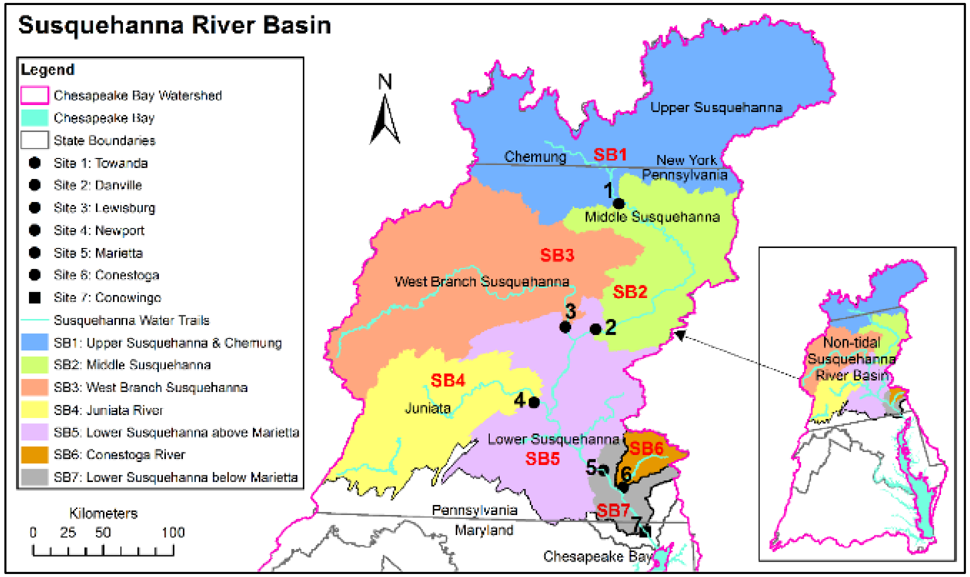

Long-term Export of Nitrogen, Phosphorus, and Sediment from the Susquehanna River Basin, USA: Analysis of Decadal-scale Trends and Sub-basin Mass Balances

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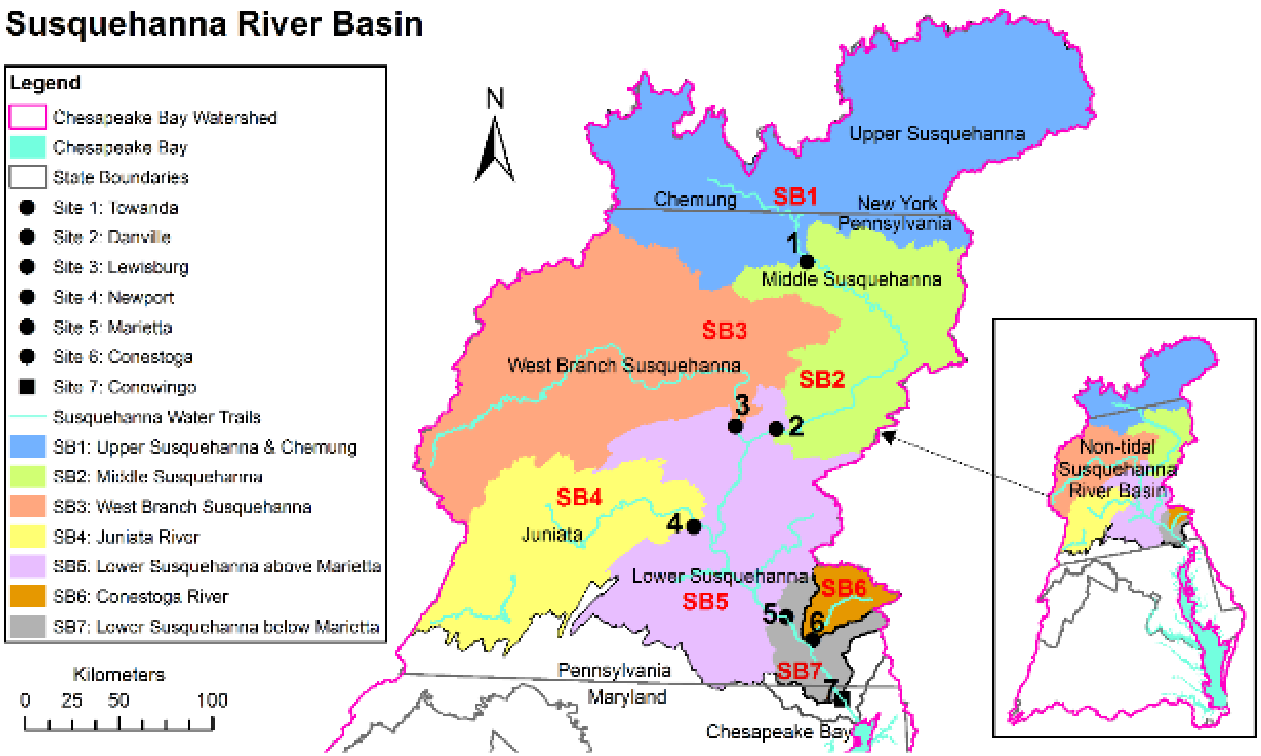
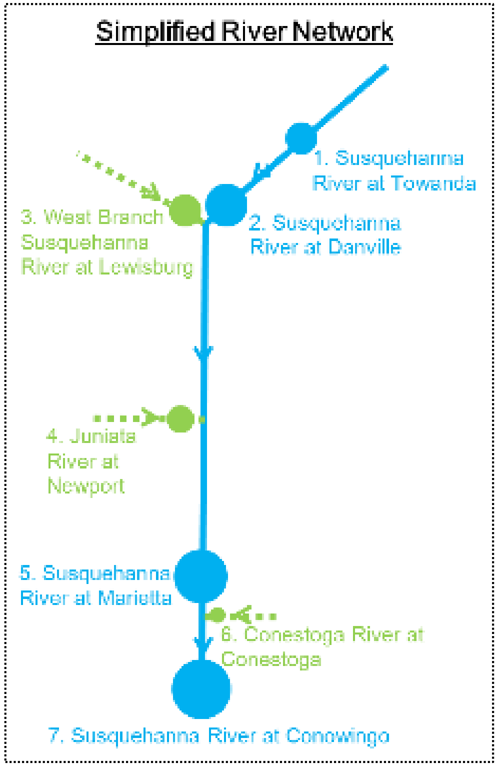
GSA Annual Meeting 2015
Baltimore MD, Nov 1

Objective

Objective: to better understand the historical progress in managing N, P, and SS exports from the Susquehanna River Basin (SRB) -- the largest tributary to Chesapeake Bay.

- Trend analysis: N, P, and SS loadings at seven sites.
- Mass-balance analysis: spatial budgets of major sub-basins, with focus on streamflow and land use effects on export.





At each site

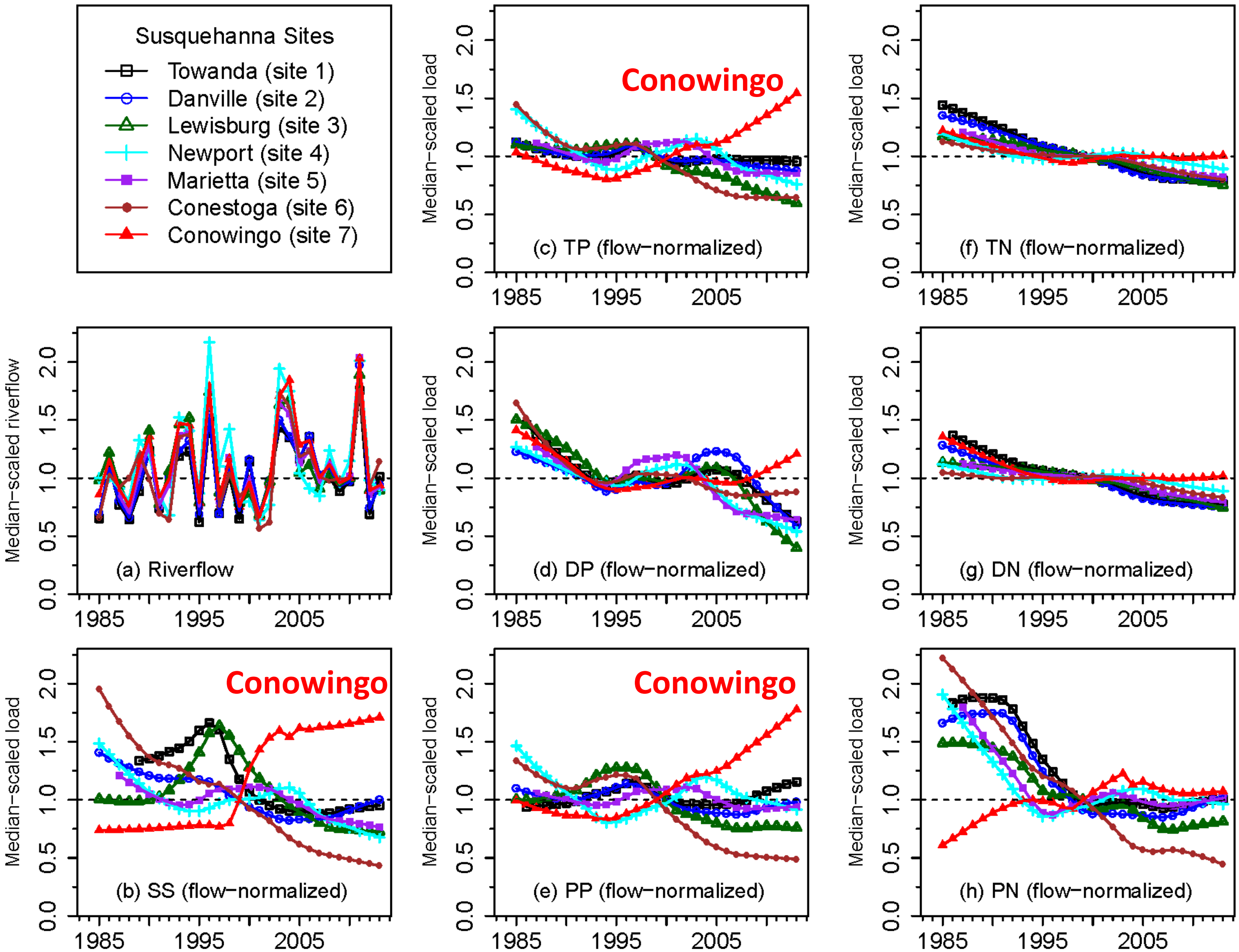
- **Monitoring data**: 25-40 sampled days per year on average; 1980s-2013.
- **WRTDS** ("Weighted Regressions on Time, Discharge, and Season", Hirsch *et al.*, 2010) was run to estimate the daily true-condition and flow-normalized loadings* for each constituent, *i.e.*, SS, TP, TN, DP, and DN. [*"Loading" = riverine fluxes, unless otherwise stated.]
- Particulate nutrients: PP = TP – DP; PN = TN – DN.
- Annual loading / drainage area = annual riverine yield (kg km^{-2} yr^{-1}).

For each sub-basin

- **Riverine input load:** flux entering the river reach = flux passing the monitoring site at the *upstream limit* of the river reach + flux entering from tributaries to that river reach (if any). [≠ Watershed source input!]
- **Riverine output load:** flux passing the site at the *downstream limit* of the river reach.
- **Net storage** = riverine input loading – riverine output loading.

Q1: What have been the general patterns of long-term trends in riverine nutrient/sediment loadings? In particular, have trends been consistent (a) across the monitoring locations and (b) between dissolved and particulate species?

Trend Analysis: Flow-normalized Loads



Trend Analysis: Flow-normalized Loads

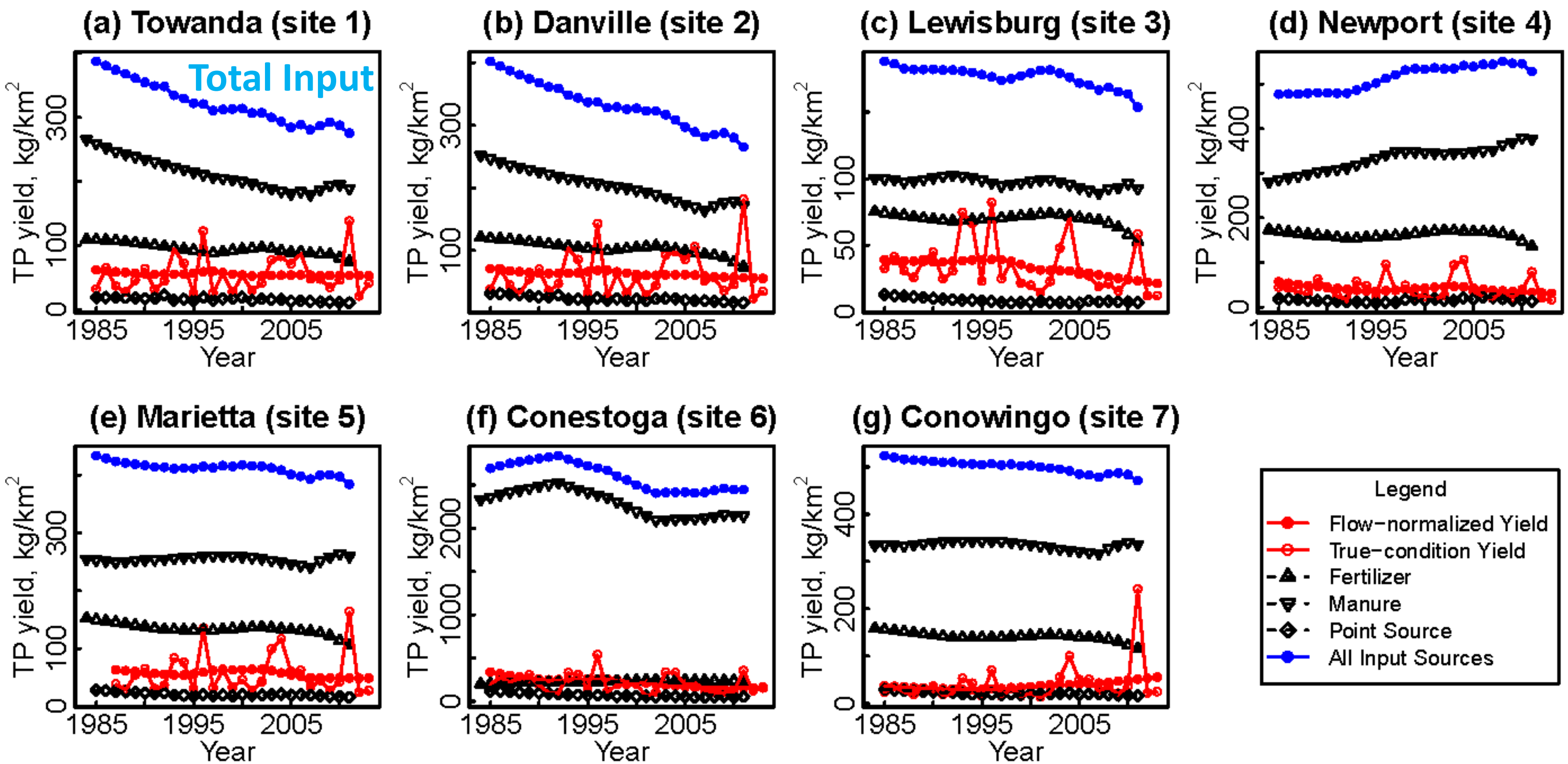
- **Upstream declines:** general declines at all sites upstream of the Conowingo Reservoir → indicating watershed-wide progress after decades of continued controls on various source inputs, including:
  - WWTP upgrade since the 1980s (CBP, 1998),
  - P-detergent ban in PA in 1990 (Litke, 1999),
  - P-based nutrient management (Weld *et al.*, 2002),
  - PA's Nutrient Management Act in 1993 and subsequent amendments for regulating CAOs/CAFOs (PA DEP, 2004),
  - Co-benefit of Clean Air Act on NOx (Linker *et al.*, 2013).

- **Conowingo rises (SS, TP, PP, PN):** primarily driven by decreased reservoir trapping capacity (Hirsch, 2012; Zhang *et al.*, 2013) and possibly associated effects on biogeochemical transformations due to reduced residence time within the reservoir system.

Q2: What have been the general changes in watershed source inputs* and how have their magnitudes compared with those in riverine loadings?

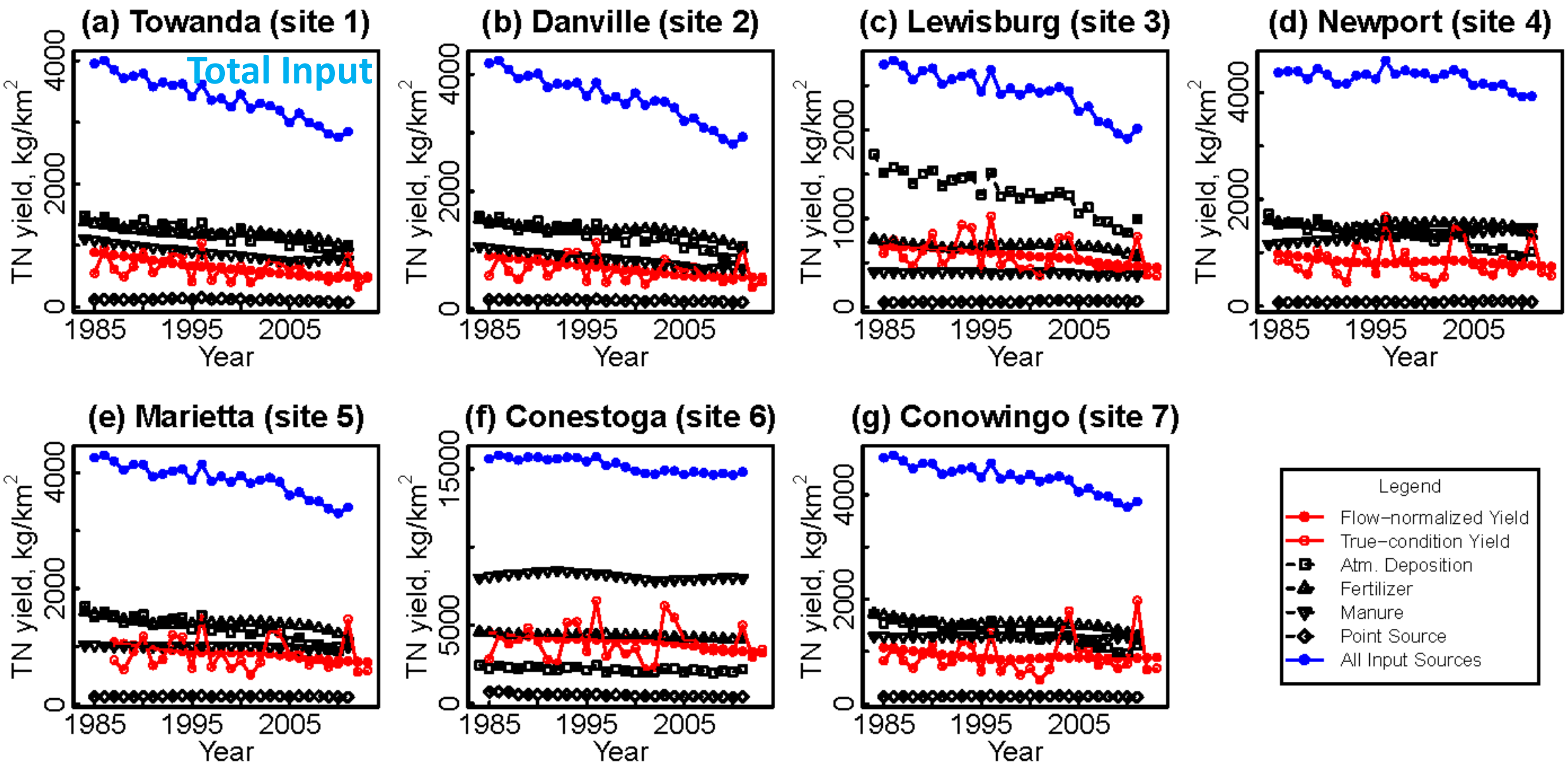
(*Based on input data from the Chesapeake Community Modeling Program, as provided by **Gary Shenk, Guido Yactayo, and Gopal Bhatt**.)

Changes in TP Source Input (1987-2011)



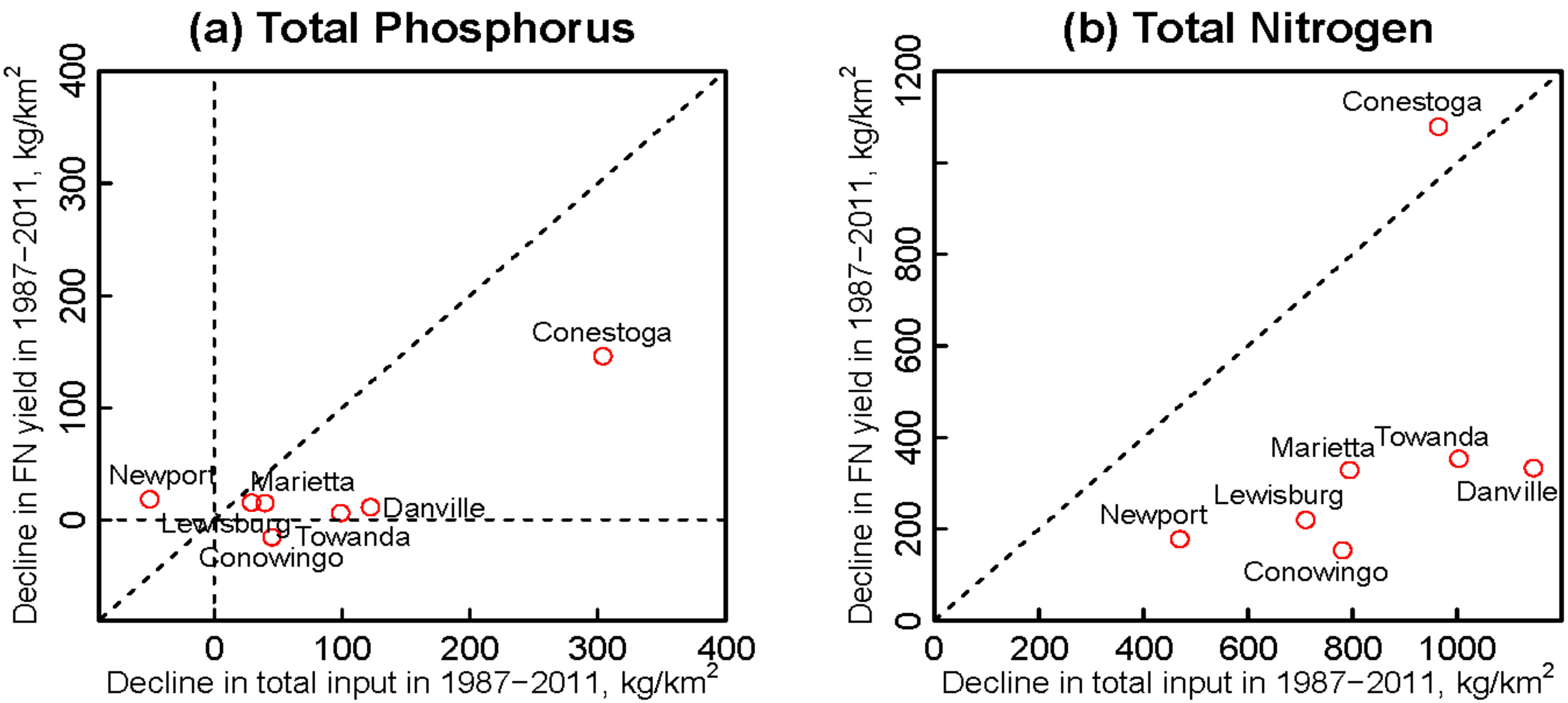
- **TP total source input:** declines at all sites except Newport, with the largest decline at Conestoga.
- **Individual sources:** negative Δ for 17 of 21 source-site combinations; dominated by manure and fertilizer reduction.
- **FN riverine yield:** negative Δ at all sites except Conowingo, with the largest decline at Conestoga.

Changes in TN Source Input (1987-2011)



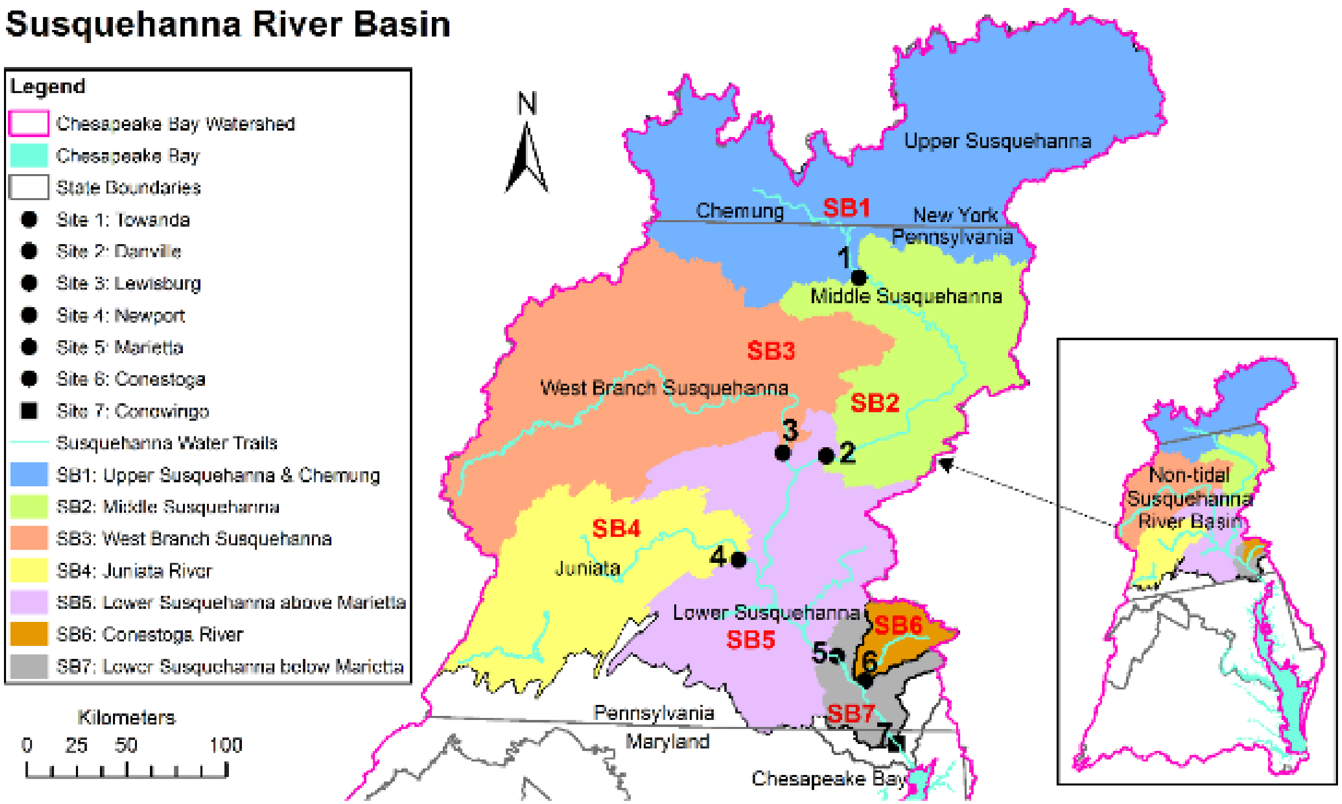
- **TN total source input:** declines at all sites, with the largest decline at Danville.
- **Individual sources:** negative Δ for 25 of 28 source-site combinations; dominated by atm. deposition (AD) reduction at all sites except Conestoga.
- **FN riverine yield:** negative Δ at all sites, with the largest decline at Conestoga.

$\Delta_{FN\text{-}Yield}$ vs. Δ_{Input} (1987-2011)

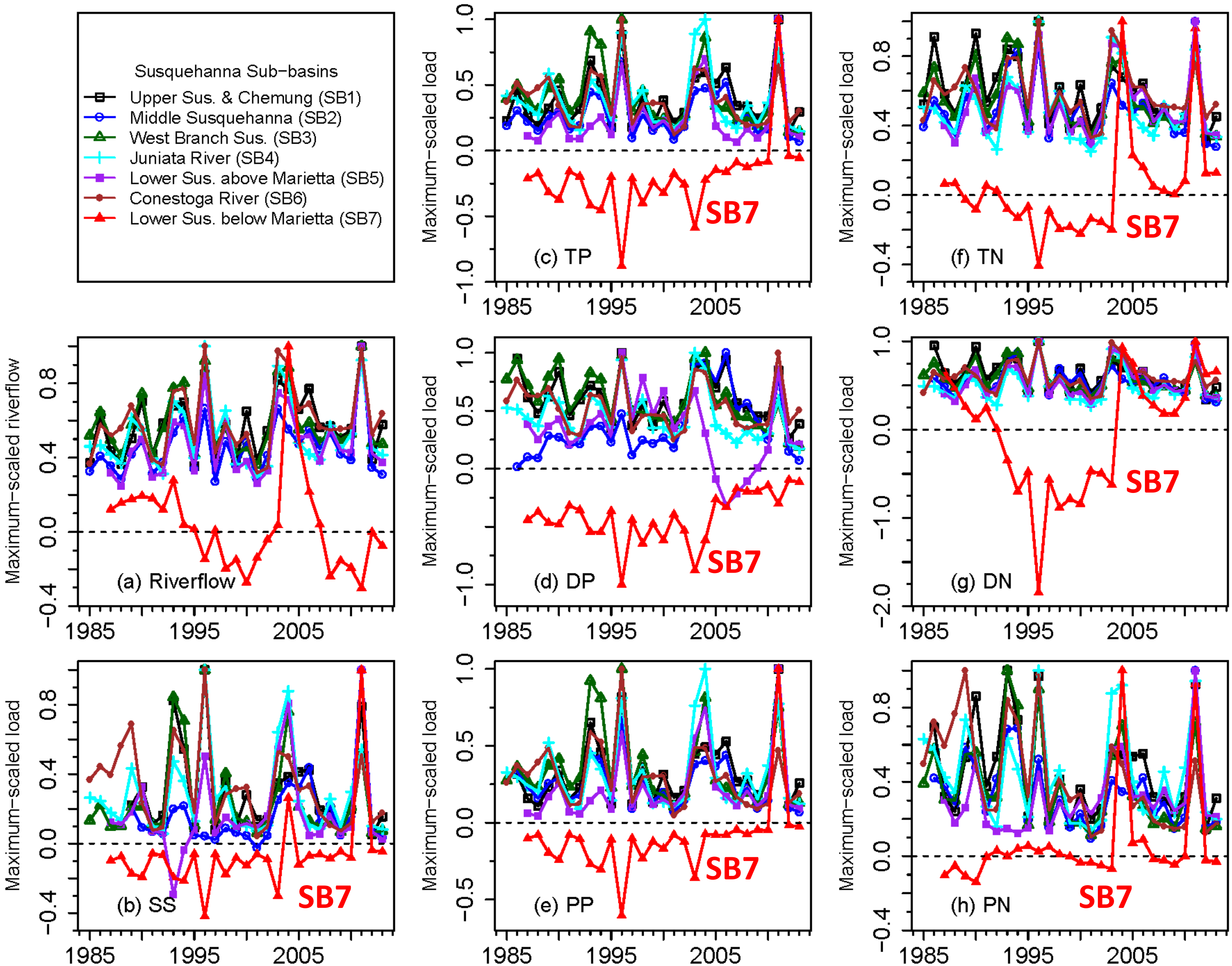


- $\Delta_{FN\text{-}Yield}/\Delta_{Input} > 0$ (12 of 14 cases) → riverine yield has declined in response to reductions in watershed source input at different parts of the SRB.
- $\Delta_{FN\text{-}Yield}/\Delta_{Input} < 1.0$ (13 of 14 cases) → likely continual contribution from legacy surface and sub-surface stores, as observed elsewhere and recognized as "biogeochemical stationarity" (Basu *et al.*, 2010; Thompson *et al.*, 2011).

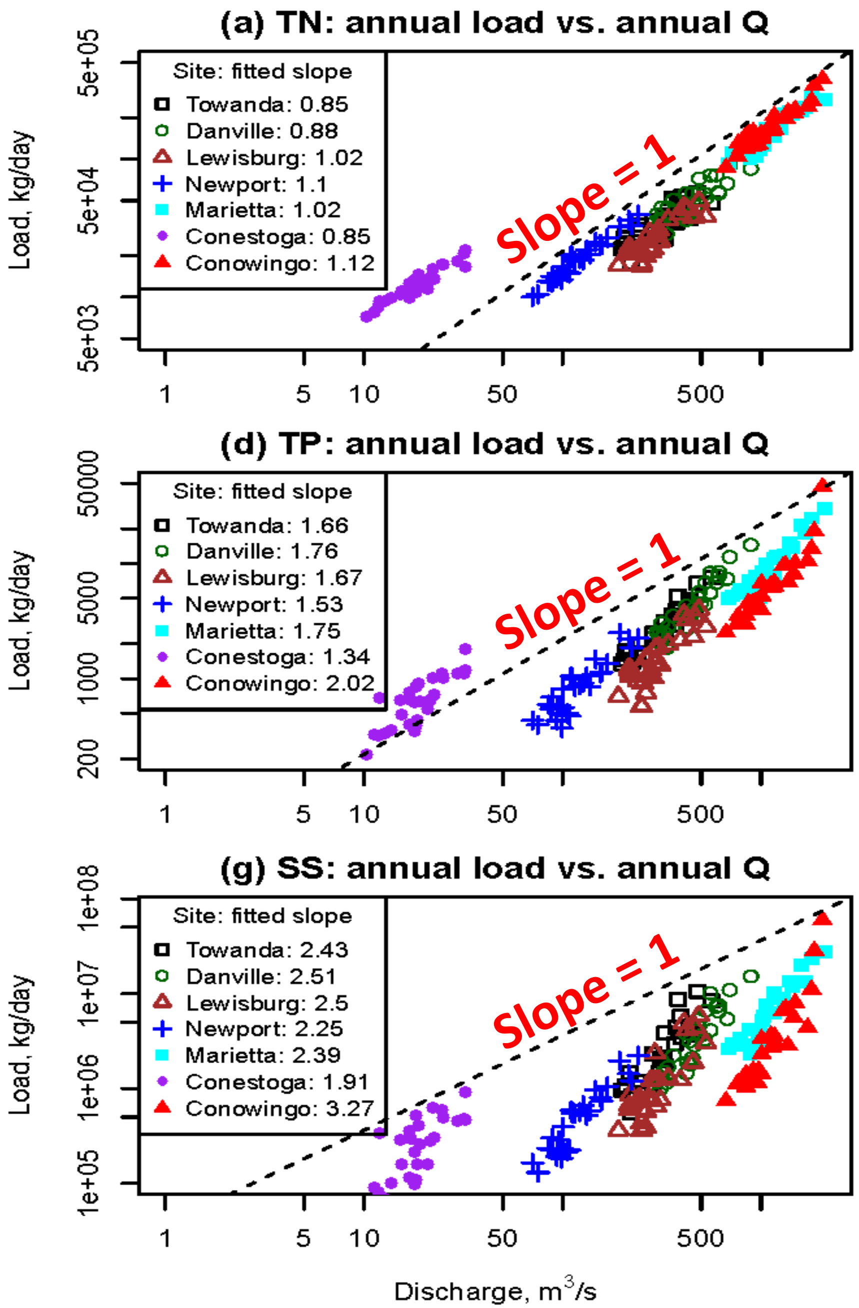
Q3: Which sub-basins have been net sources (or storages) of loadings and what have been the role of streamflow on constituent export?



Sub-basins: Net Sinks or Sources?

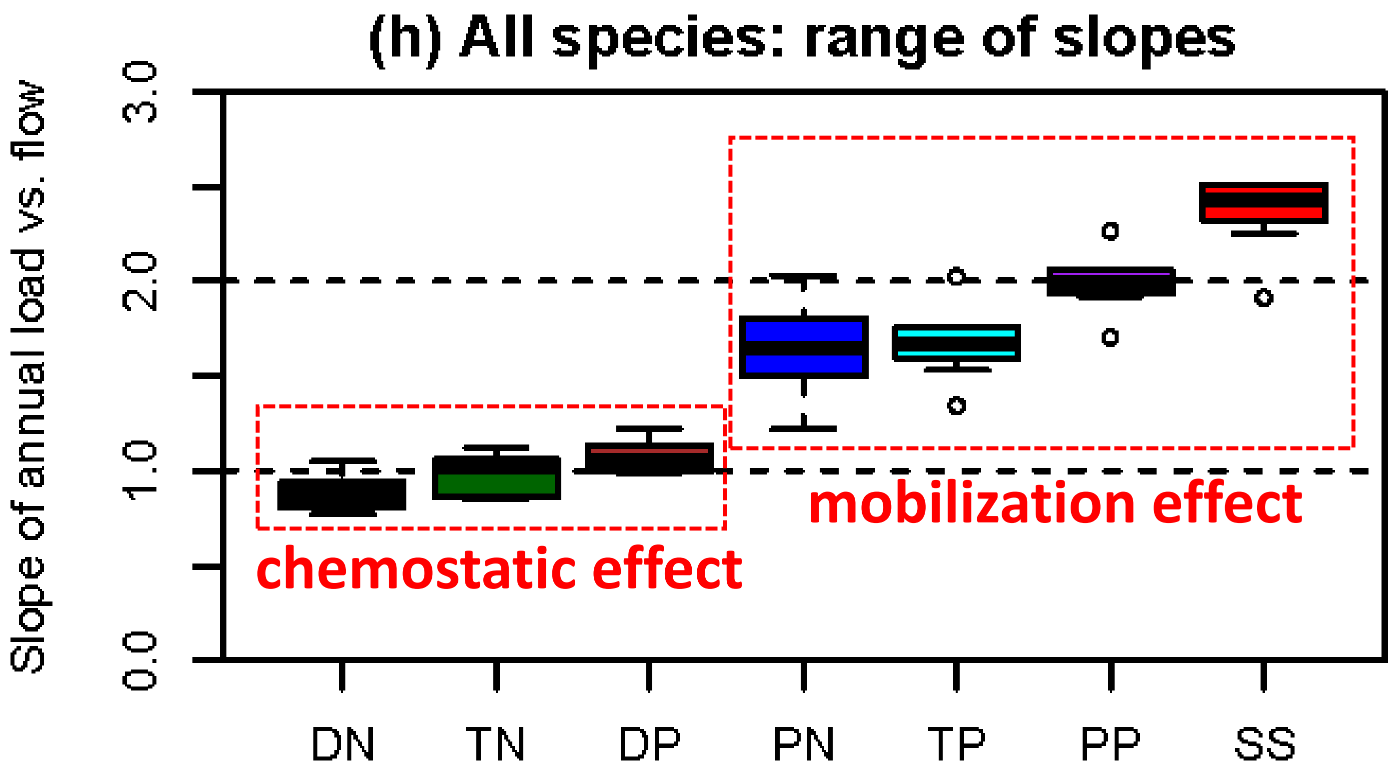


Sub-basins: Loading vs. Discharge Relationships



- **SB1-SB6:** concurrent peaks and troughs for Q and all constituents, showing a striking similarity with respect to the timing of significant export.
- **Hypothesis:** streamflow has been the principal factor controlling mass flux export in relative to other factors (*e.g.*, biogeochemical processes).
- **Validation:** strong log-linear relationships (p-value < 0.01) between annual loading and annual discharge for all species at all sites (DN, DP, PN, PP not shown) → Streamflow is a strong predictor of rates of N/P/SS export.
- **Literature:** consistent with studies on watersheds elsewhere (*e.g.*, Alvarez-Cobelas *et al.*, 2008; Basu *et al.*, 2010; Howarth *et al.*, 2006).

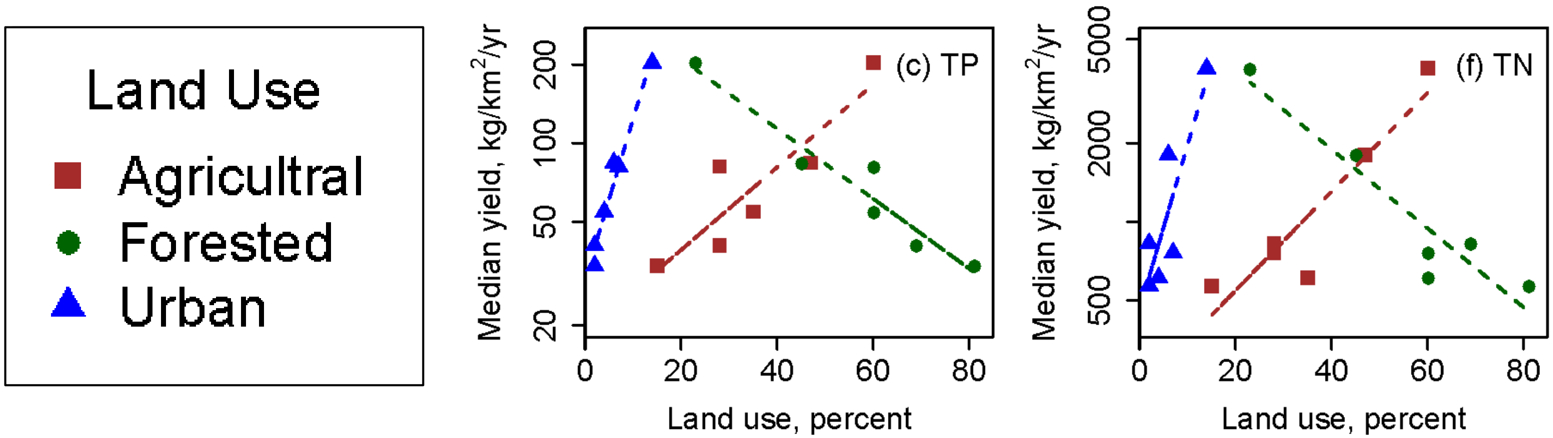
Sub-basins: Loading vs. Discharge Relationships

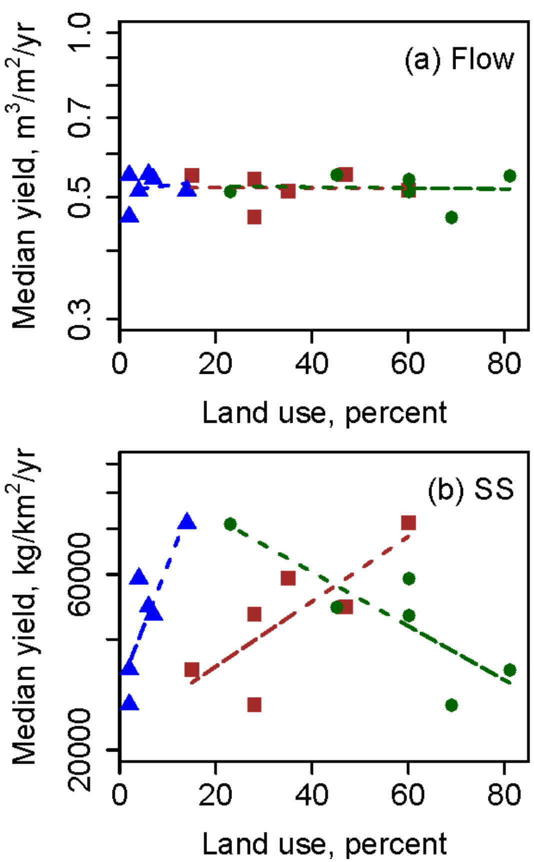


- **Implications:**
  - ✓ exports not supply-limited;
  - ✓ large storages despite decades of management efforts;
  - ✓ "biogeochemical stationarity" (Basu *et al.*, 2010).

Q4: What have been the rankings of sub-basins with respect to nutrient/sediment yield and how have the rankings related to land use?

Effects of Land Use





- **Streamflow**: annual flow yield is almost invariable with land use.
- **SS/TP/DP/PP/TN/DN/PN**: annual constituent yields correlate positively with the area fraction of agricultural land and urban land but negatively with that of forested land (due to lower source inputs and/or higher assimilation capacity).
- **Flow classes**: similar patterns observed with different flow classes (wet, dry, and average).
- **Literature**: consistent with findings discussed above and those on other watersheds (*e.g.*, Harris, 2001; Jordan *et al.*, 1997).

Conclusions

- N, P, and SS loads have declined at all Susquehanna sites upstream of Conowingo Reservoir.
- Smaller annual reductions in riverine yield than source input imply contribution of legacy sources.
- Riverflow has been a principal factor controlling rates of constituent export.
- Dissolved and particulate species show chemostasis and mobilization effects, respectively.
- Long-term yields of all species correlate positively with the fraction of agricultural or urban area but negatively with that of forested land.
- The study illustrates the value of maintaining long-term water-quality monitoring at multiple locations in watersheds.

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Acknowledgements

- Maryland Sea Grant (NA10OAR4170072 and NA14OAR1470090)
- Maryland Water Resources Research Center (2015MD329B)
- National Science Foundation (CBET-1360415)
- Gary Shenk, Guido Yactayo, and Gopal Bhatt (Chesapeake Bay Program Office)
- Di Ha, Hengchen Wei (former JHU students)
- U.S. Geological Survey (NWIS data)
- Susquehanna River Basin Commission (SNAP data)

Questions?
Comments?