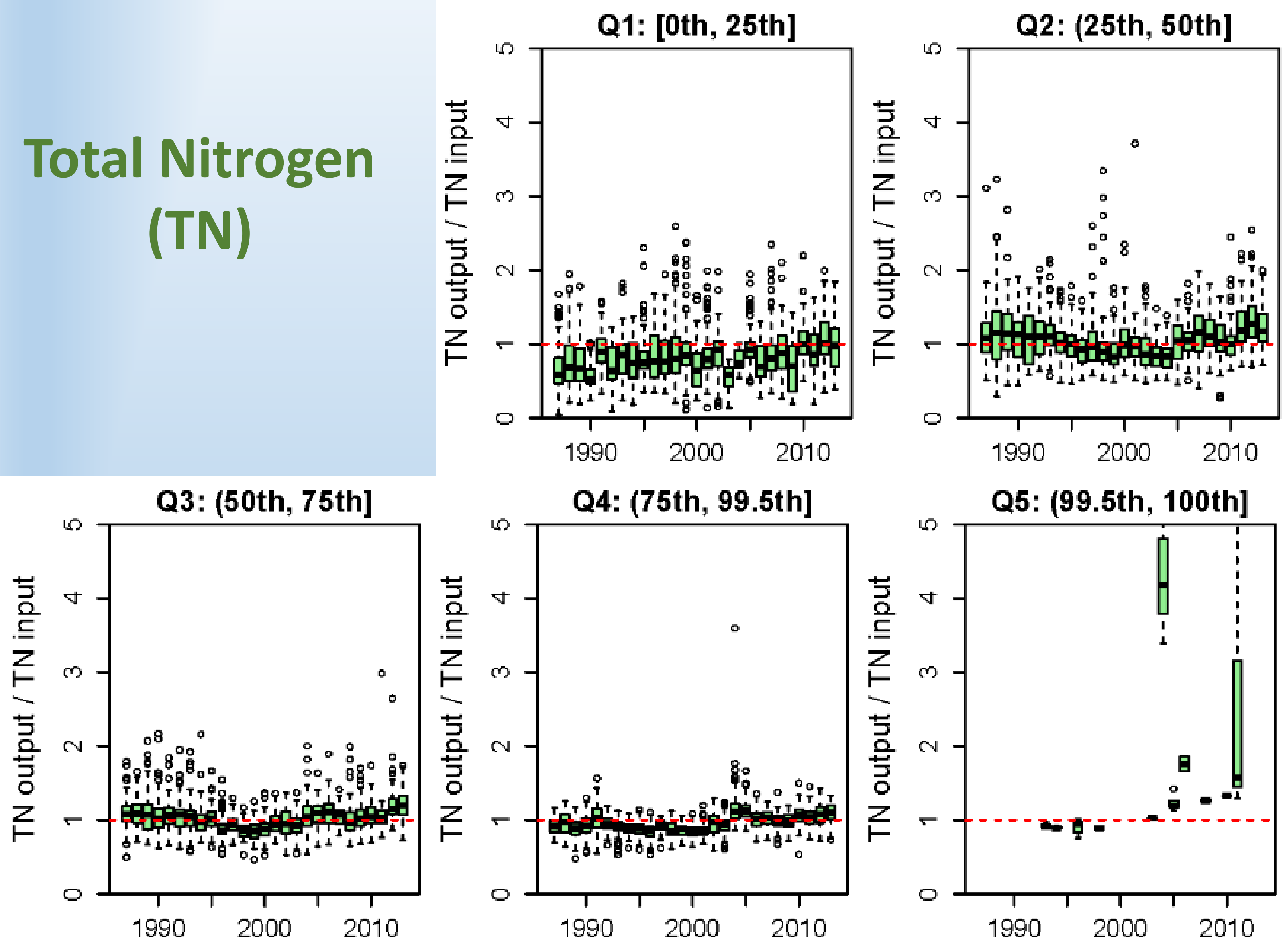
Q_{scour}: ~ 11,000 m^3/s

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: O/I ratios by flow class

Total Nitrogen (TN)



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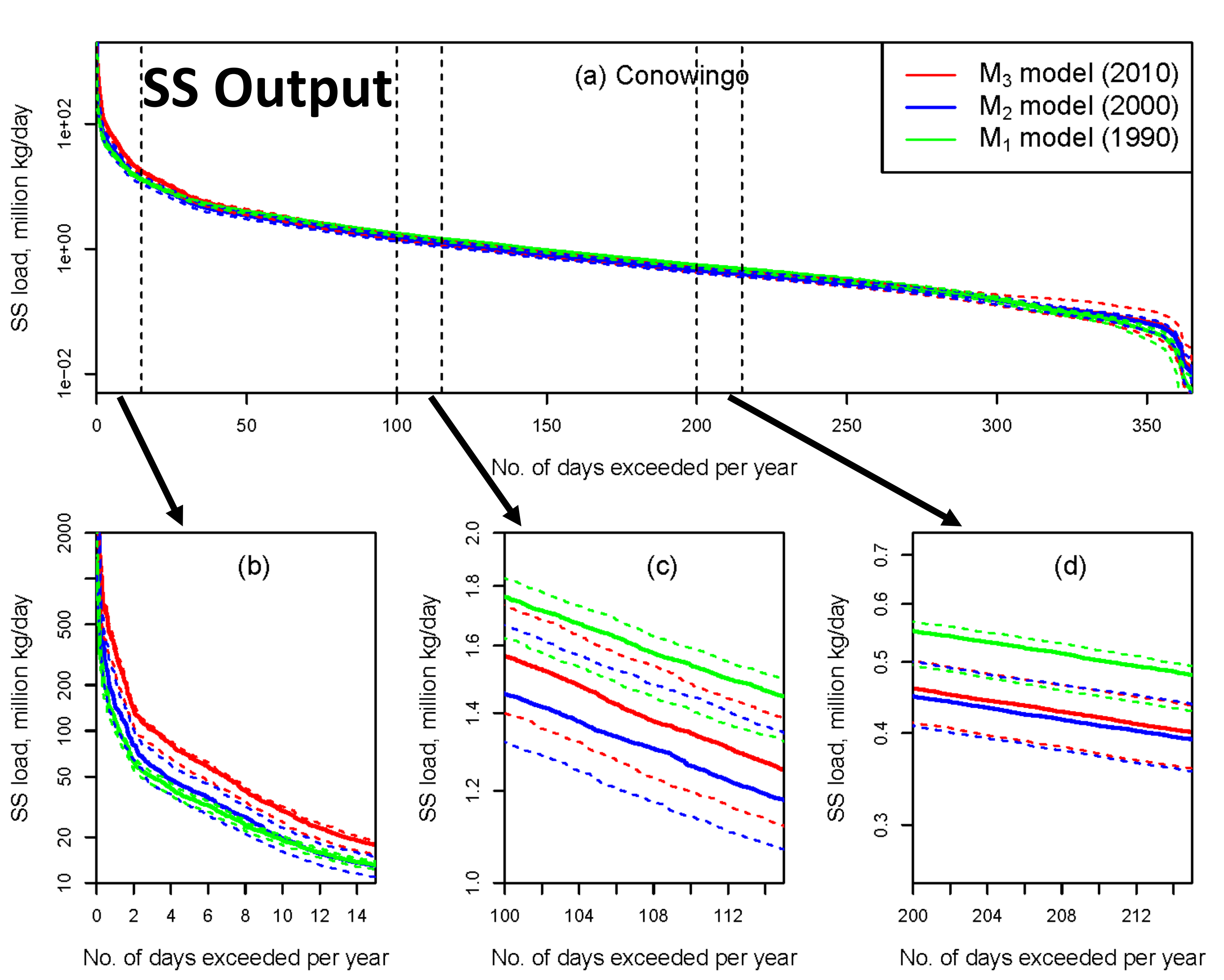
4. (cont'd) Effects of the changing WRTDS regression surface [$C(Q, t_{season})$]

Frequency Plots of Ranked Loadings



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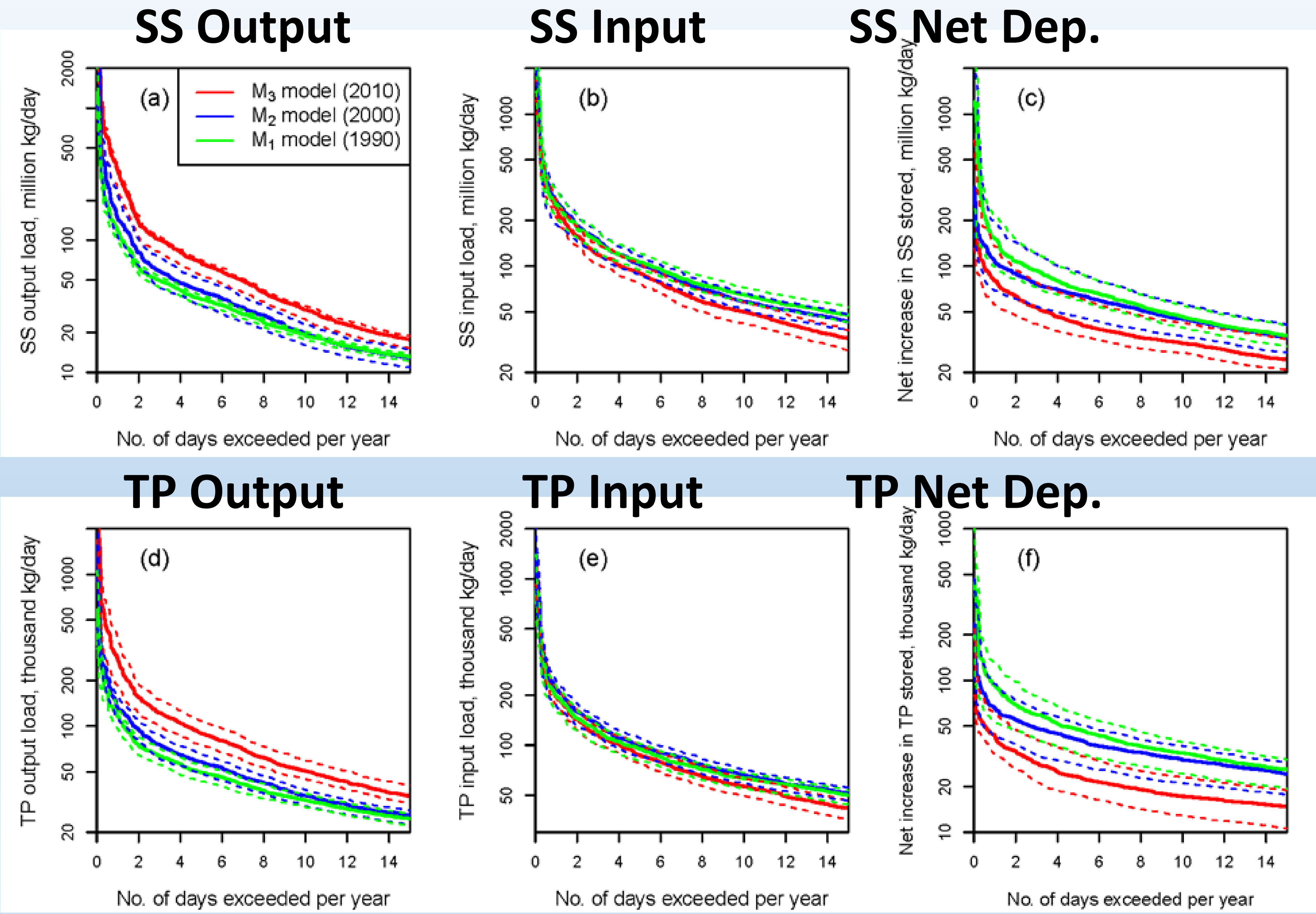
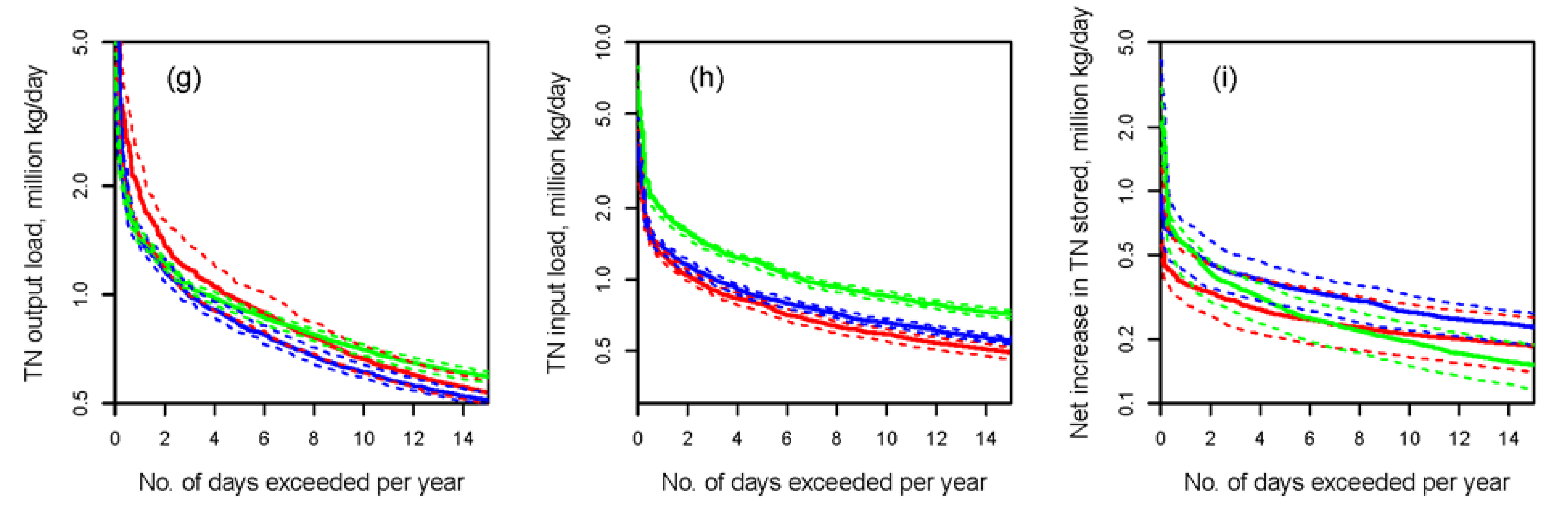


4. (cont'd) Effects of the changing WRTDS regression surface [$C(Q, t_{season})$]

TN Output   TN Input   TN Net Dep.

Frequency Plots of Ranked Loadings

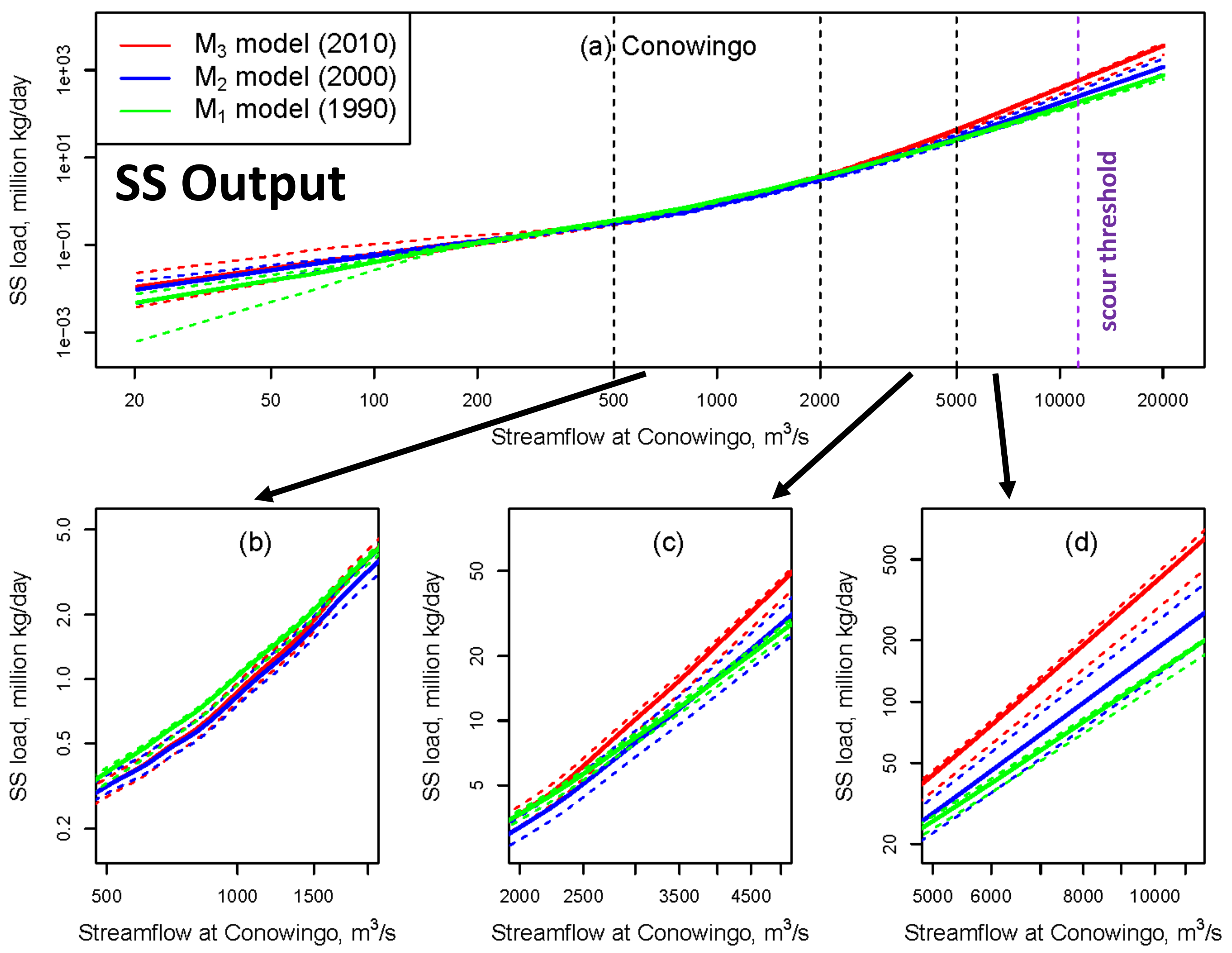


<u>Stationary-Model Summary (1)</u>

- 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



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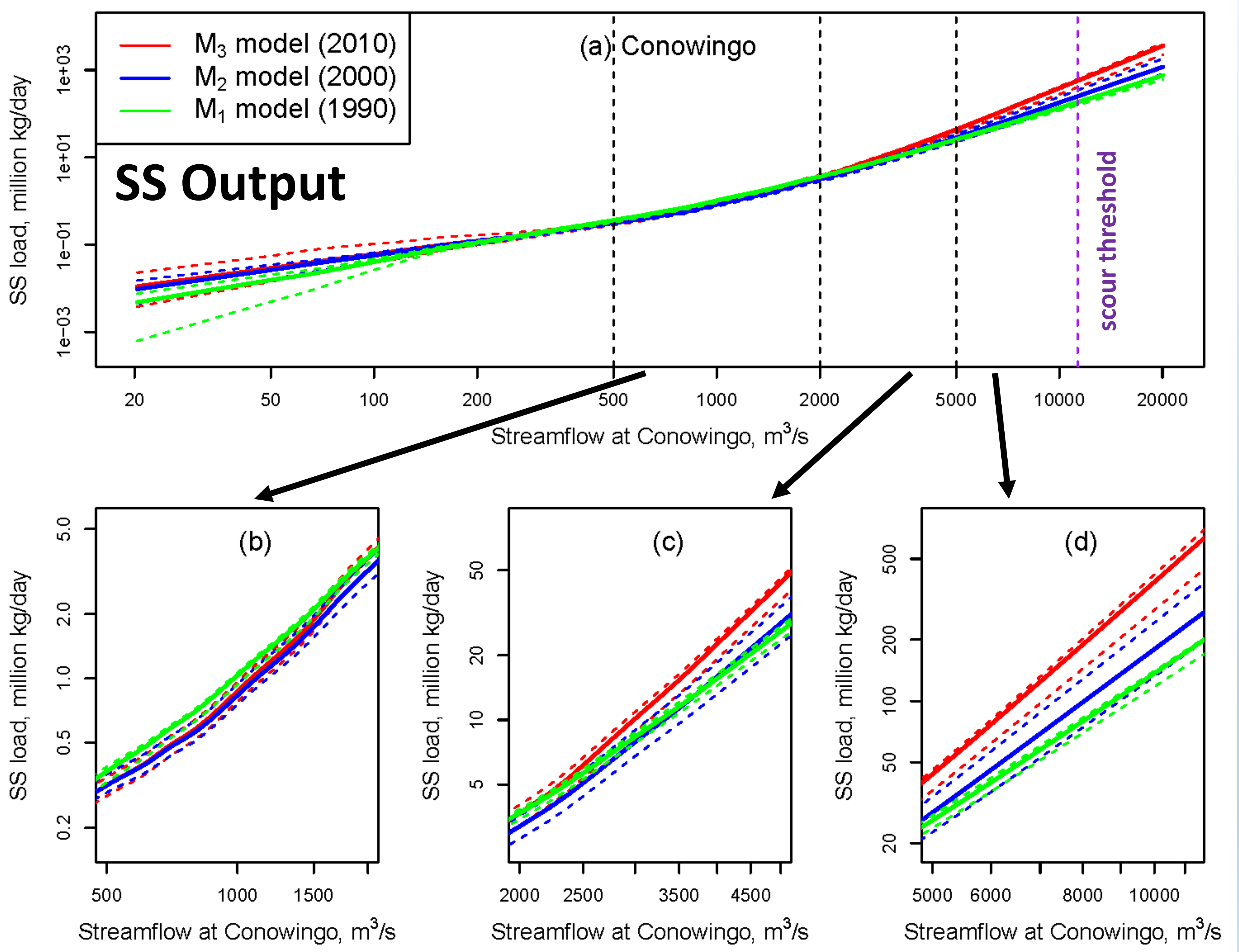
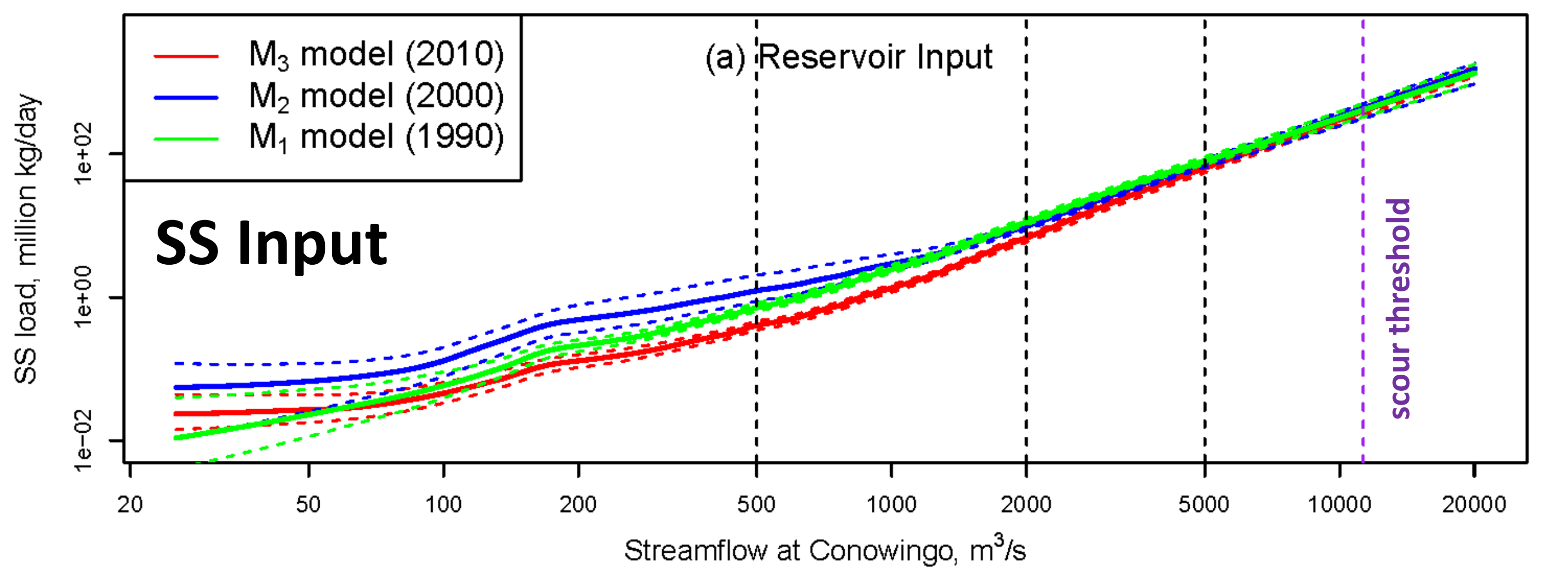
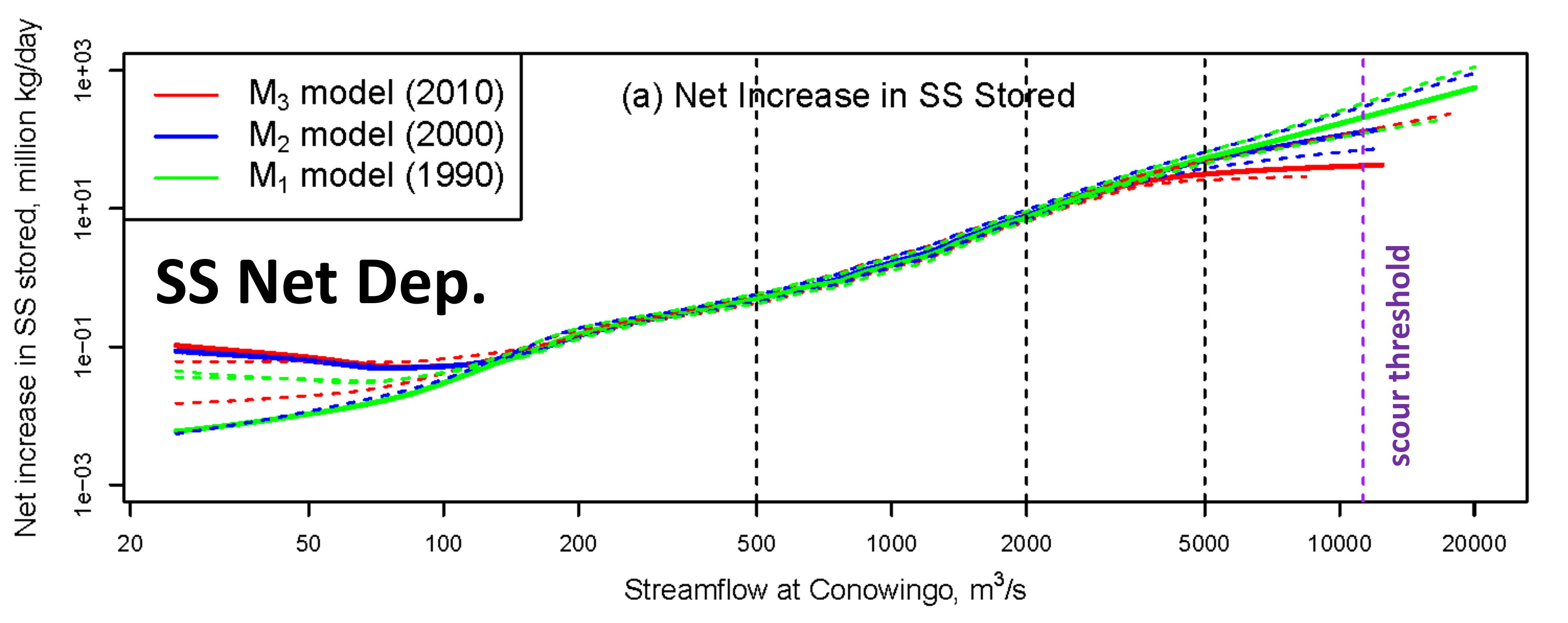


Changes in Reservoir Trapping by Flow Intervals





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