Nutrient Loads: Overview of approaches, and the Chesapeake Bay experience

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US Geological Survey
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Outline of the presentation

1. Multiple reasons to estimate loads
2. Sampling approaches
3. Calculation approaches
4. A story: “The thrill of victory, the agony of defeat”
5. The Chesapeake Bay Experience

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Motivation:
Quote From Ralph Keeling

The only way to figure out what is happening to our planet is to measure it,

and this means tracking changes decade after decade

and poring over the records.

Keeling, 2008, Recording Earth's vital signs, Science, p1771-1772

USGS

Why estimate loads?

1) To understand how a Lake responds to inputs, we need a time-history of inputs.

2) To build early warning systems.

3) Estimate long-term averages to compare watersheds.

4) Assess progress toward watershed goals.

5) Build understanding of the impacts of various management practices.

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How do we gather the data?

1) Collect a water sample such that it integrates the flux over the whole cross-section.

2) Collect a sample from the water surface.

3) Collect a sample from a fixed point at depth in the cross section.

4) Use sensors at a fixed location in the cross section to measure surrogates.

USGS

Can these provide unbiased estimates of load?

1) Collect a water sample such that it integrates the flux over the whole cross-section. YES

2) Collect a sample from the water surface. YES if calibrated with whole cross-section.

3) Collect a sample from a fixed point at depth in the cross section. YES if calibrated with whole cross-section.

4) Use sensors at a fixed location in the cross section to measure surrogates. YES if calibrated with whole cross section.

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When do we gather the data?

1) On a fixed calendar (e.g. weekly or monthly)

2) On a fixed calendar plus high flow events

3) Approximately daily (perhaps increased during events)

4) Sensor measurements at very high frequency

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5 broad categories of calculation methods

- They each have multiple variations
- Their suitability depends on the characteristics of the data set and behavior of the variable
- Probably all have an appropriate use, but we need to be mindful of their strengths and weaknesses

USGS

Major distinctions among methods

- How do we portray E(C) as a function of Q?
- Do we use data from one year to help predict loads in other years?
- How do we treat seasonality?
- How do we estimate the variability?
- How do we use samples close to the time for which we are making the estimate?

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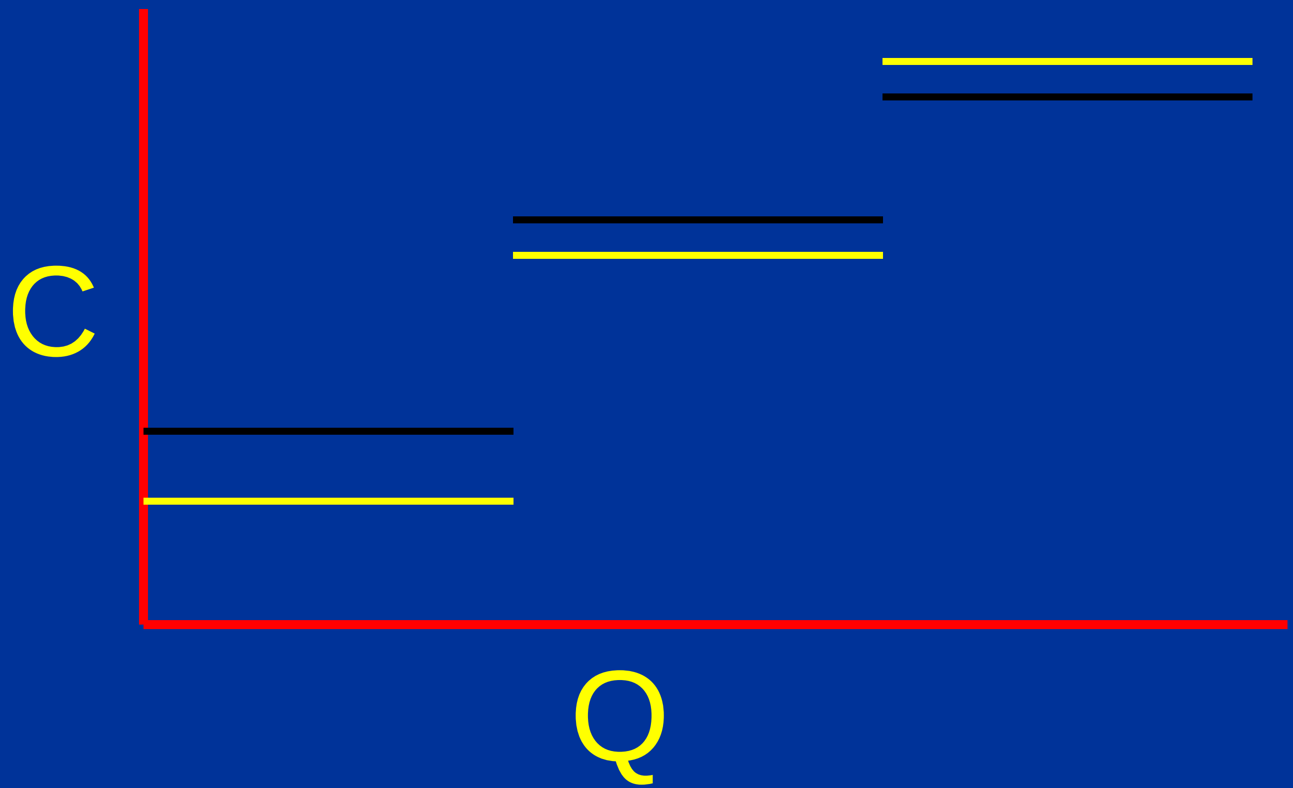
Selection of methods needs to be driven by two primary factors

- What’s the nature of the data set? In particular, what’s the frequency at which the data are collected (data may be a sample or an instrument reading)?
- What’s the question we are trying to answer?

Ratio estimates



Can make it seasonal.

Excellent from a bias standpoint.
Excellent with large data sets. (e.g. 500 per decade)
How do they use data beyond the year collected?

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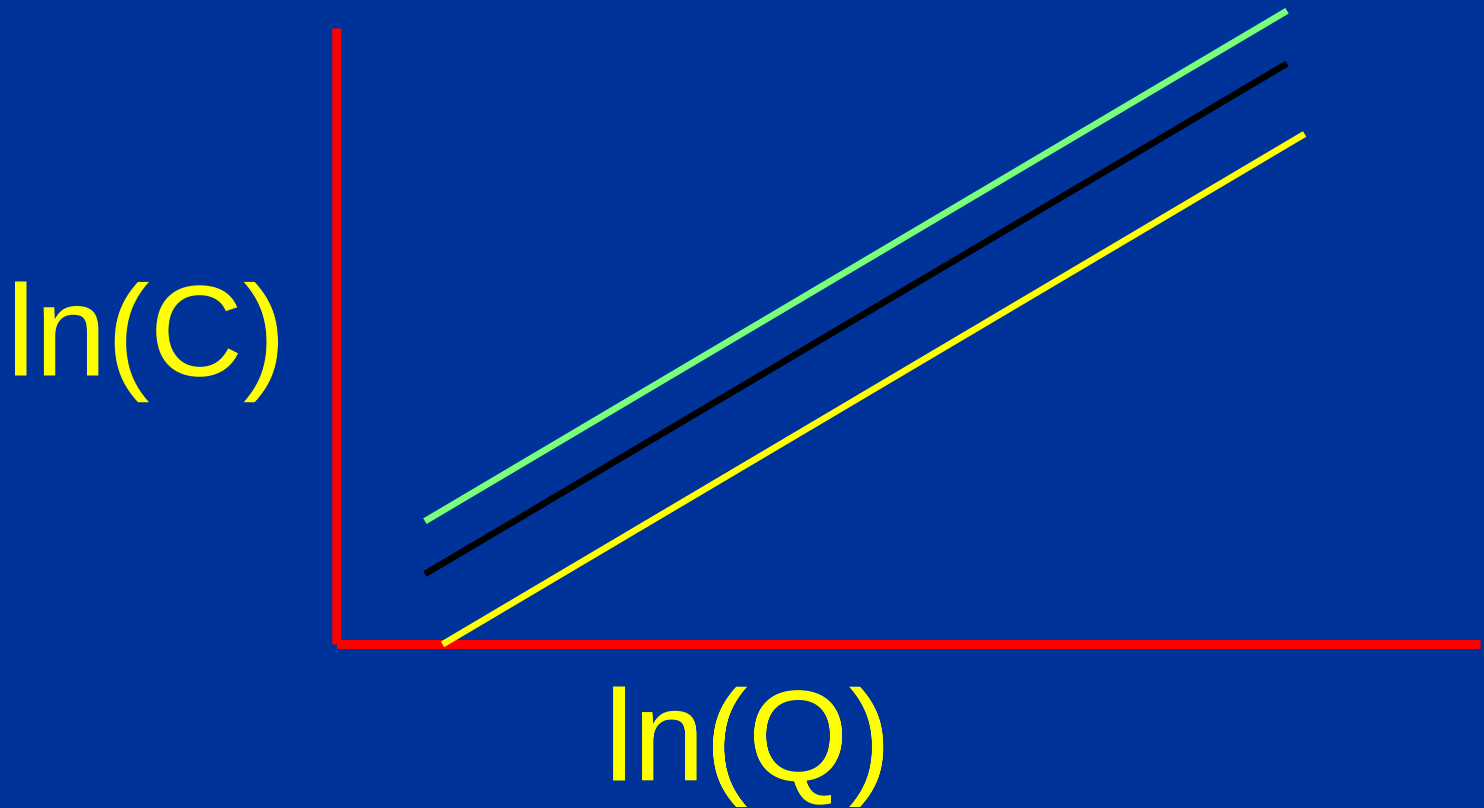
Regression estimates



Can make it seasonal and can handle long-term trend.

Can have bias problems if not careful.
Well suited to moderate data sets. (~150 per decade)
Curvature and extrapolation issues can be serious.

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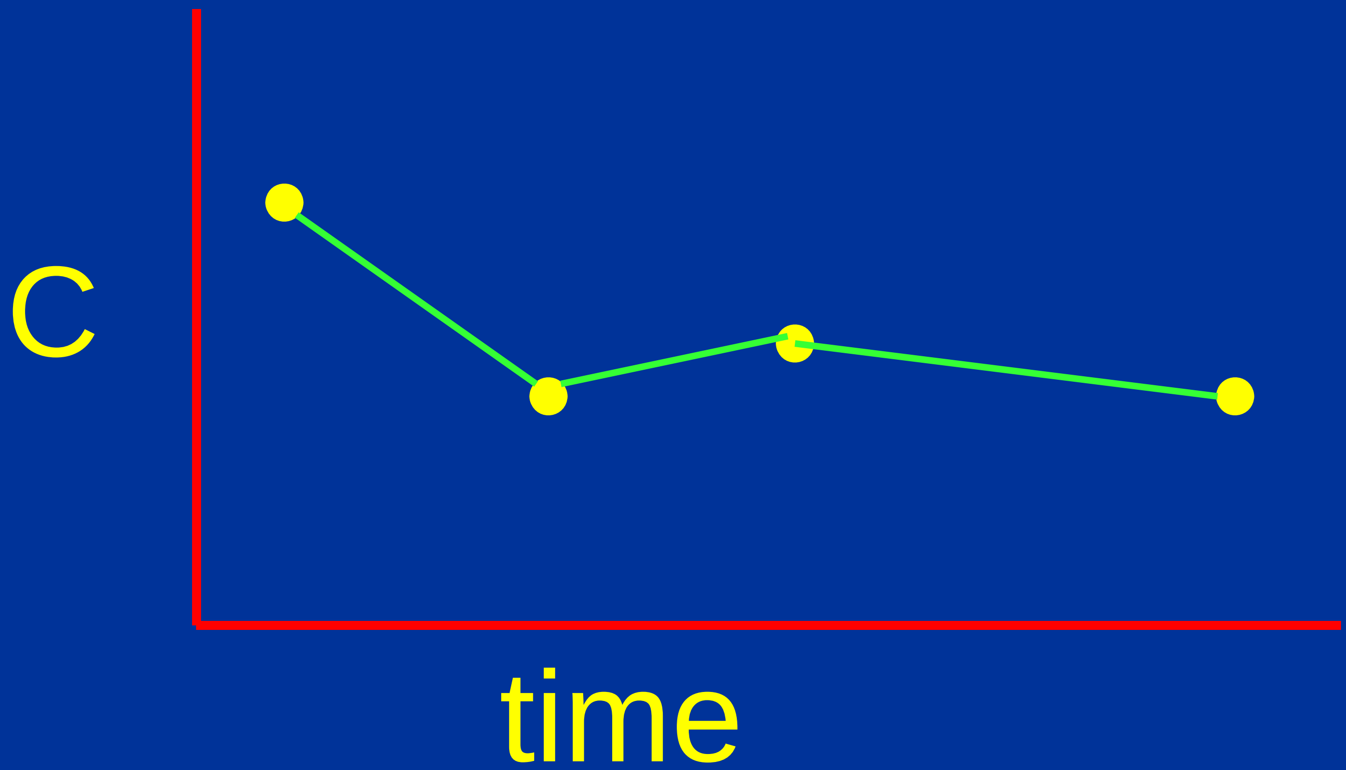
Interpolation methods

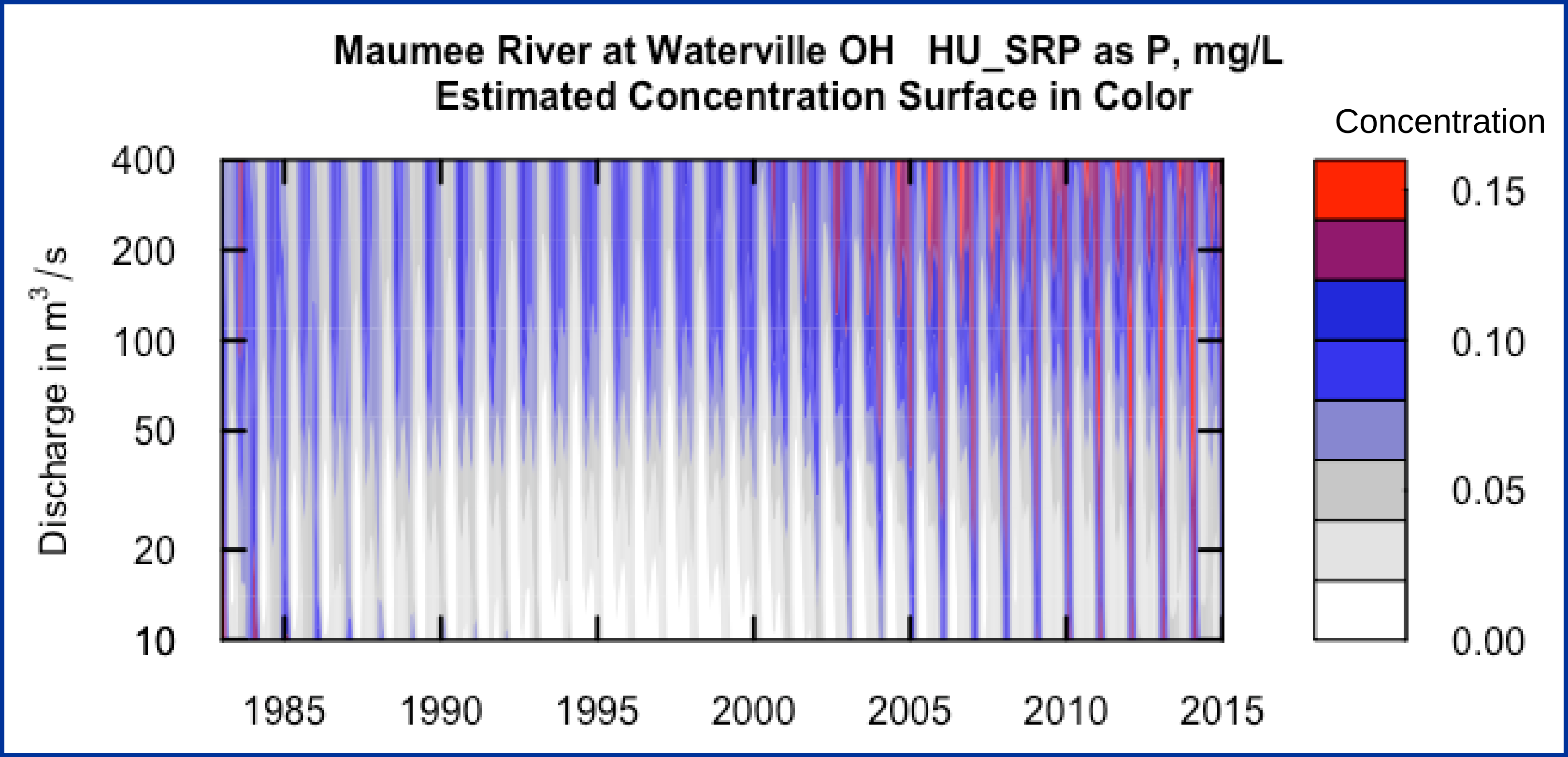


Composite method is a hybrid between regression and interpolation.

It interpolates regression residuals.

Great if samples are frequent. (>2000 per decade)
Terrible with large gaps.
If "events" happen between samples: very poor.

Smoothing: WRTDS (or GAM)



Performs well with respect to bias.
Best with >200 samples in a decade.

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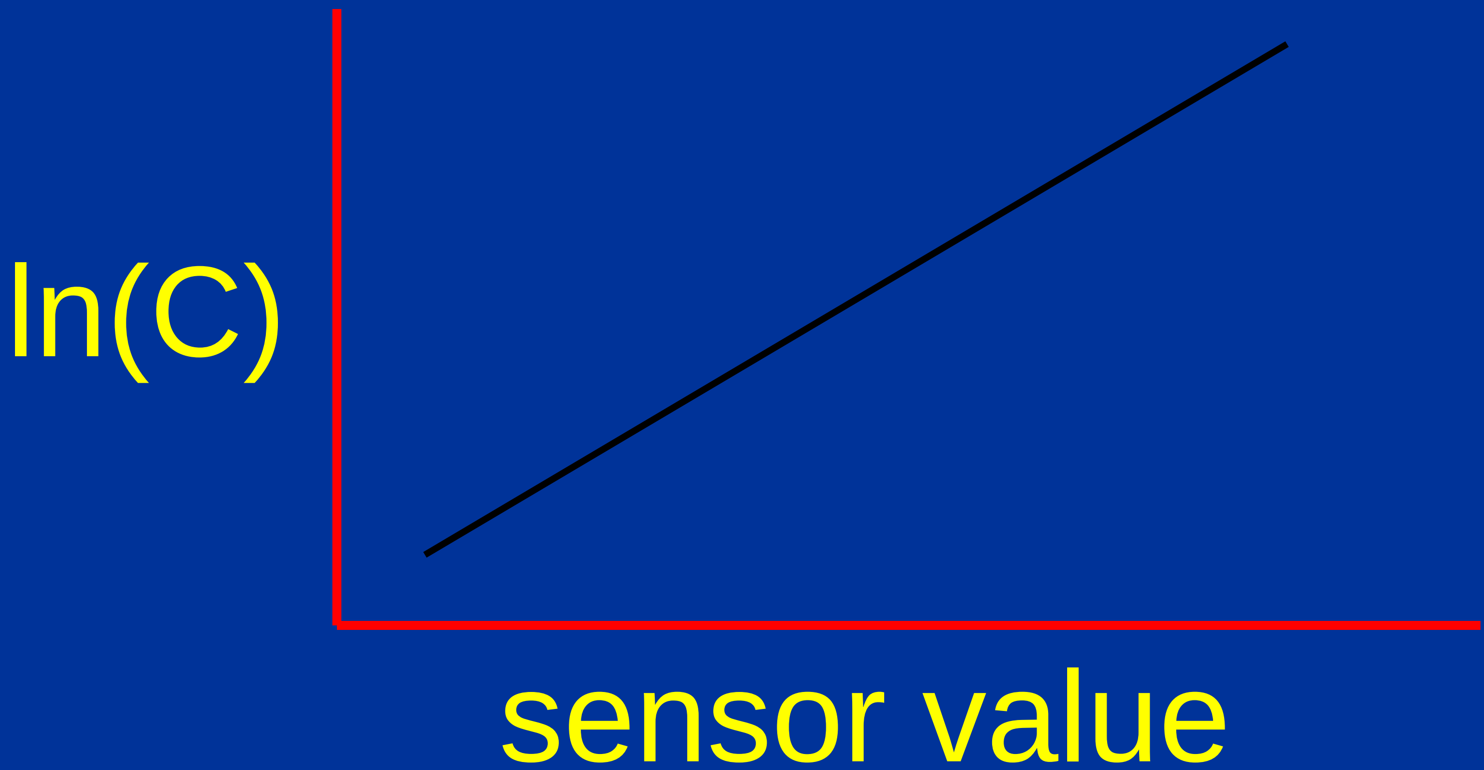
Surrogate Regressions



Sensor might be turbidity, nitrate, specific conductance, …?

Multiple sensors can be used simultaneously
Well suited to moderate data sets. (~150 per decade)
Less prone to extrapolation errors.

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An aside about evaluating methods

- We need to look at the data both from the standpoint of concentration and the standpoint of load.

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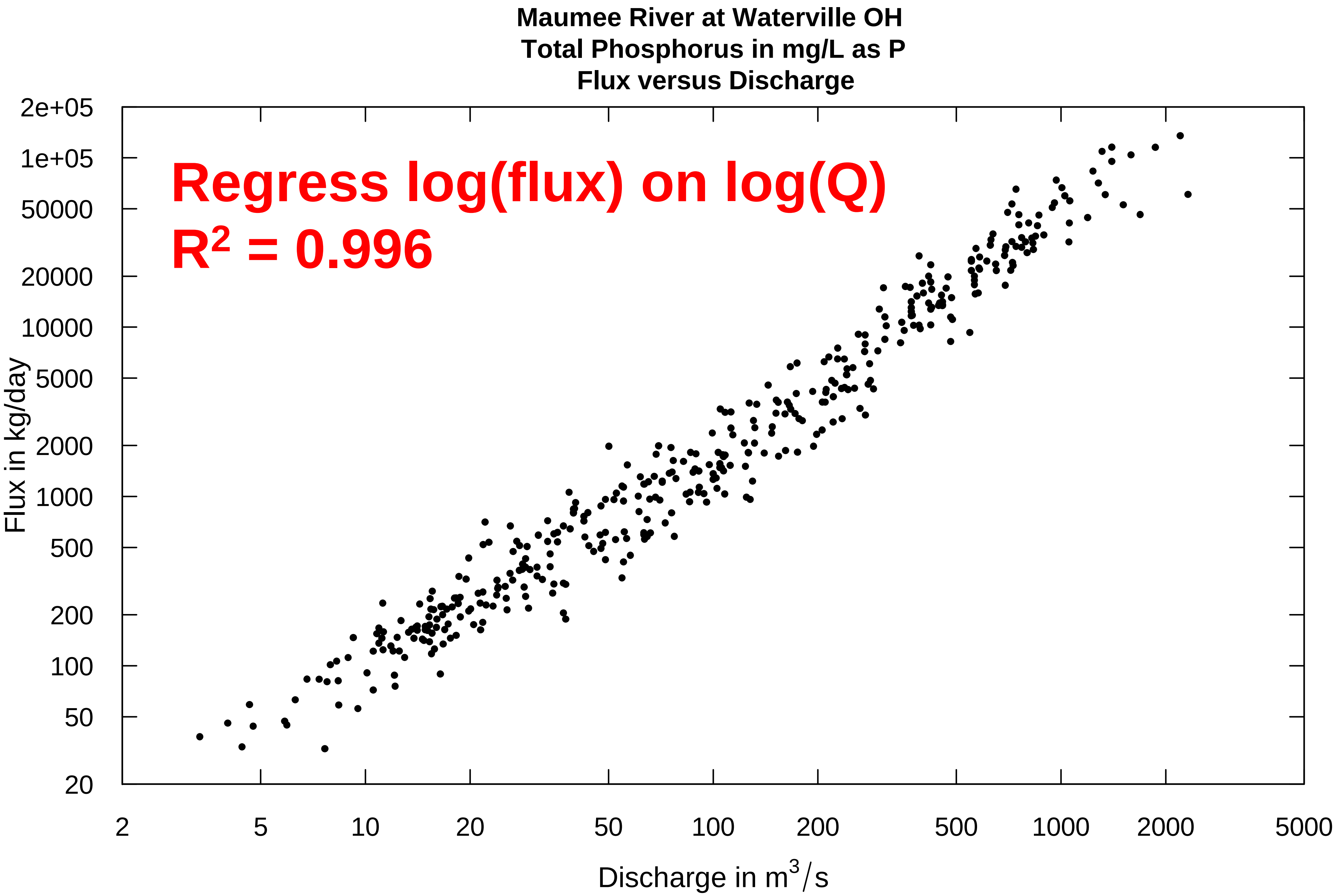
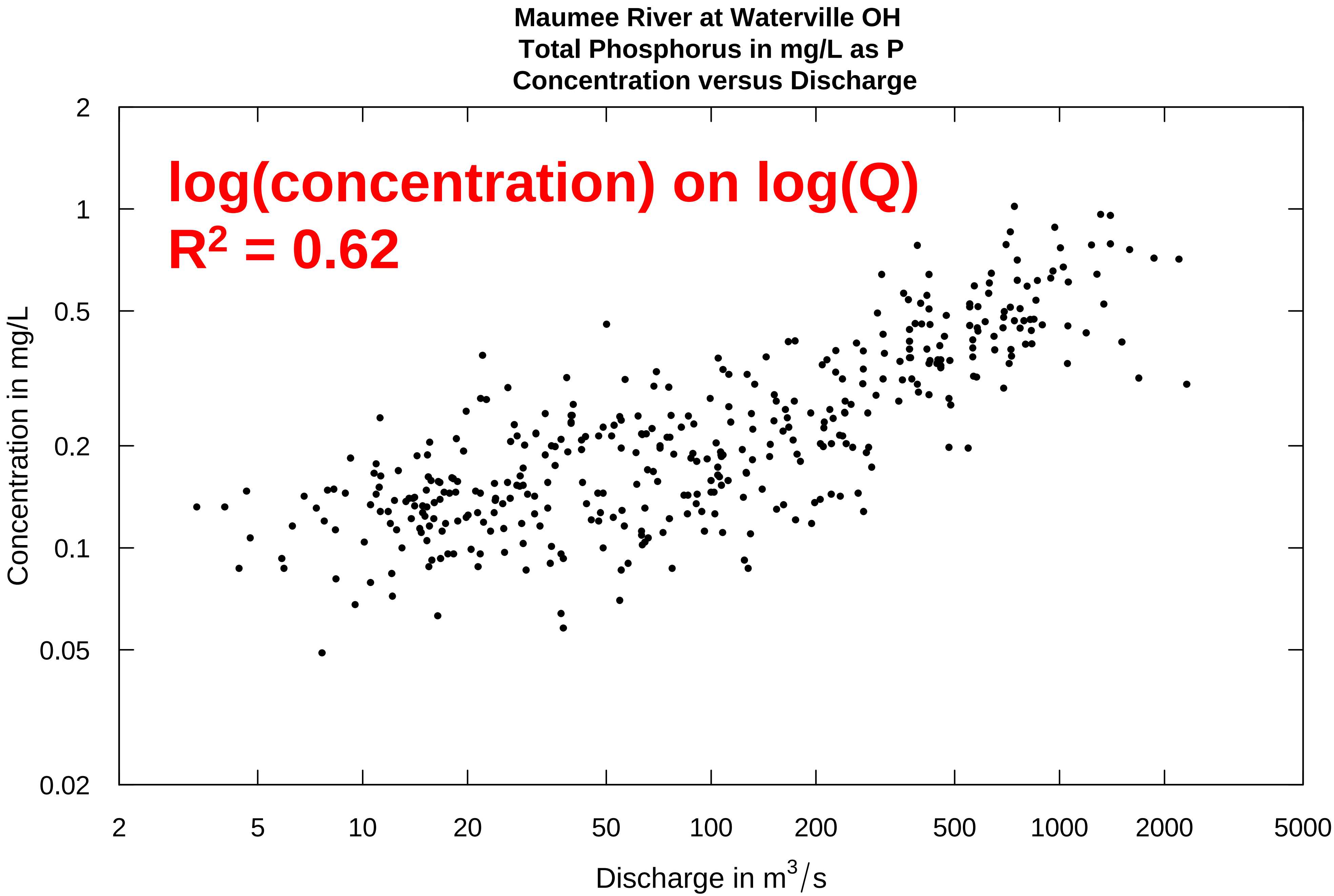
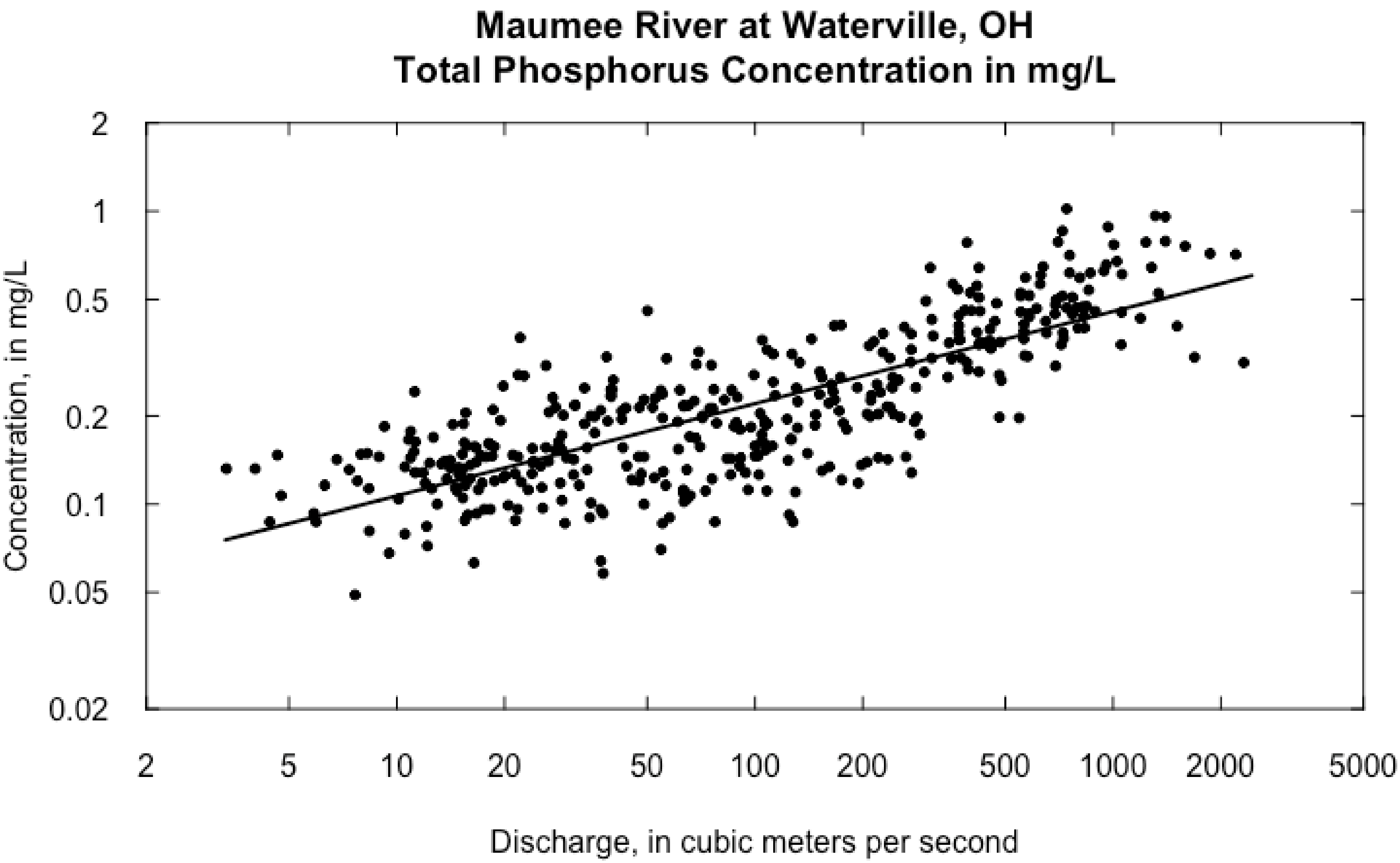
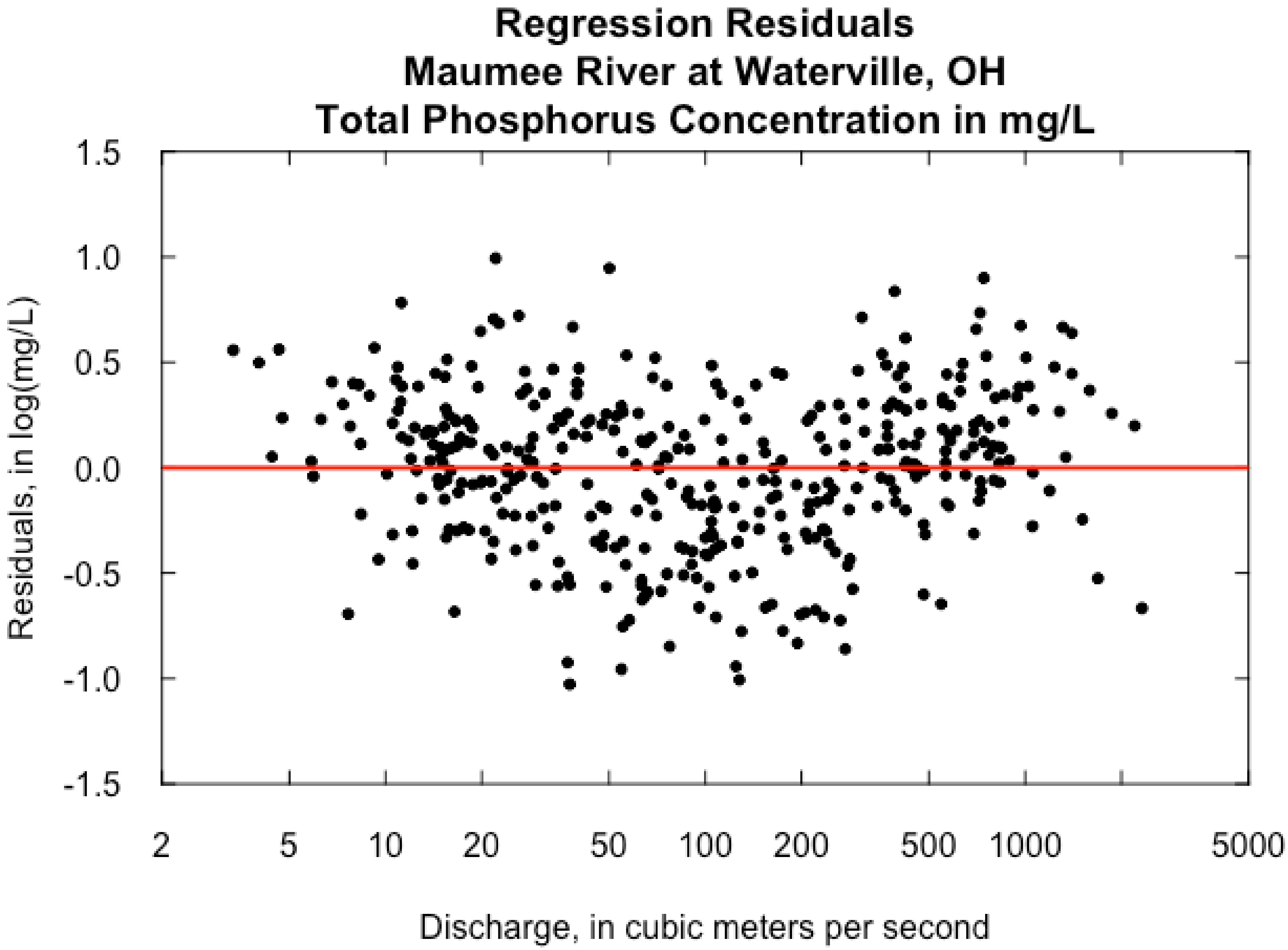
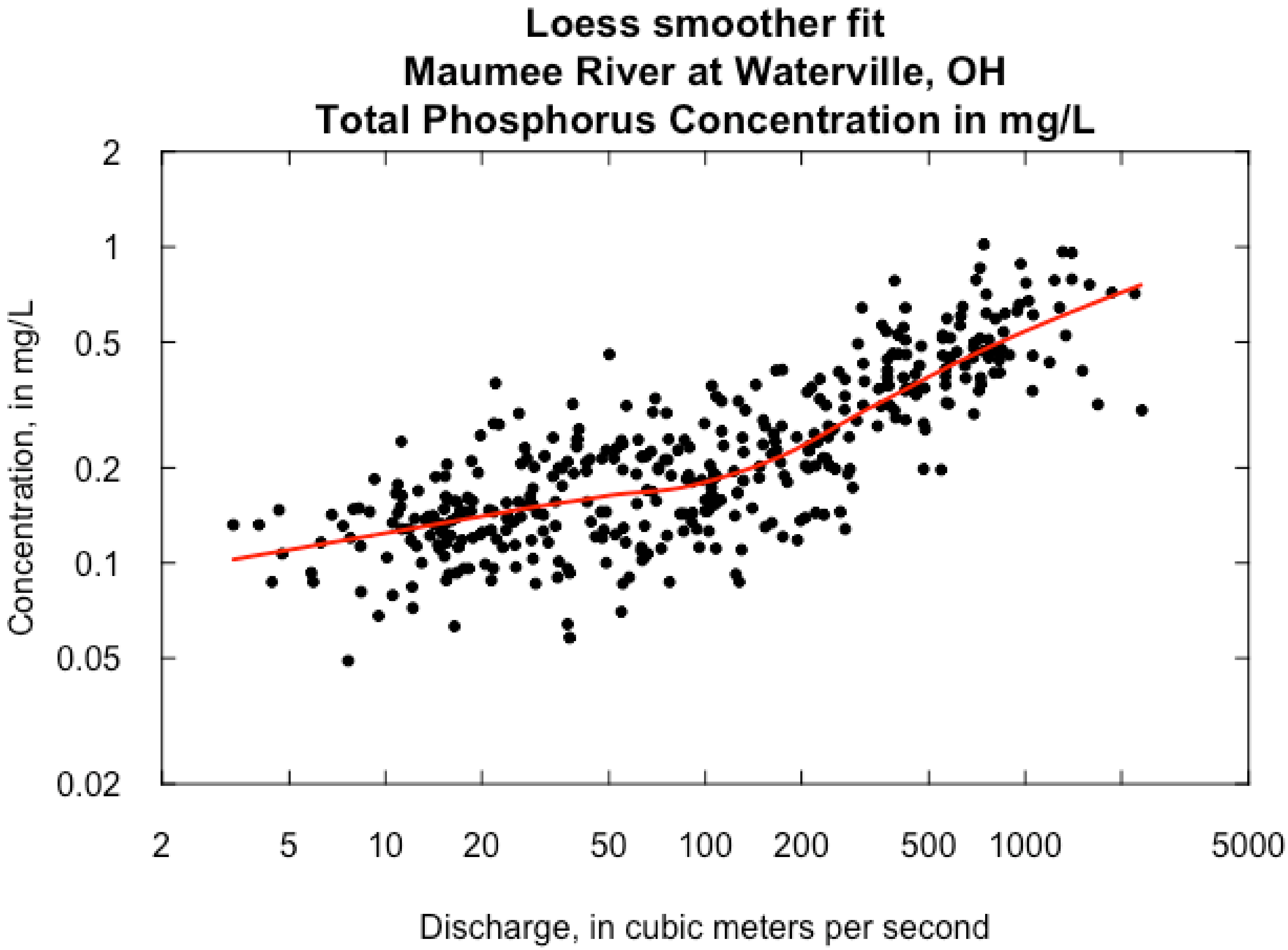

Maumee River at Waterville OH
Total Phosphorus in mg/L as P
Flux versus Discharge
Regress log(flux) on log(Q)
$R^2 = 0.996$
Flux in kg/day
2e+05
1e+05
50000
20000
10000
5000
2000
1000
500
200
100
50
20
2
5
10
20
50
100
200
500
1000
2000
5000
Discharge in m^3/s


Maumee River at Waterville OH
Total Phosphorus in mg/L as P
Concentration versus Discharge
log(concentration) on log(Q)
R2 = 0.62
Concentration in mg/L
2
1
0.5
0.2
0.1
0.05
0.02
2
5
10
20
50
100
200
500
1000
2000
5000
Discharge in m3/s


Maumee River at Waterville, OH
Total Phosphorus Concentration in mg/L
Concentration, in mg/L
2
1
0.5
0.2
0.1
0.05
0.02
2
5
10
20
50
100
200
500
1000
2000
5000
Discharge, in cubic meters per second



Regression Residuals
Maumee River at Waterville, OH
Total Phosphorus Concentration in mg/L
Residuals, in log(mg/L)
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
2
5
10
20
50
100
200
500
1000
5000
Discharge, in cubic meters per second


Loess smoother fit
Maumee River at Waterville, OH
Total Phosphorus Concentration in mg/L
Concentration, in mg/L
2
1
0.5
0.2
0.1
0.05
0.02
2
5
10
20
50
100
200
500
1000
5000
Discharge, in cubic meters per second

What are my points here

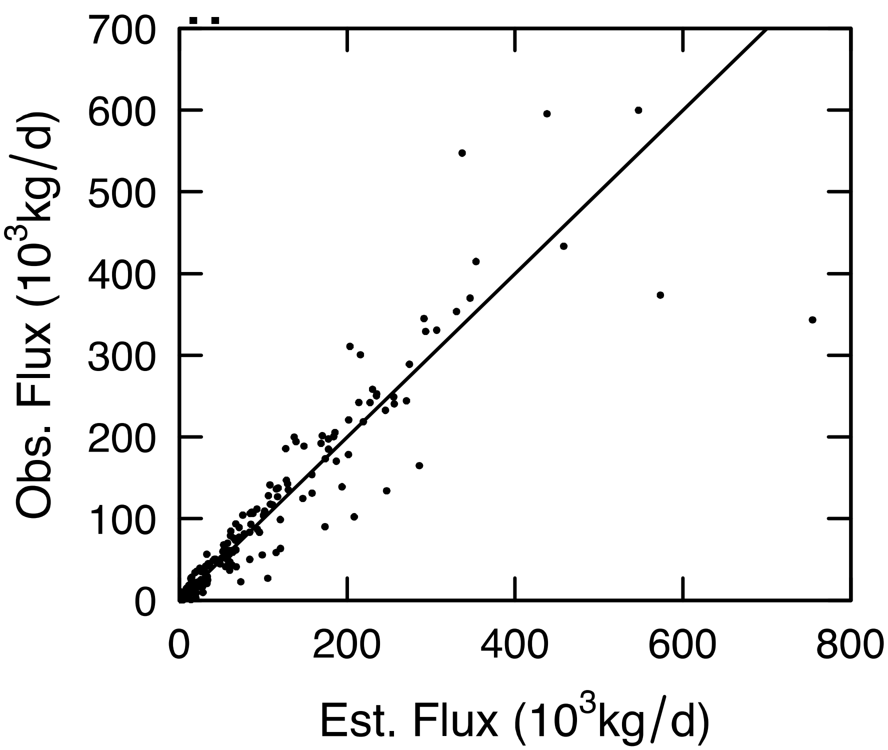
- Hard to see the lack of fit when estimating log(flux). R^2 is not informative.
- Easier to see lack of fit when estimating log(concentration). R^2 is meaningful.
- Best to see lack of fit looking at residuals.
- Using polynomial fits may cause the “tail to wag the dog” and bias estimates at the high discharges.

One more thought about looking at residuals

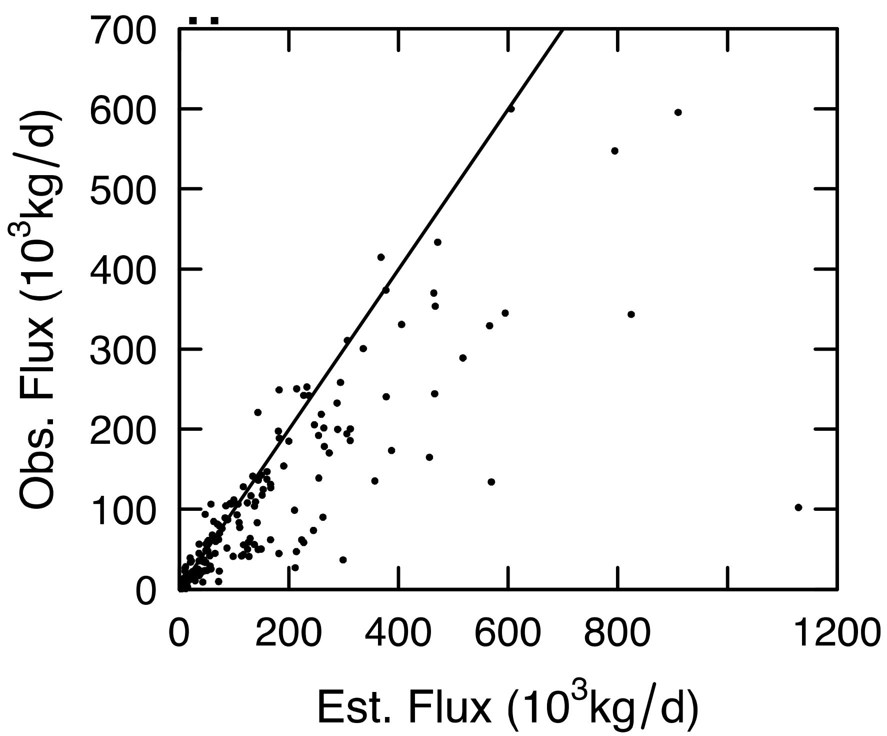
Never forget to look at real loads.

Data set is nitrate from Raccoon River at Des Moines, IA

WRTDS



Loadest 7



Selection of methods needs to be mindful of some common properties of water quality data

- Relationship to discharge
- Seasonal variations
- Typically skewed
- May be censored (“less than values”)
- Serial correlation

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Selection of methods

- Do the methods consider the actual properties of the data?
- Have we put them to a test against very rich data sets?

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Selection of methods:

- Consideration of purpose of the analysis
- Assessements of progress can be easily obscured by the random, but persistent, patterns of wet and dry years
- I call this: "The thrill of victory, the agony of defeat"

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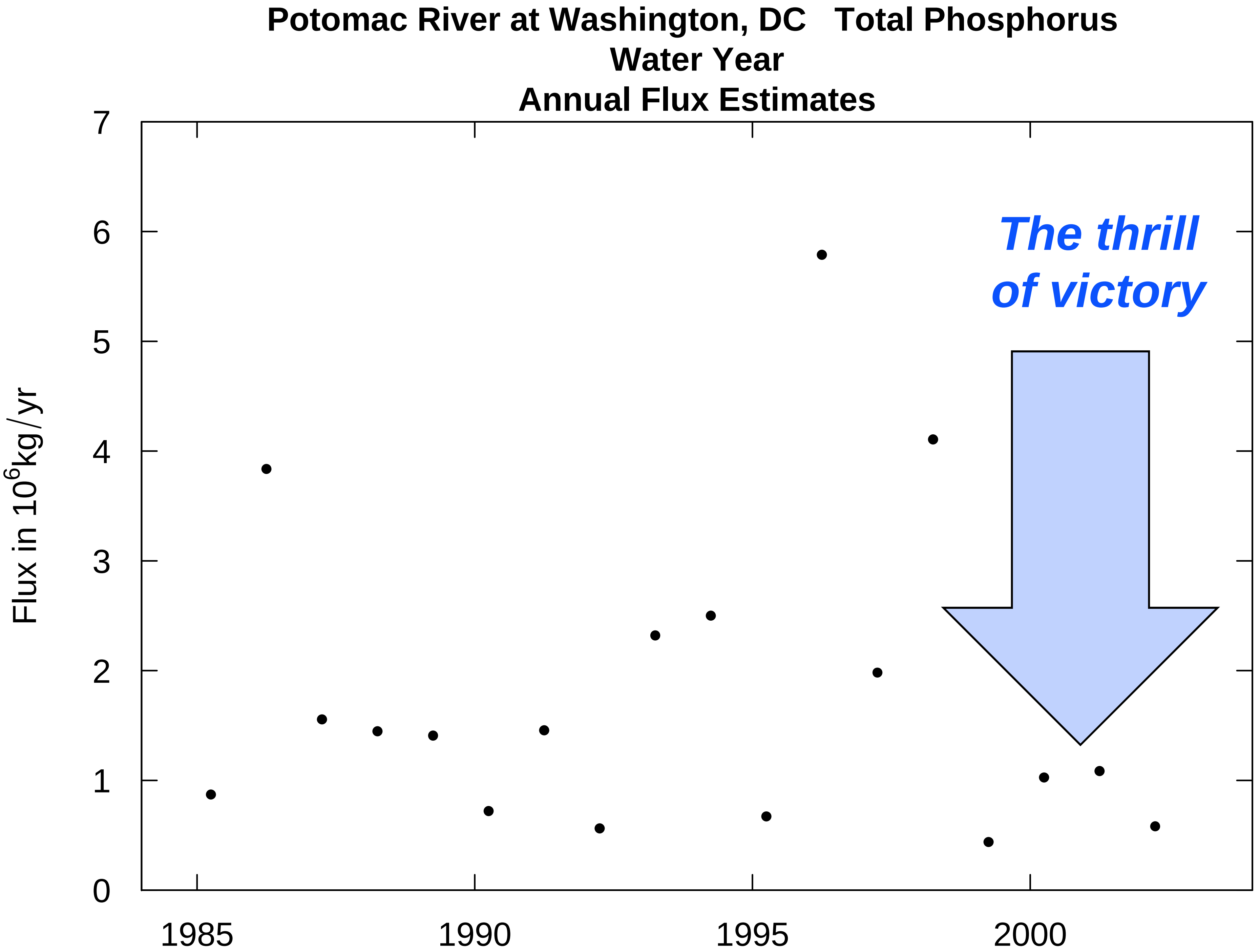
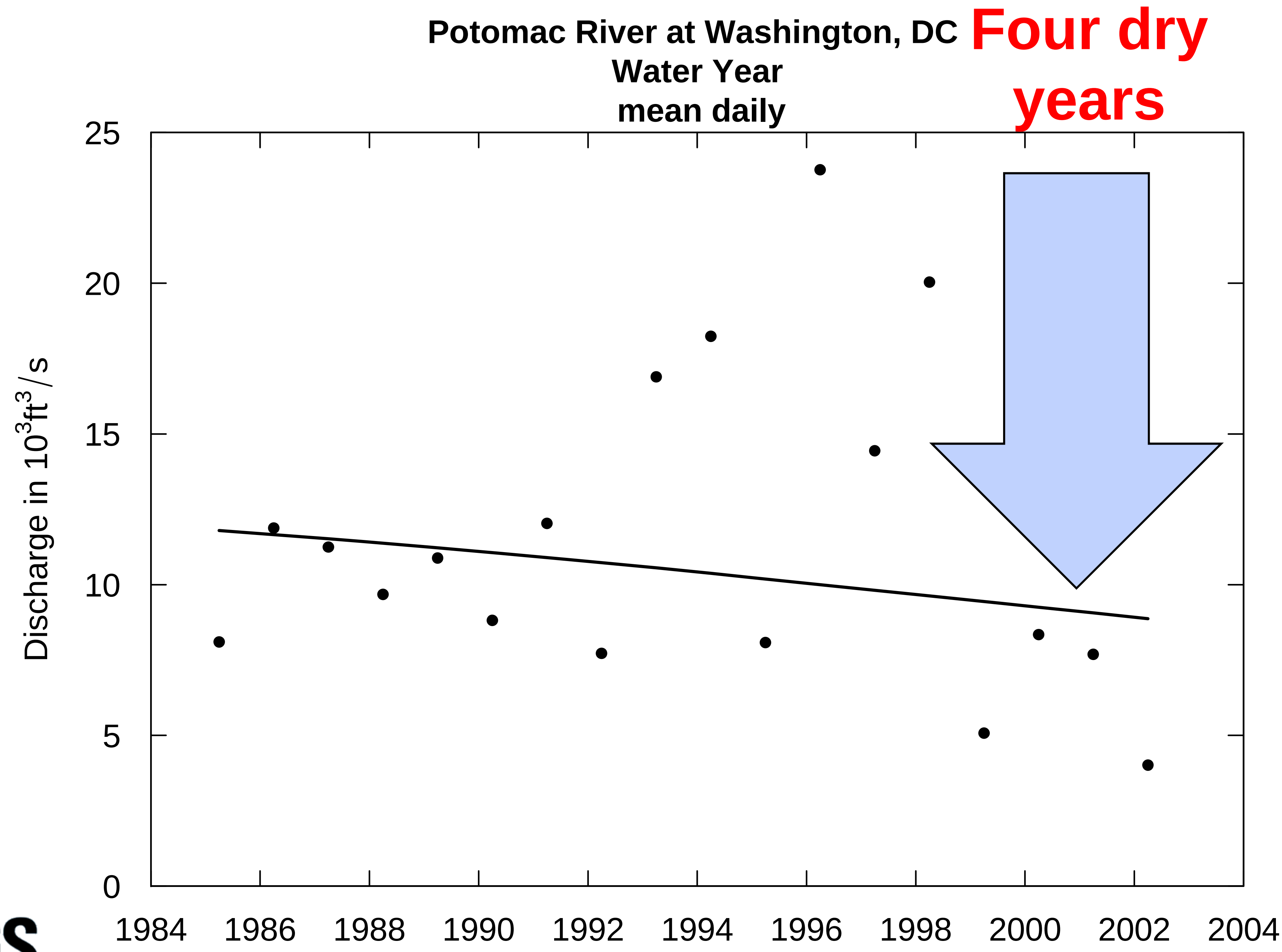
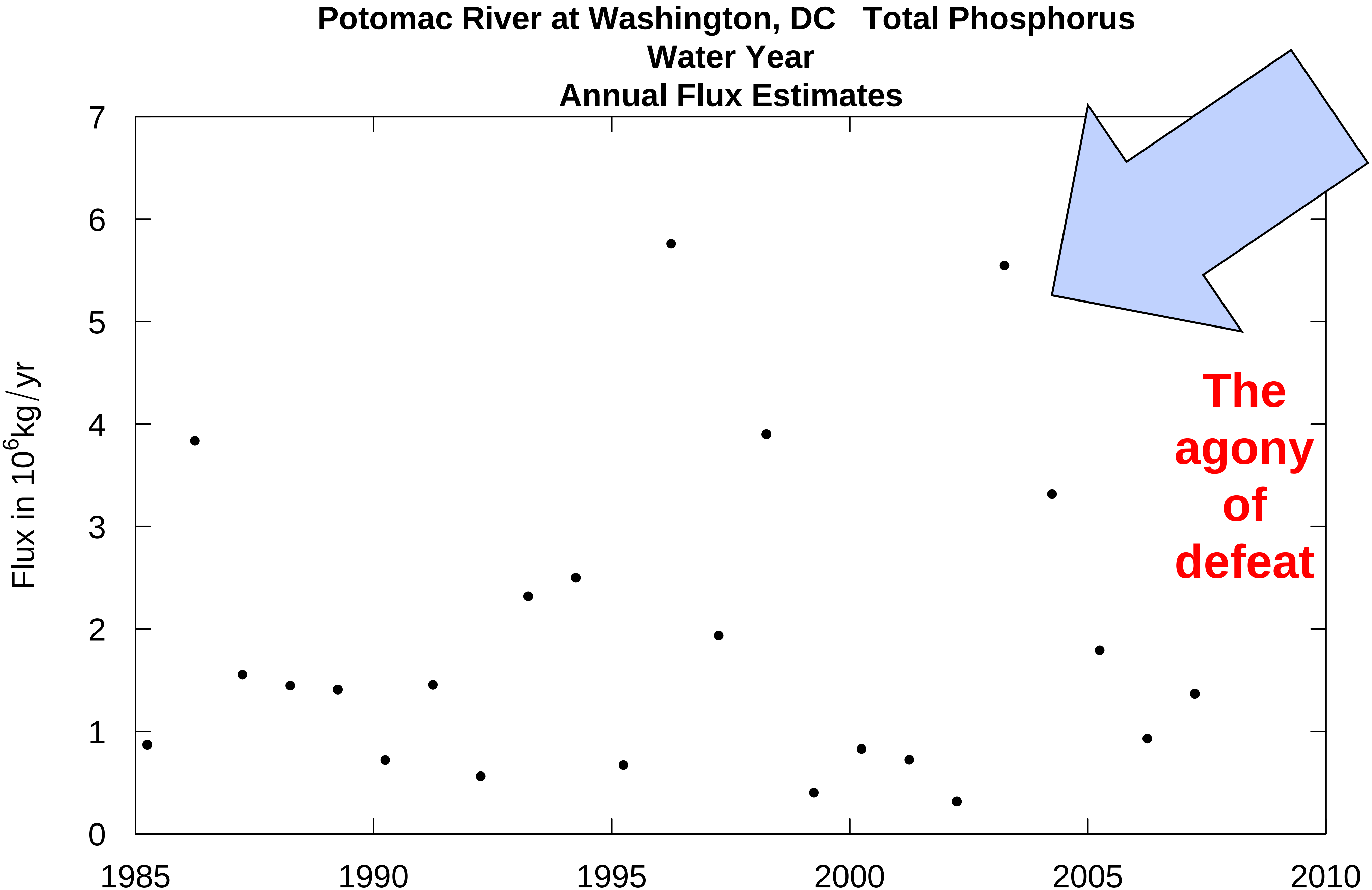


Potomac River at Washington, DC Total Phosphorus
Water Year
Annual Flux Estimates
Flux in 10^6 kg/yr
0
1
2
3
4
5
6
7
1985
1990
1995
2000
The thrill
of victory

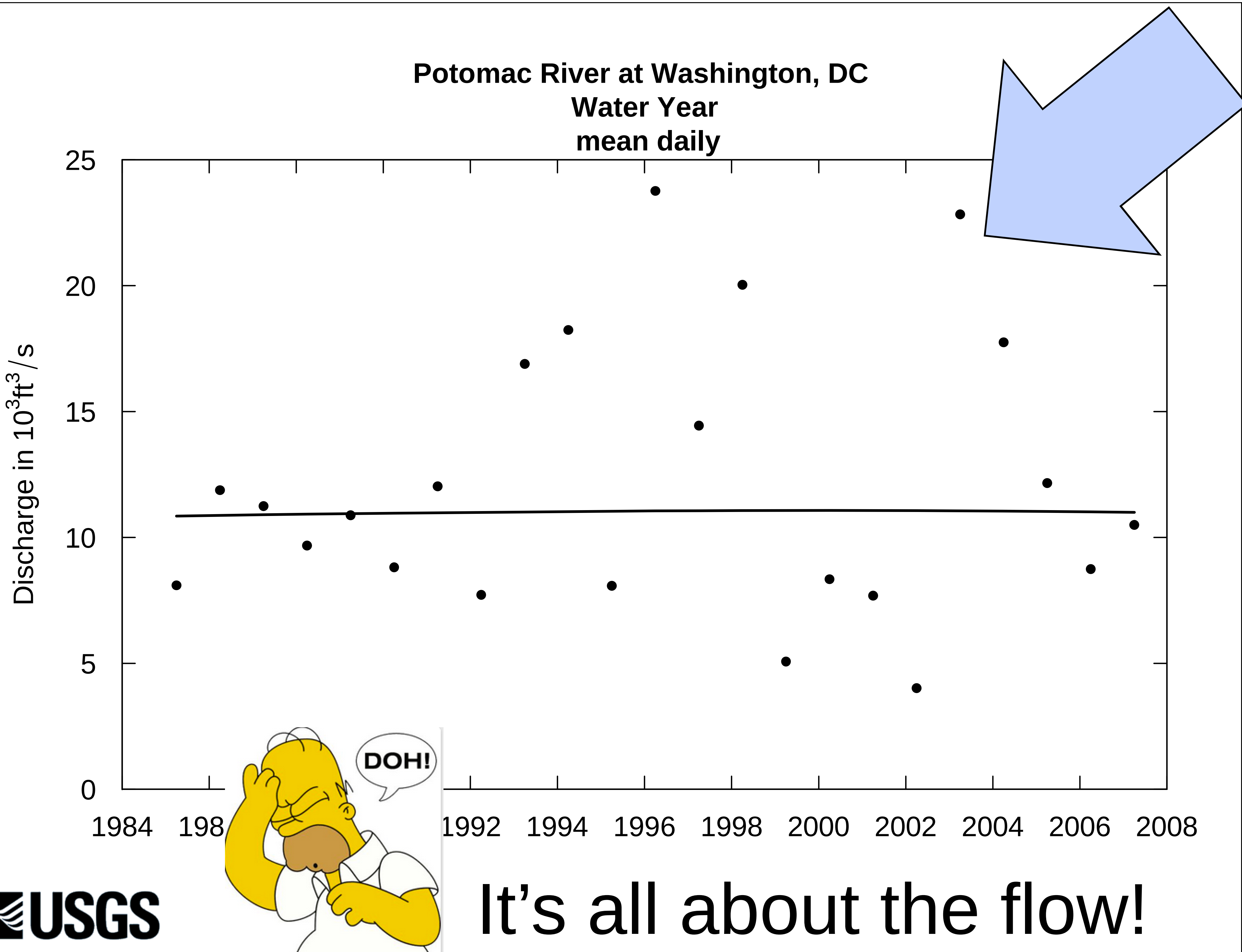
USGS

Look at the discharge record



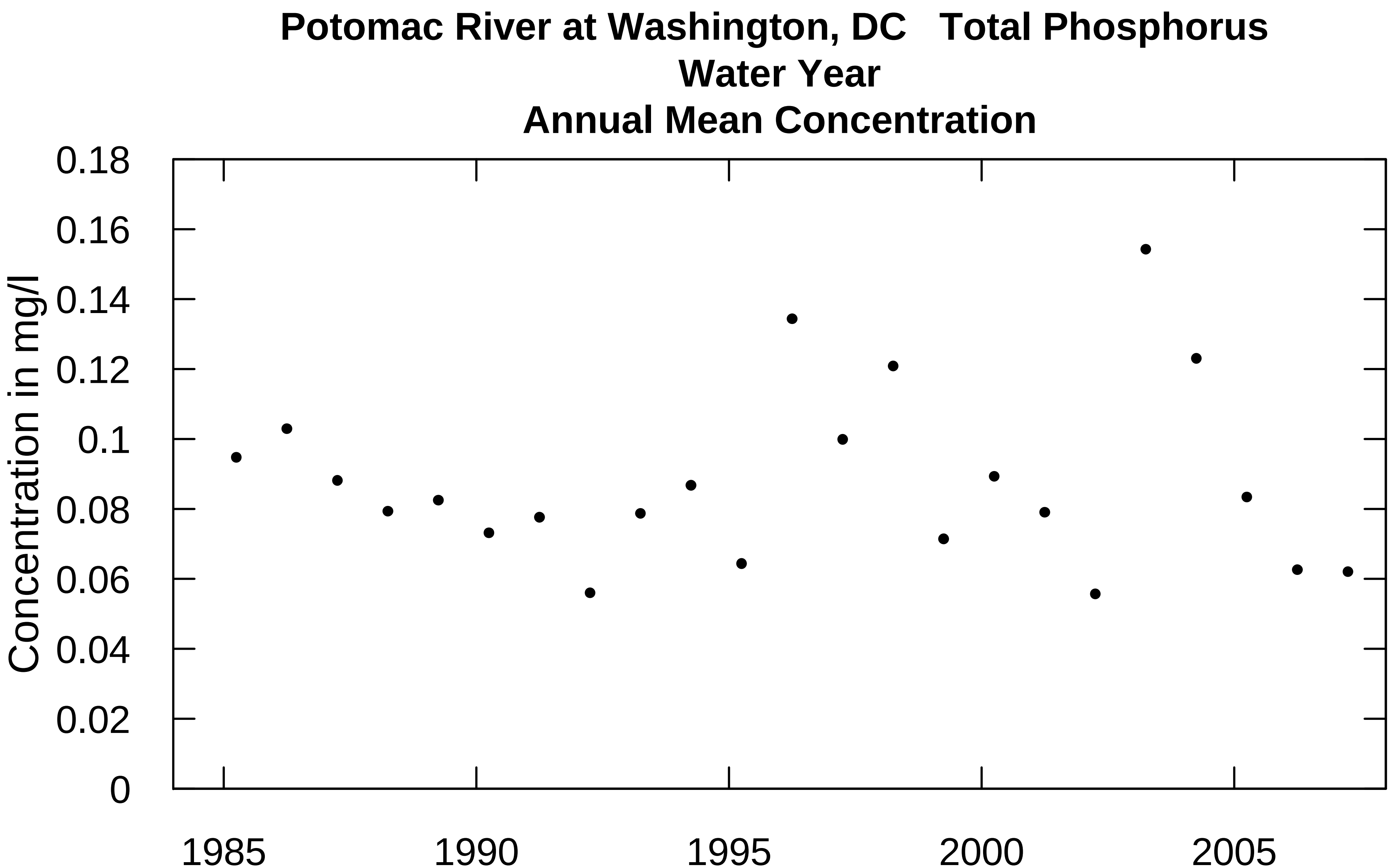


Potomac River at Washington, DC Total Phosphorus
Water Year
Annual Flux Estimates
Flux in 10^6kg/yr
0
1
2
3
4
5
6
7
1985
1990
1995
2000
2005
2010
The agony of defeat



It’s all about the flow!

Some might say, you can get rid of the problem if you just look at concentration rather than flux



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Sorry to say, the problem remains

What's my point here?

- **Although the history of loadings can be very useful to ecologists studying the drivers of the receiving water body**
- **It is not useful for assessing progress in the watershed.**
- **We are smarter than Homer! We can deal with the influence of flow.**

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How might we do this?

- Develop a statistical model for how the system behaves in response to discharge and season (exogenous variables).
- And how the system behavior changes over time.
- Then integrate that over the distribution of discharge (and season) to describe the trend in watershed behavior.

We want to describe to the managers:

- How the system behavior is changing, independent of the particulars of the year-to-year random variation in discharge.
- One approach is to use the annual values of flow-normalized flux, one of the outputs of WRTDS (Weighted Regressions on Time, Discharge and Season)

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Chesapeake Bay Experience

- Slides are from Doug Moyer, USGS, Virginia Water Science Center: coordinator of the Non-tidal network for Chesapeake Bay Program.
- Data collection by several agencies
- Load and trend in load results are at http://cbrim.er.usgs.gov/summary.html

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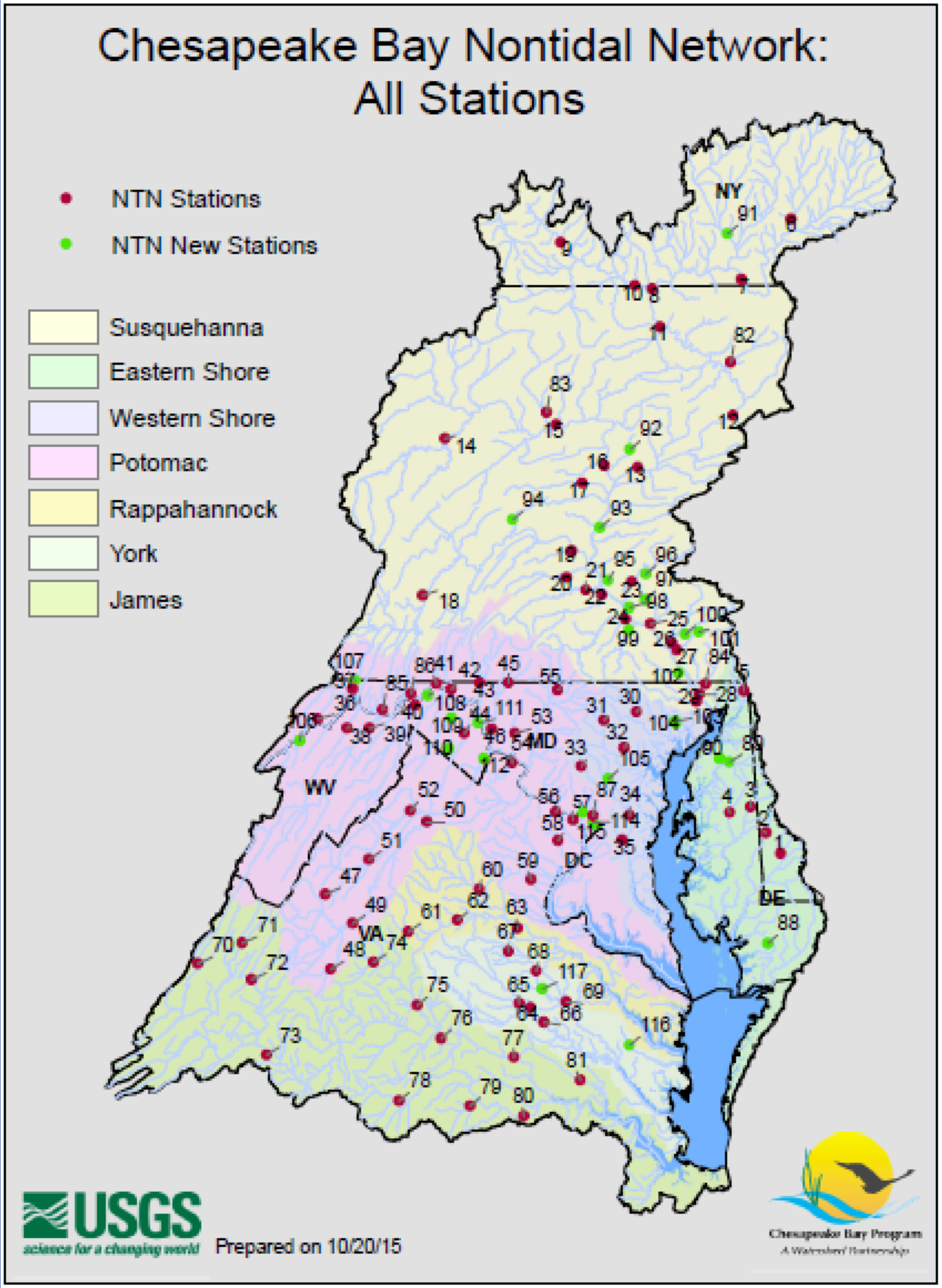

Chesapeake Bay Nontidal Monitoring Network

Monitoring Stations

- 117 monitoring stations
  - 30 with records > 30 yrs
  - 87 with records > 10 yrs
  - 30 (green on map) with records < 5 years
- Drainage areas range from 1 to 27,100 mi^2
- Six States, D.C., SRBC, USGS, and EPA
- $6M Annually - $50K per site
- USGS responsible for load and trend computation
- Discharge data available at all sites
- Sampling by Equal Width Intervals (integrated samples with isokinetic samplers)

Data Collection

Sampling Goals

Collect 20 water-quality samples per year
12 Routine Samples
8 Storm-Impacted Samples
(required for load quantification)

Water-Quality Measurements

Streamflow
Field parameters
Nitrogen (TN, DN, PN, NOx, NH_4^+)
Phosphorus (TP, DP, PP, SRP)
Sediment (SSC, TSS, VSS, FSS)

Equal Width Increment "EWI"

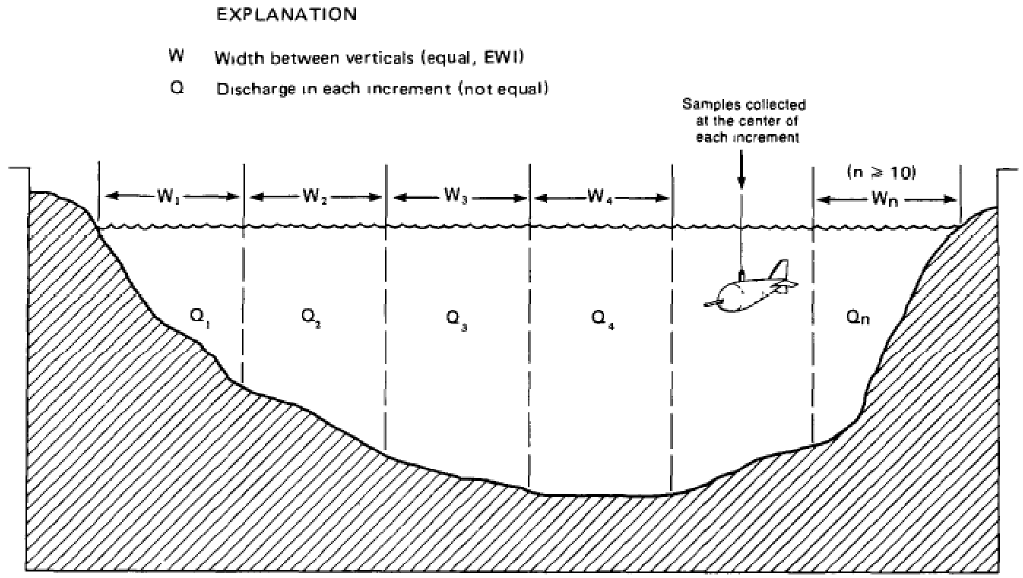

Figure 36. Equal-width-increment sampling technique.

Figure 36. Equal-width-increment sampling technique.

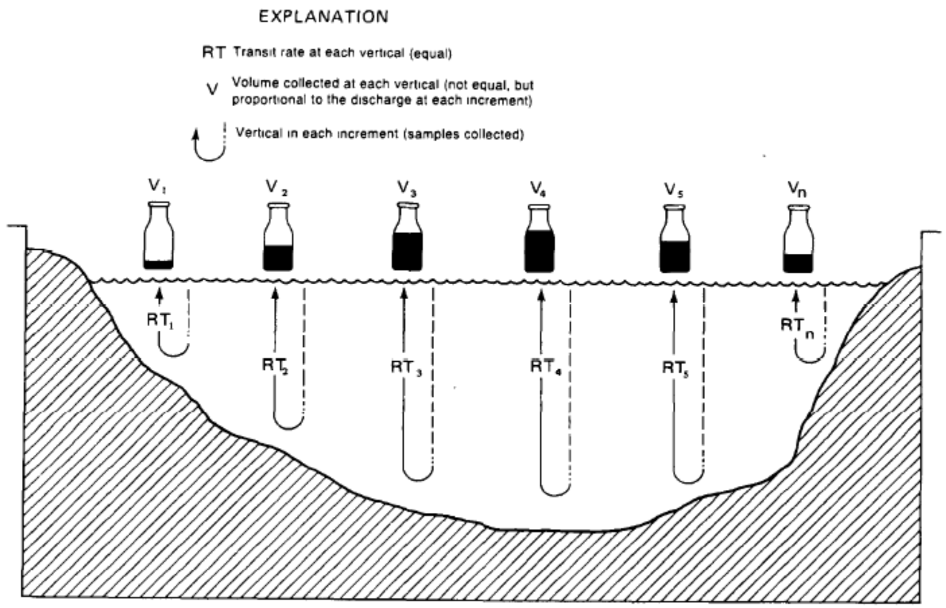

Figure 37. Equal-width-increment vertical transit rate relative to sample volume, which is proportional to water discharge at each vertical.

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Data Collection

WBH-96

Data Collection

DH-95

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Total Nitrogen per Acre Loads

Total nitrogen loads range from 1.19 to 33.4 lbs/ac with an average load of 7.33 lbs/ac

3 Categories of Loads:

(1) Low =
≤ 6.88 lbs/ac
52 of 81 stations

(2) Medium =
> 6.88 to ≤ 13.75
15 of 81 stations

(3) High Yields = ≥ 13.76
14 of 81 stations

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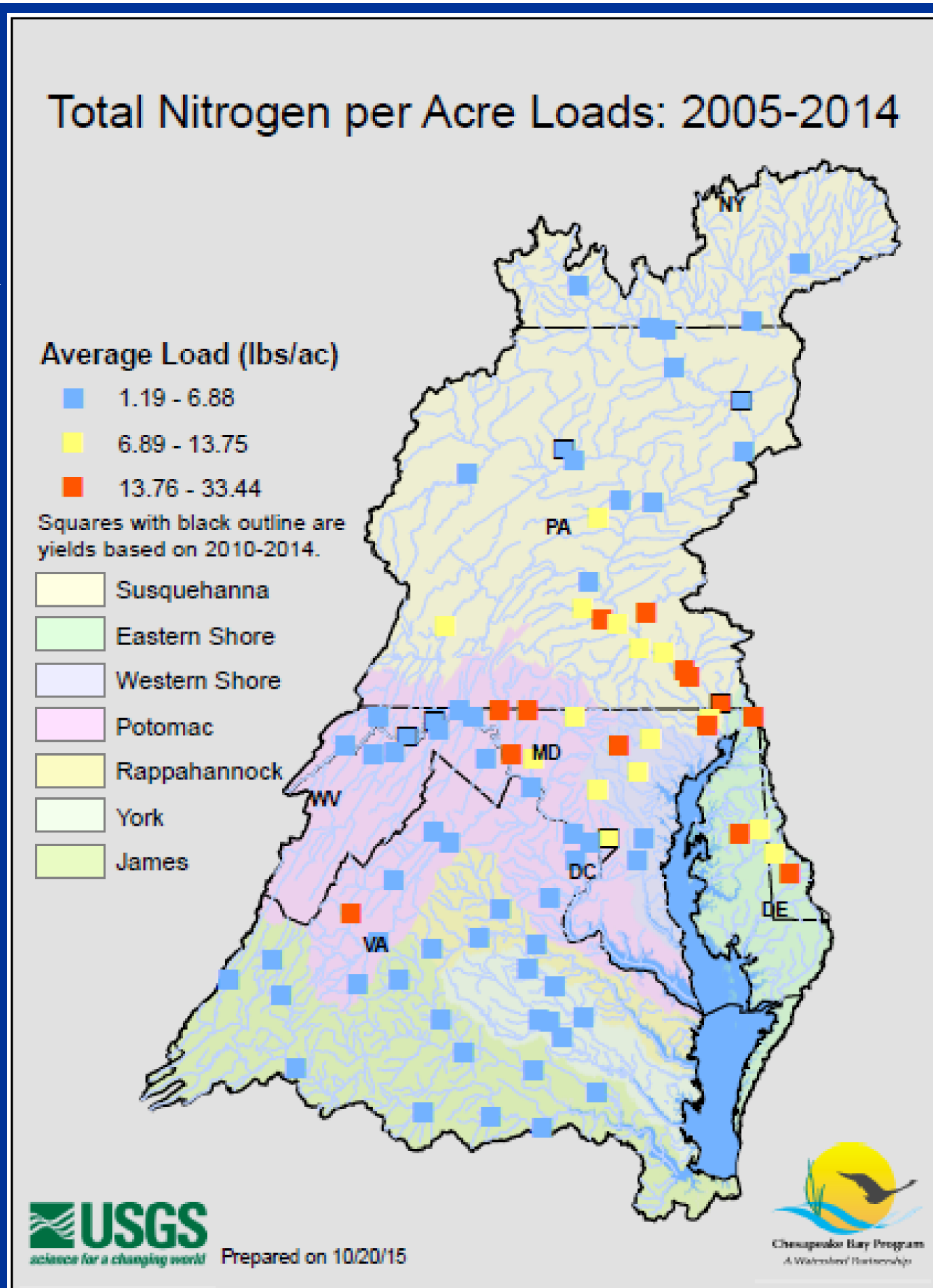

Total Nitrogen per Acre Loads and Trends: 2005-2014

Improving Trends = 44 of 81 (54%)
Degrading Trends = 22 of 81 (27%)
No Trend = 15 of 81 (19%)

Of the 14 stations with the highest per acre loads for Total Nitrogen:

- 6 have improving trends
- 3 have degrading trends
- 4 have no trends
- 1 has insufficient data for trends

Results by major basins

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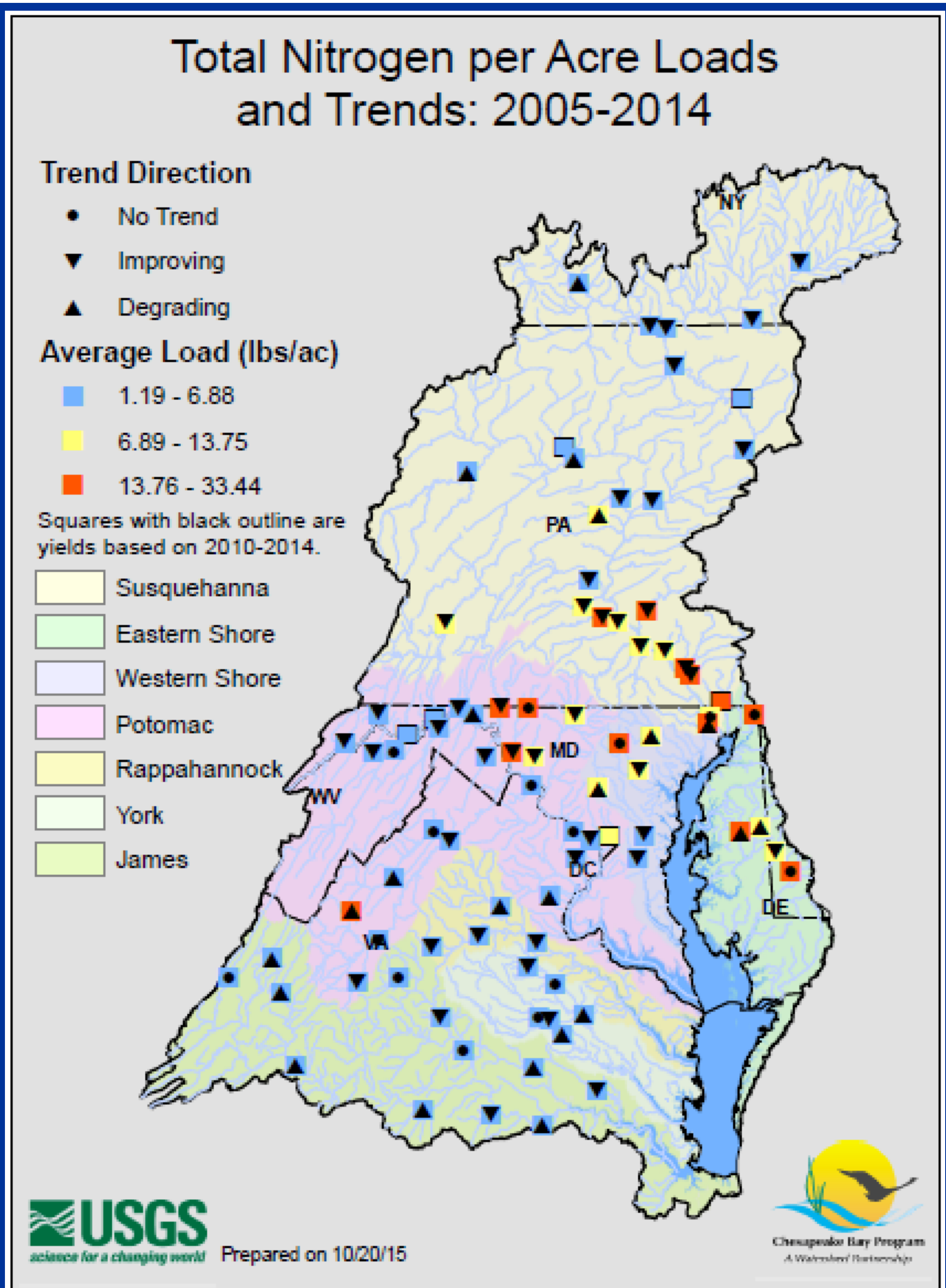
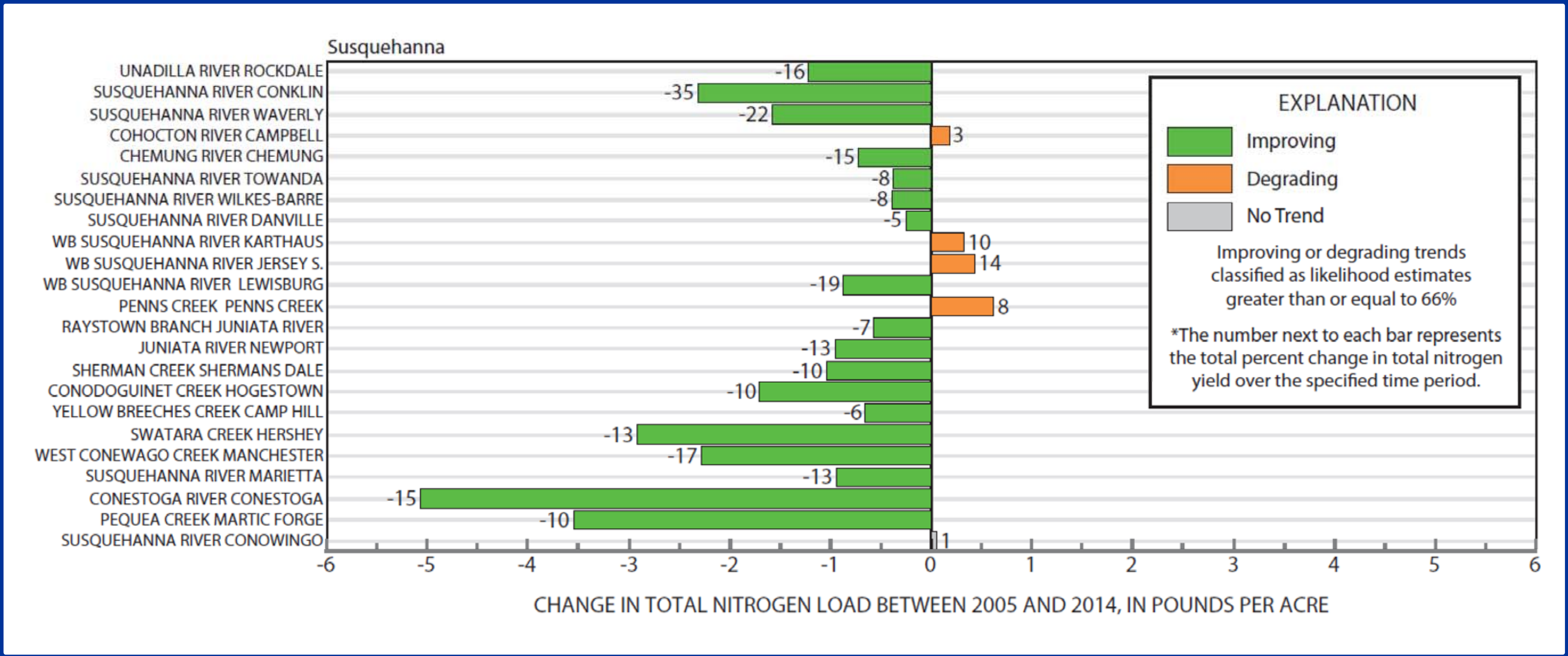


Changes in Nitrogen per Acre Loads: 2005-2014

Example from the Susquehanna Watershed



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Changes in Nitrogen per Acre Loads: 2005-2014

Trend in load network is the first of its kind

Improving Stations

Range = -0.10 to -5.07 lbs/ac

Median = -0.68 lbs/ac (-10.0%)

Degrading Stations

Range = 0.04 to 1.21 lbs/ac

Median = 0.33 lbs/ac (7.84%)

Download figure:
http://cbrim.er.usgs.gov/maps.html

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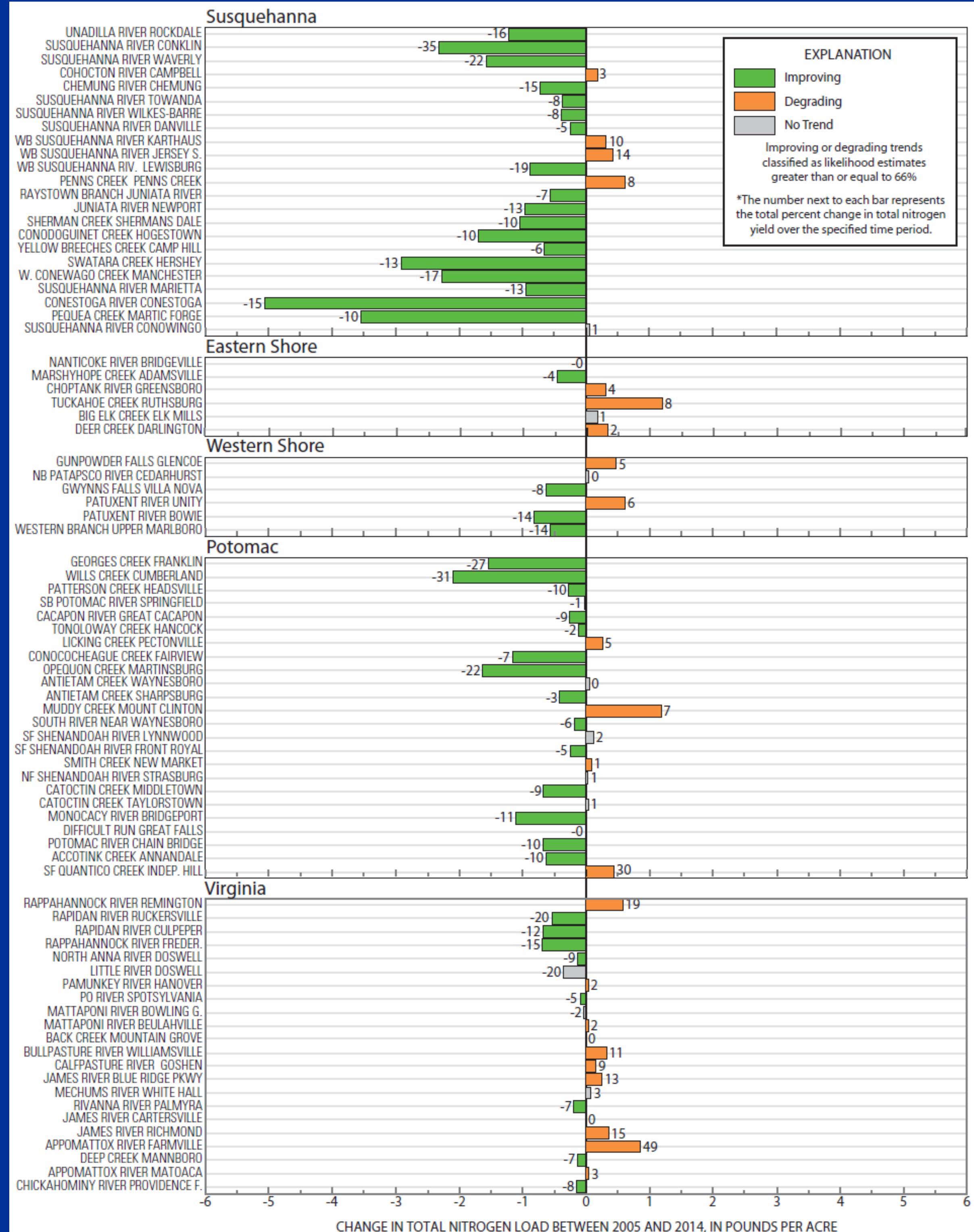

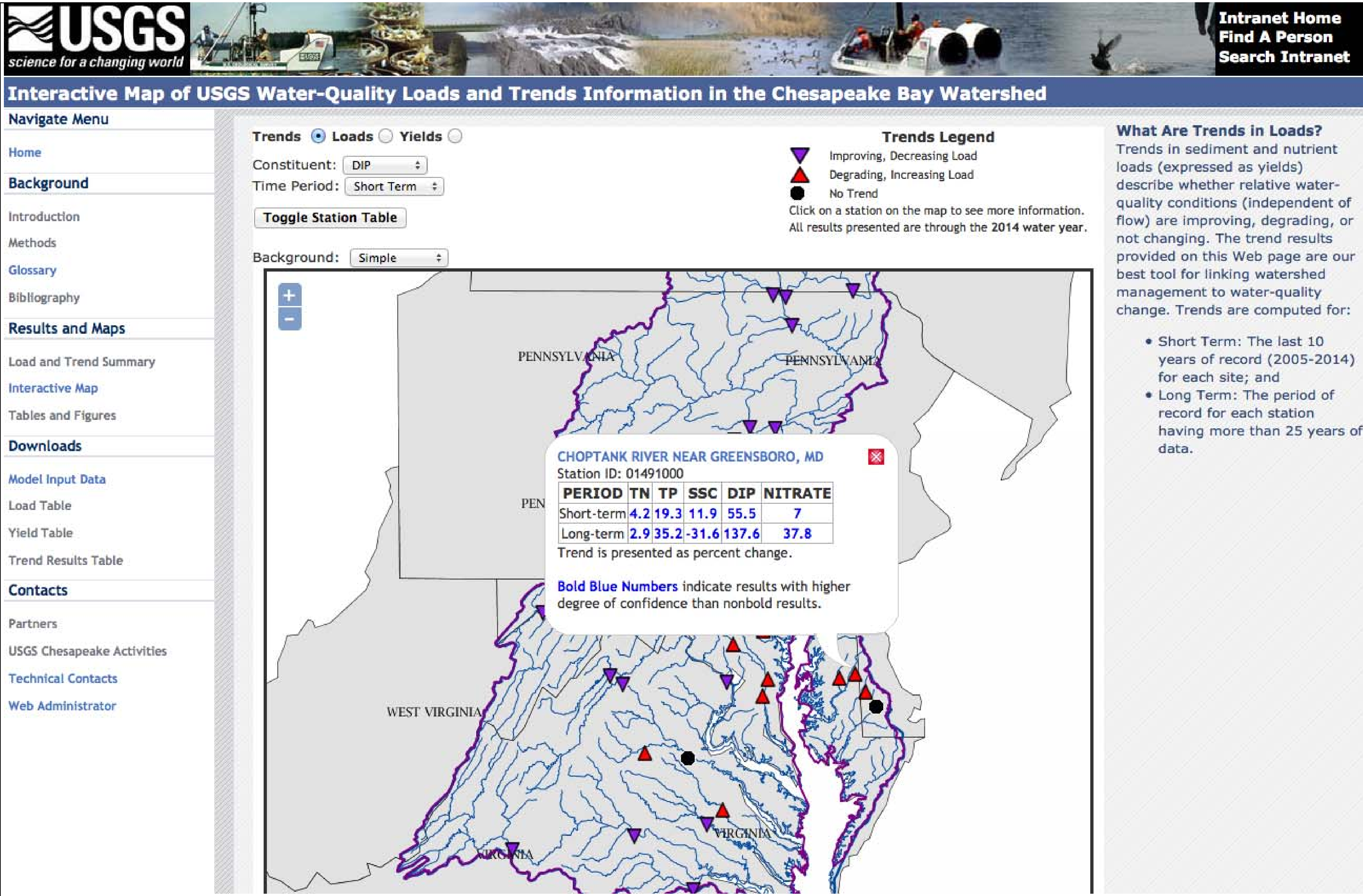
USGS
science for a changing world
Intranet Home
Find A Person
Search Intranet
Interactive Map of USGS Water-Quality Loads and Trends Information in the Chesapeake Bay Watershed
Navigate Menu
Home
Background
Introduction
Methods
Glossary
Bibliography
Results and Maps
Load and Trend Summary
Interactive Map
Tables and Figures
Downloads
Model Input Data
Load Table
Yield Table
Trend Results Table
Contacts
Partners
USGS Chesapeake Activities
Technical Contacts
Web Administrator
Trends Loads Yields
Constituent: DIP
Time Period: Short Term
Toggle Station Table
Background: Simple
Trends Legend
Improving, Decreasing Load
Degrading, Increasing Load
No Trend
Click on a station on the map to see more information.
All results presented are through the 2014 water year.
PENNSYLVANIA
PENNSYLVANIA
WEST VIRGINIA
VIRGINIA
CHOPTANK RIVER NEAR GREENSBORO, MD
Station ID: 01491000
PERIOD | TN | TP | SSC | DIP | NITRATE
Short-term | 4.2 | 19.3 | 11.9 | 55.5 | 7
Long-term | 2.9 | 35.2 | -31.6 | 137.6 | 37.8
Trend is presented as percent change.
Bold Blue Numbers indicate results with higher degree of confidence than nonbold results.
What Are Trends in Loads?
Trends in sediment and nutrient loads (expressed as yields) describe whether relative water-quality conditions (independent of flow) are improving, degrading, or not changing. The trend results provided on this Web page are our best tool for linking watershed management to water-quality change. Trends are computed for:
• Short Term: The last 10 years of record (2005-2014) for each site; and
• Long Term: The period of record for each station having more than 25 years of data.

These results are being used to:

- **explain change**
- **enhance models**
- **measure progress**
- **inform strategies**

It is built on a 3-decade effort with many partners.

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Partners

US Environmental Protection Agency (US EPA)

Maryland Department of Natural Resources (MD DNR)

Virginia Department of Environmental Quality (VA DEQ)

Pennsylvania Department of Environmental Protection (PA DEP)

West Virginia Department of Environmental Protection (WV DEP)

Delaware Department of Natural Resources and Environmental Control (DNREC)

New York State Department of Environmental Conservation (NYSDEC)

Susquehanna River Basin Commission (SRBC)

District Department of the Environment (DDOE)

Parting thoughts

- Developing an integrated network has been a large and long-term investment.
- The Chesapeake Bay Program is now seeing payoffs.
- Because of the uniform loading-trend results there is now a very active interagency research program on “Factors Affecting Trends”
- Already have found at least two areas where the TMDL model and observations don’t agree
  - Role of stored phosphorus in soils with conservation tillage
  - Changing trapping efficiency of an old reservoir.

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Parting thoughts - 2

- WRTDS does more than provide a measure of progress
- It provides tools for improved understanding
- The EGRET-R software, provides a toolbox for many types of inquiries. WRTDS and more.
- EGRET = Exploration and Graphics for RivEr Trends
- A couple of examples:

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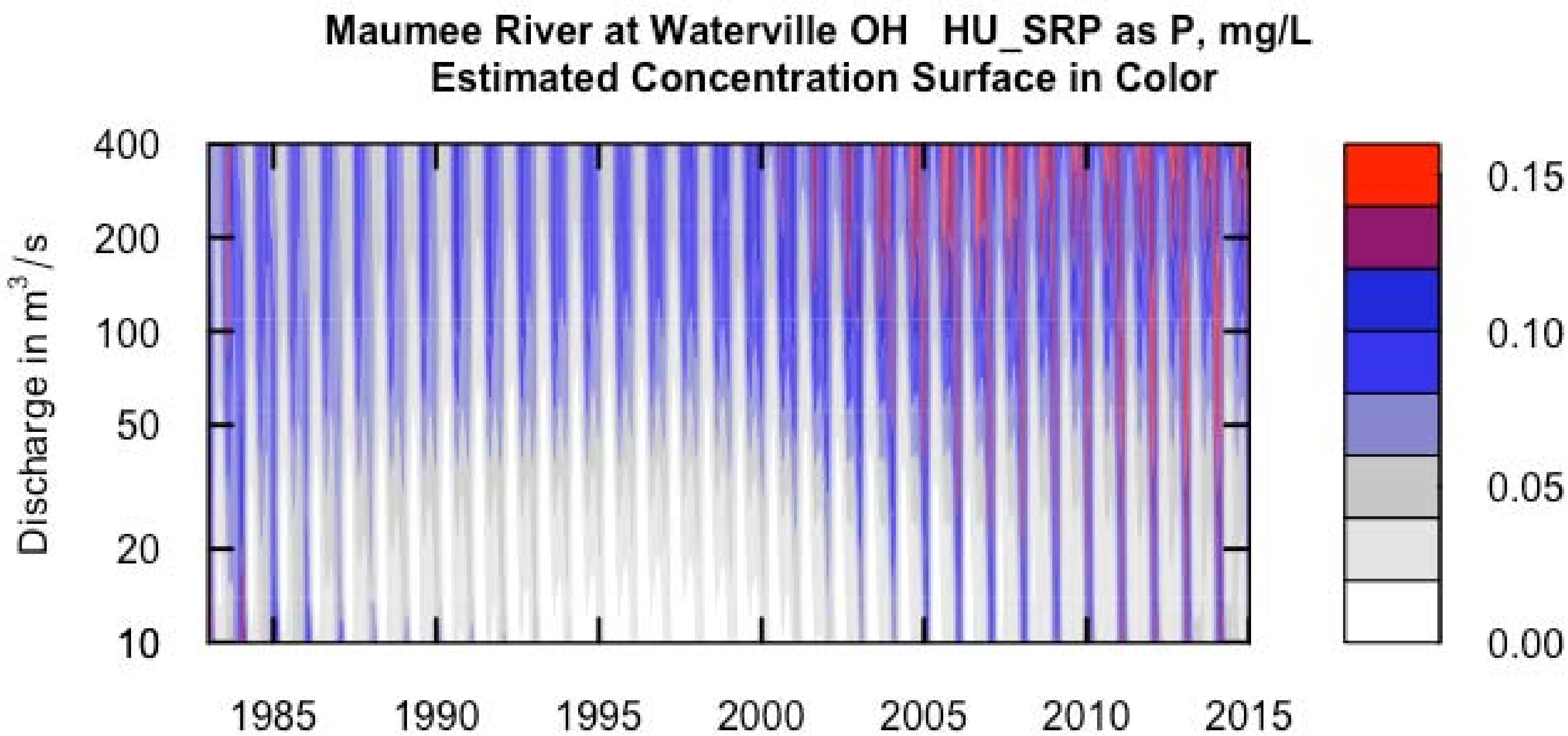
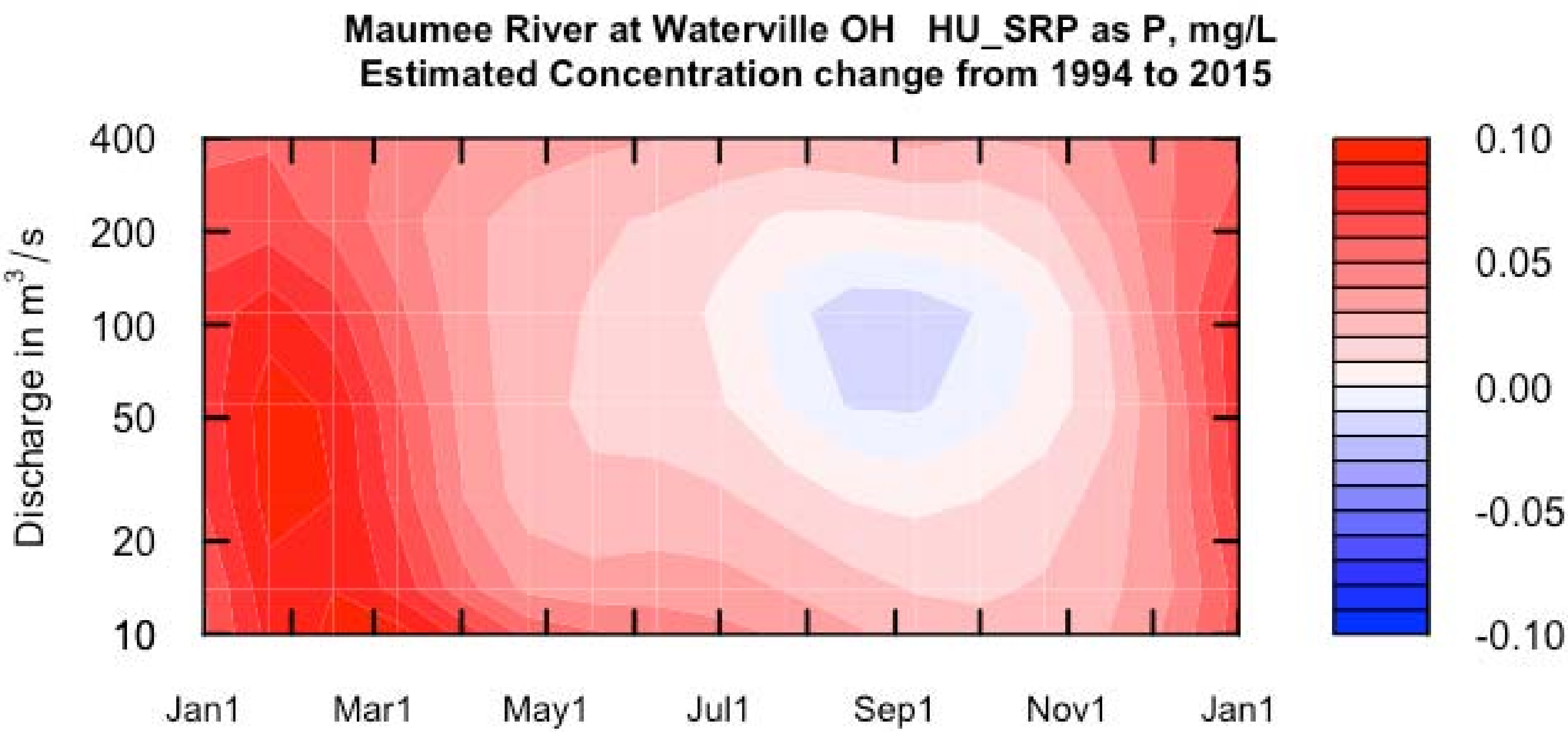
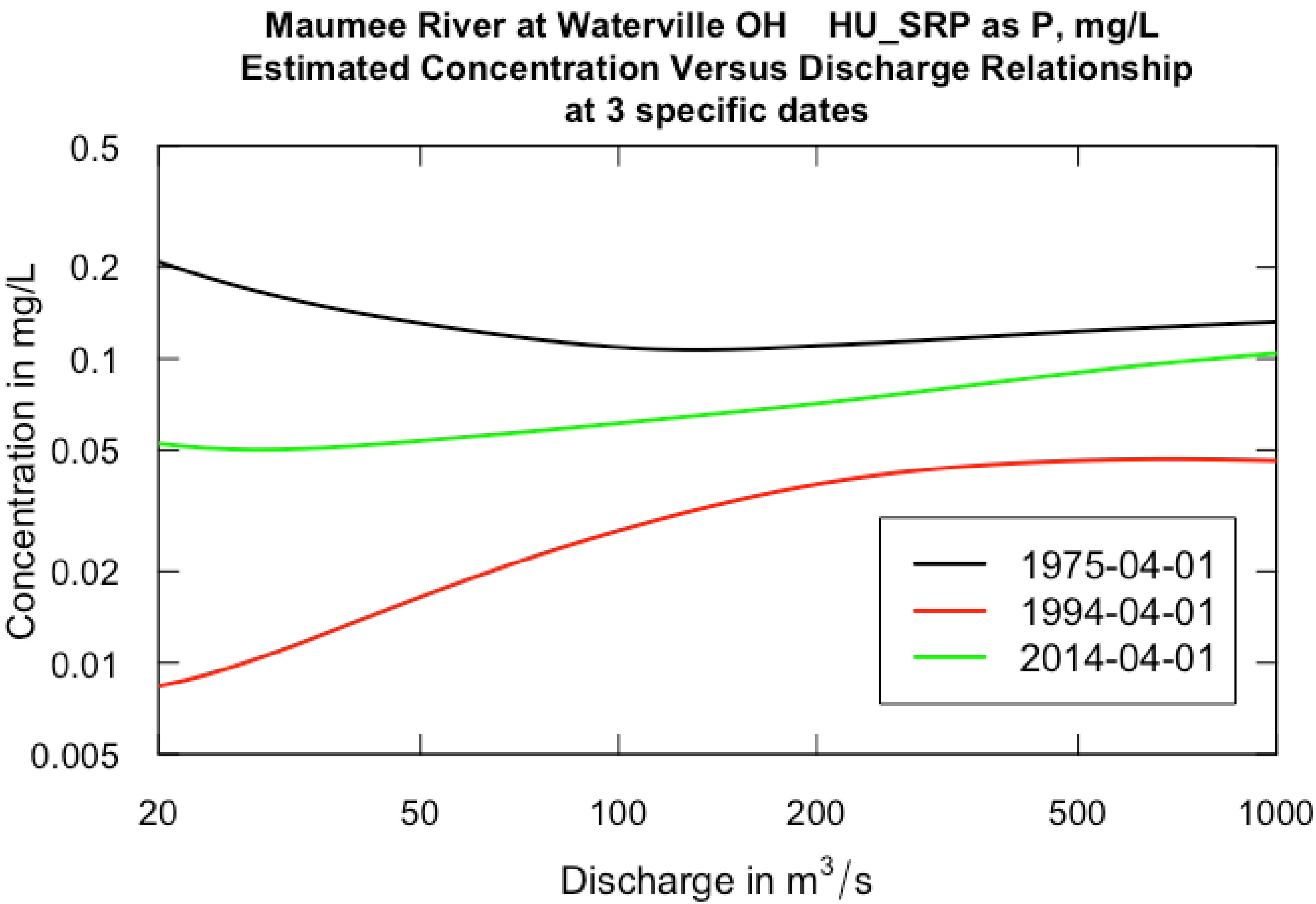
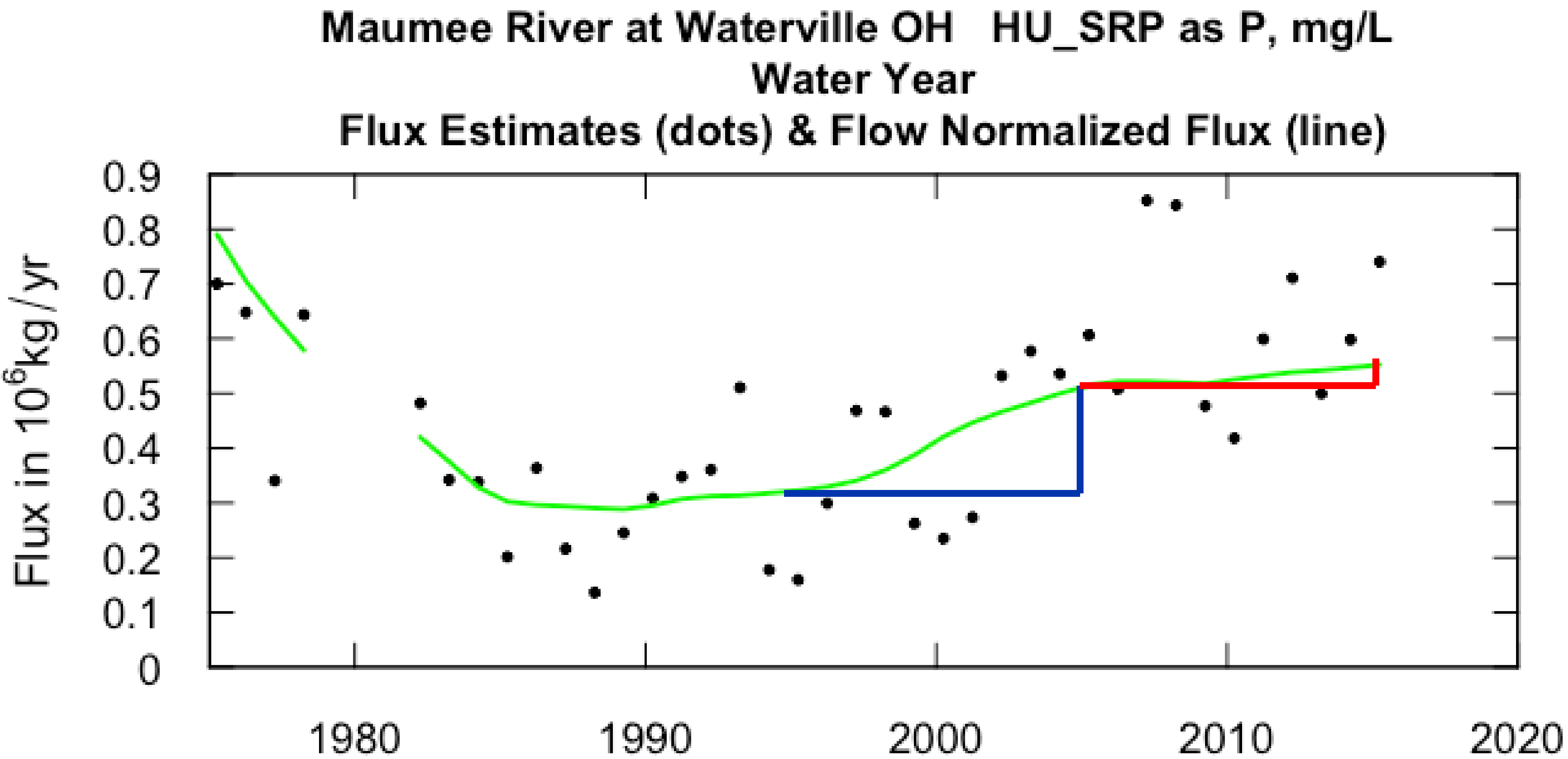

Maumee River at Waterville OH HU_SRP as P, mg/L
Estimated Concentration Surface in Color
Discharge in m^3/s
400
200
100
50
20
10
1985
1990
1995
2000
2005
2010
2015
0.15
0.10
0.05
0.00


Maumee River at Waterville OH HU_SRP as P, mg/L
Estimated Concentration change from 1994 to 2015
Discharge in m^3/s
400
200
100
50
20
10
Jan1
Mar1
May1
Jul1
Sep1
Nov1
Jan1
0.10
0.05
0.00
-0.05
-0.10



Maumee River at Waterville OH HU_SRP as P, mg/L
Estimated Concentration Versus Discharge Relationship
at 3 specific dates
Concentration in mg/L
0.5
0.2
0.1
0.05
0.02
0.01
0.005
20
50
100
200
500
1000
Discharge in m3/s
1975-04-01
1994-04-01
2014-04-01

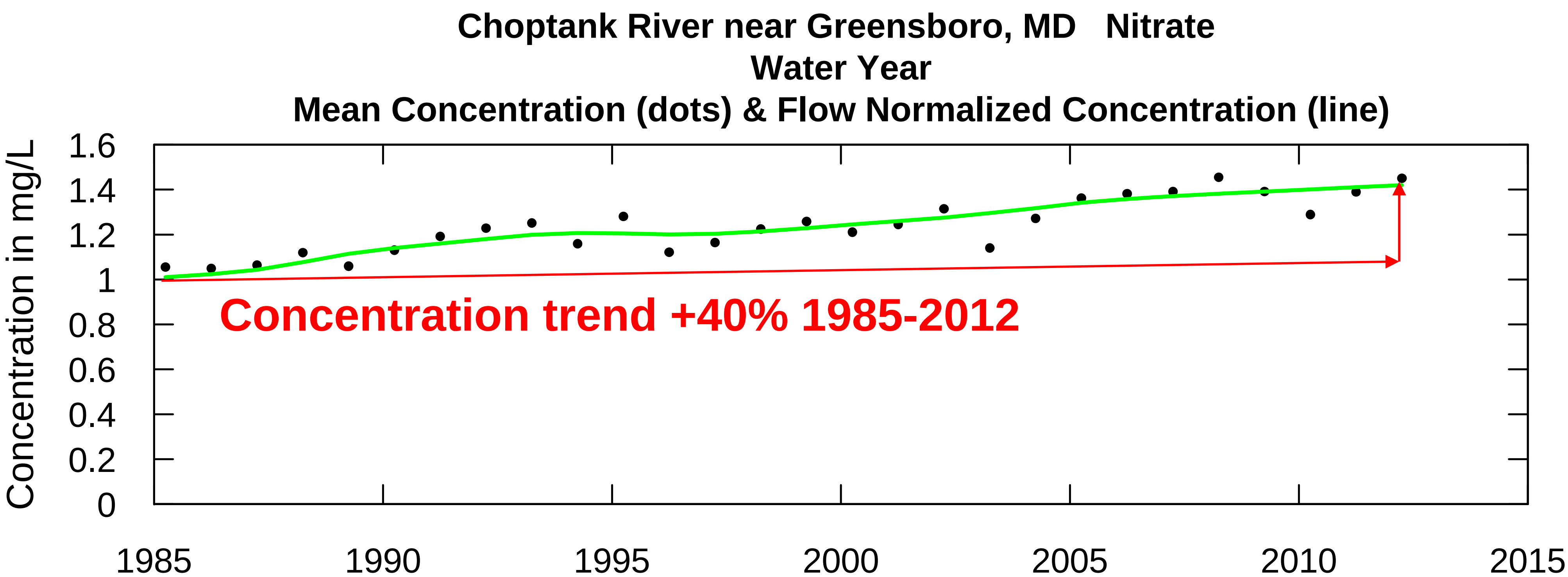


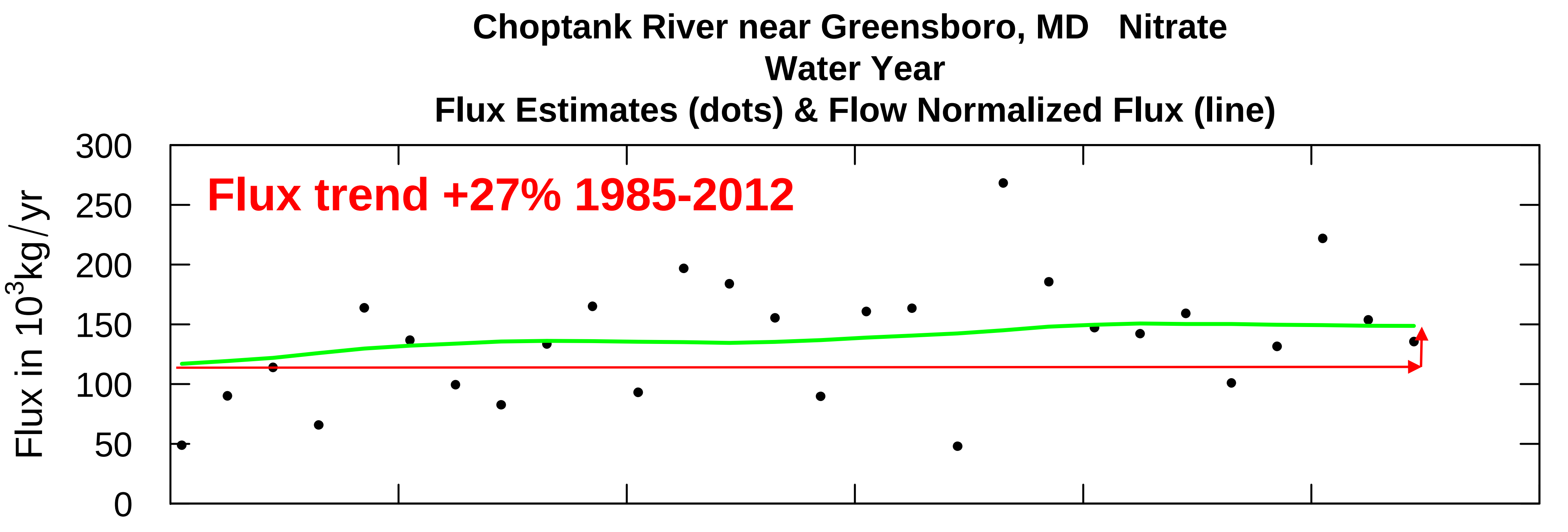
Trend from 1995 to 2005 = +6% per year

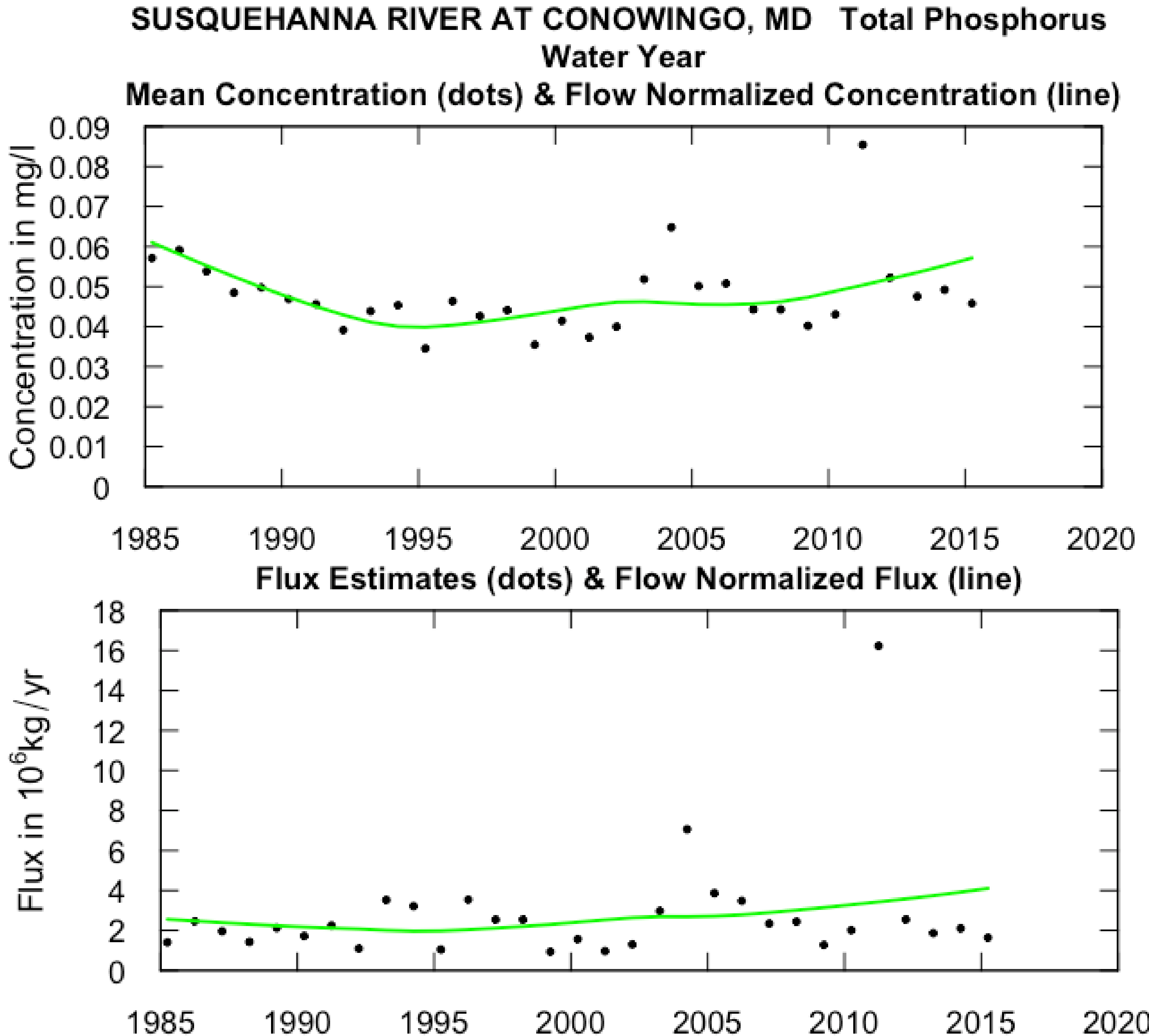
Trend from 2005 to 2015 = +0.7% per year

Two examples where the difference between concentration trends and flux trends proved to be highly informative

USGS


Choptank River near Greensboro, MD Nitrate
Water Year
Mean Concentration (dots) & Flow Normalized Concentration (line)
Concentration in mg/L
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Concentration trend +40% 1985-2012
1985
1990
1995
2000
2005
2010
2015


Choptank River near Greensboro, MD Nitrate
Water Year
Flux Estimates (dots) & Flow Normalized Flux (line)
Flux in 10^3kg/yr
300
250
200
150
100
50
0
Flux trend +27% 1985-2012



1995-2015 trend +2.2%/yr

1995-2015 trend +5.4%/yr

Parting thoughts - 3

- Protocols don’t have to be identical, but their functional similarity needs to be demonstrated
- The Chesapeake Bay network was planned over 20 years ago using the best technology at the time.
- In my opinion, evolving technology points the way to more use of continuous sensors, coupled with highly-accurate calibration samples on a regular basis over a range of conditions.
- For loading trends there will need to be explicit consideration of the drift in the relationship of instrument values to actual concentrations.

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