Use of Dynamic SPARROW Modeling in Characterizing Time-Lags in Nitrogen Transport in the Potomac River Basin

Presented By

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Workshop:

"Lag Times in the Watershed and Their Influence on Chesapeake Bay Restoration"

Scientific and Technical Advisory Committee, Chesapeake Bay Program
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Presentation Outline

- Brief overview of the SPARROW model
  - Limitations of the steady–state formulation and goals of developing a dynamic formulation: “Space for time?”
- Significance of watershed storage and derivation of a recursive regression equation
- Use of Enhanced Vegetation Index data
- Results of dynamic SPARROW calibration
- Application of model to WRTDS load estimates

What is SPARROW?

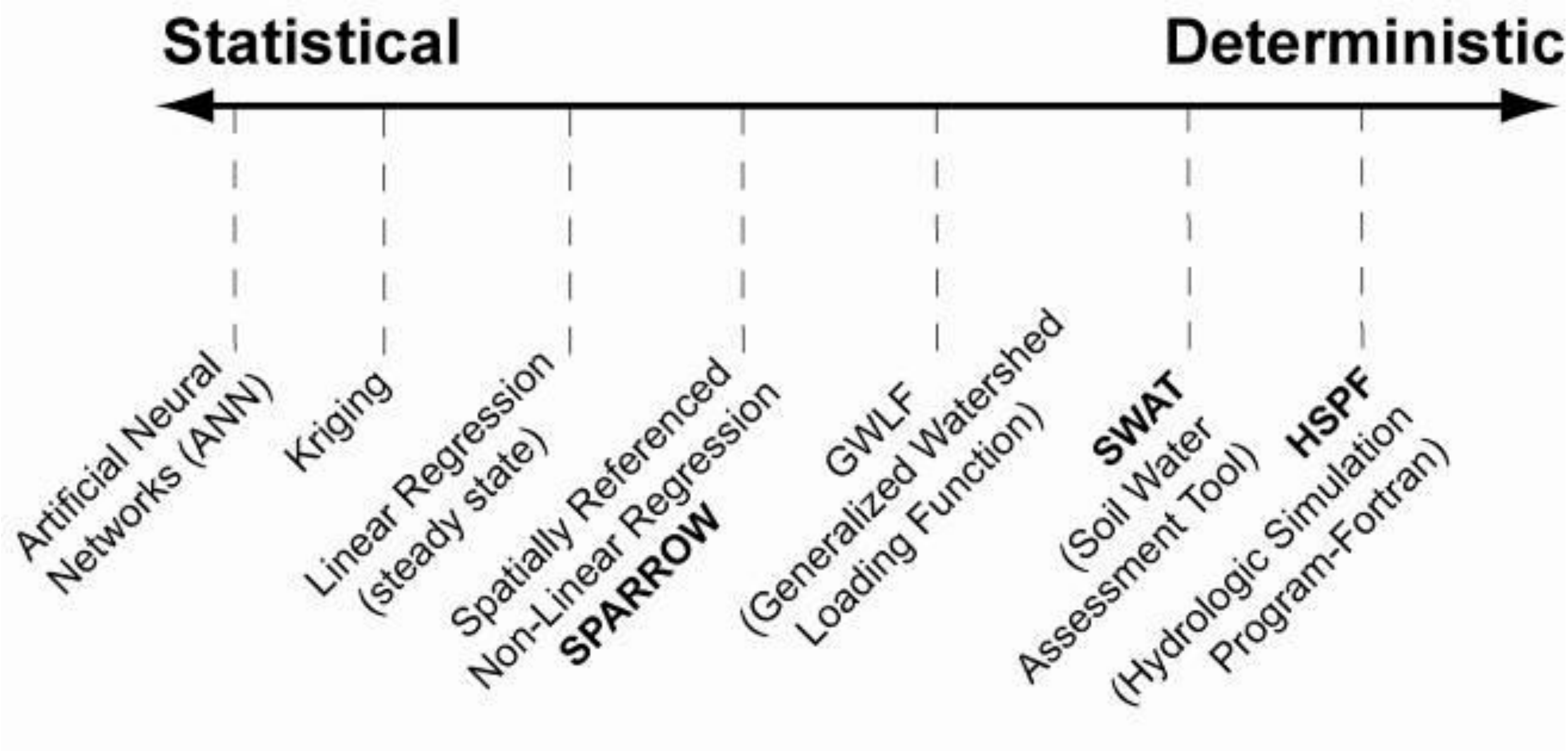
SPAtially Referenced Regressions On Watershed Attributes

- Hybrid empirical / mechanistic watershed WQ model
- Explains spatial variation in WQ data from monitoring networks
- Spatially detailed predictions
- Maintains mass balance in channel network
- Calibration through statistical optimization
- Predictions accompanied by error estimates

Watershed Modeling Continuum
Wide variety of model types

Data Driven (Inductive)

Physically Based (Deductive)



Schwarz et al., 2006, USGS Techniques and Methods Report

SPARROW's Reach-Scale Mass Balance

Reach network relates watershed data to monitored loads

$$LOAD_i = \left\{ \sum_{j \in J(i)} \left[\sum_{n=1}^{N} S_{n,j} \beta_n \exp(-\alpha' Z_j) \right] \prod_m \exp(-\delta_m^s T_{i,j,m}) \prod_l 1/(1+\lambda^r q_{i,j,l}^{-1}) \right\} \exp(\varepsilon_i)$$

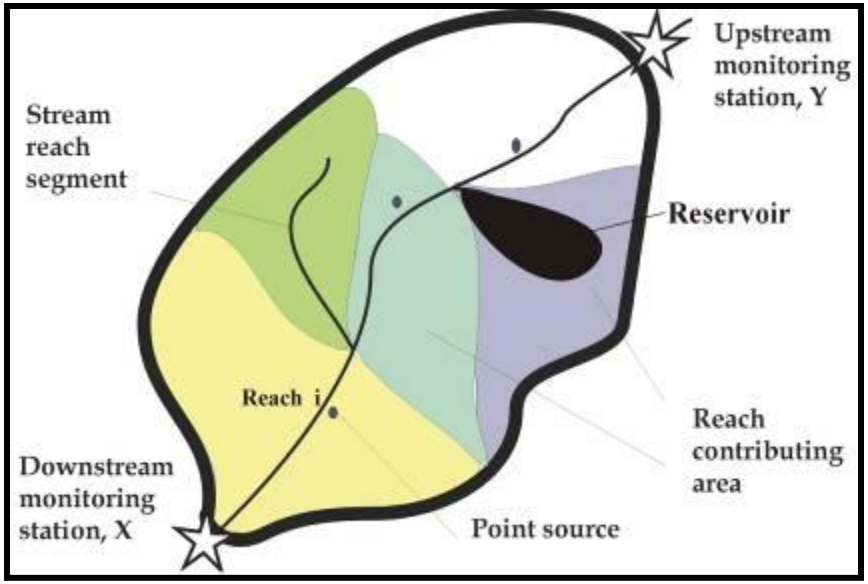
Monitored Stream Load

Sources

Land-to-water transport

Aquatic transport

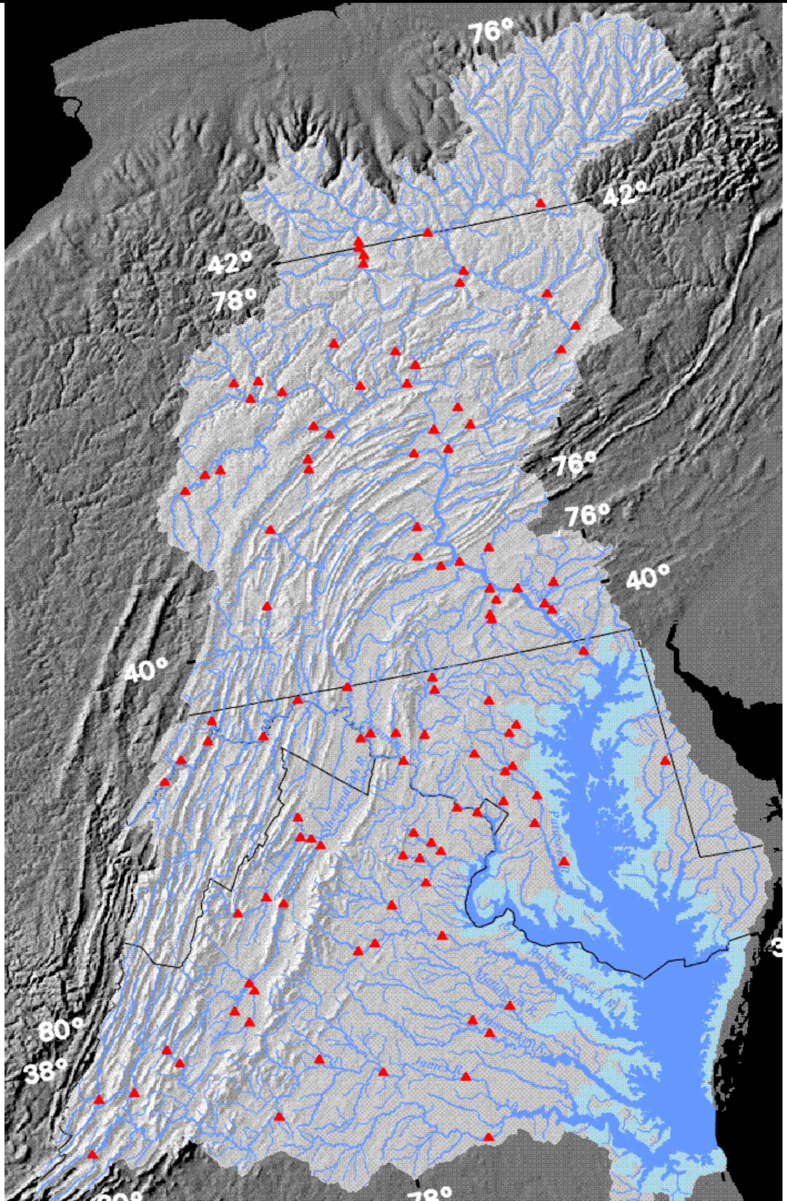
Error



- **Spatial reference frame is stream network, coupled to DEM**
- **Fundamental spatial element is stream reach and associated incremental drainage area**
- **SPARROW estimates the optimal set of rate coefficients that balance material mass (source inputs, stream loads, and storage/loss)**

Importance of Large Numbers of WQ Sites

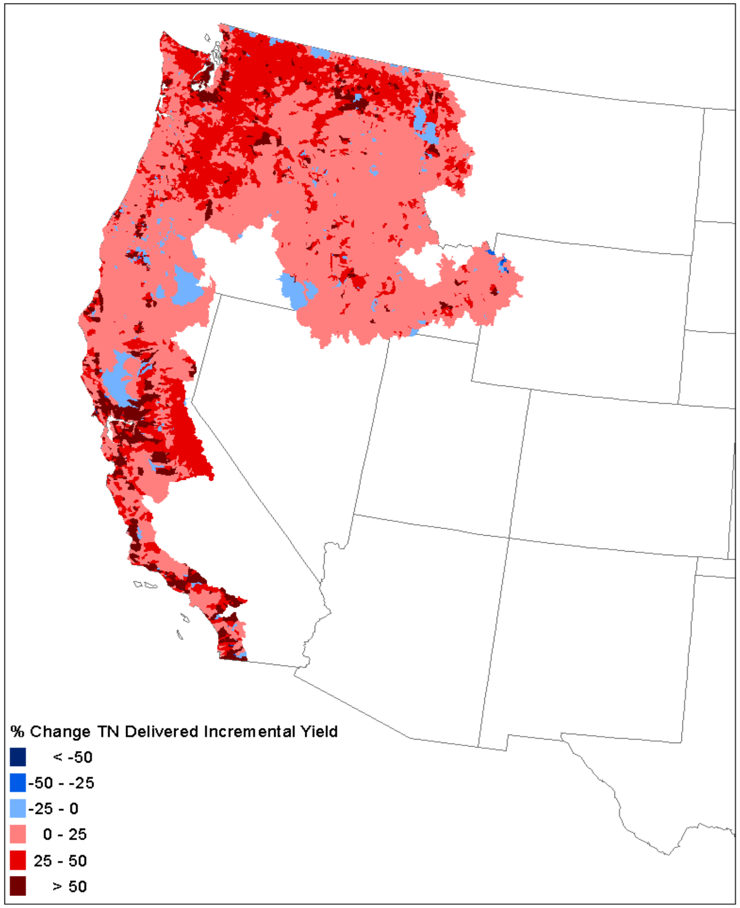
Chesapeake Bay Example



Example Application

Predicted Percent Change in TN Yield Delivered to the West Coast of the Conterminous US By 2050 Based on Projected* Land Use Changes

*IPCC Scenario A2;
USGS Land Carbon Project

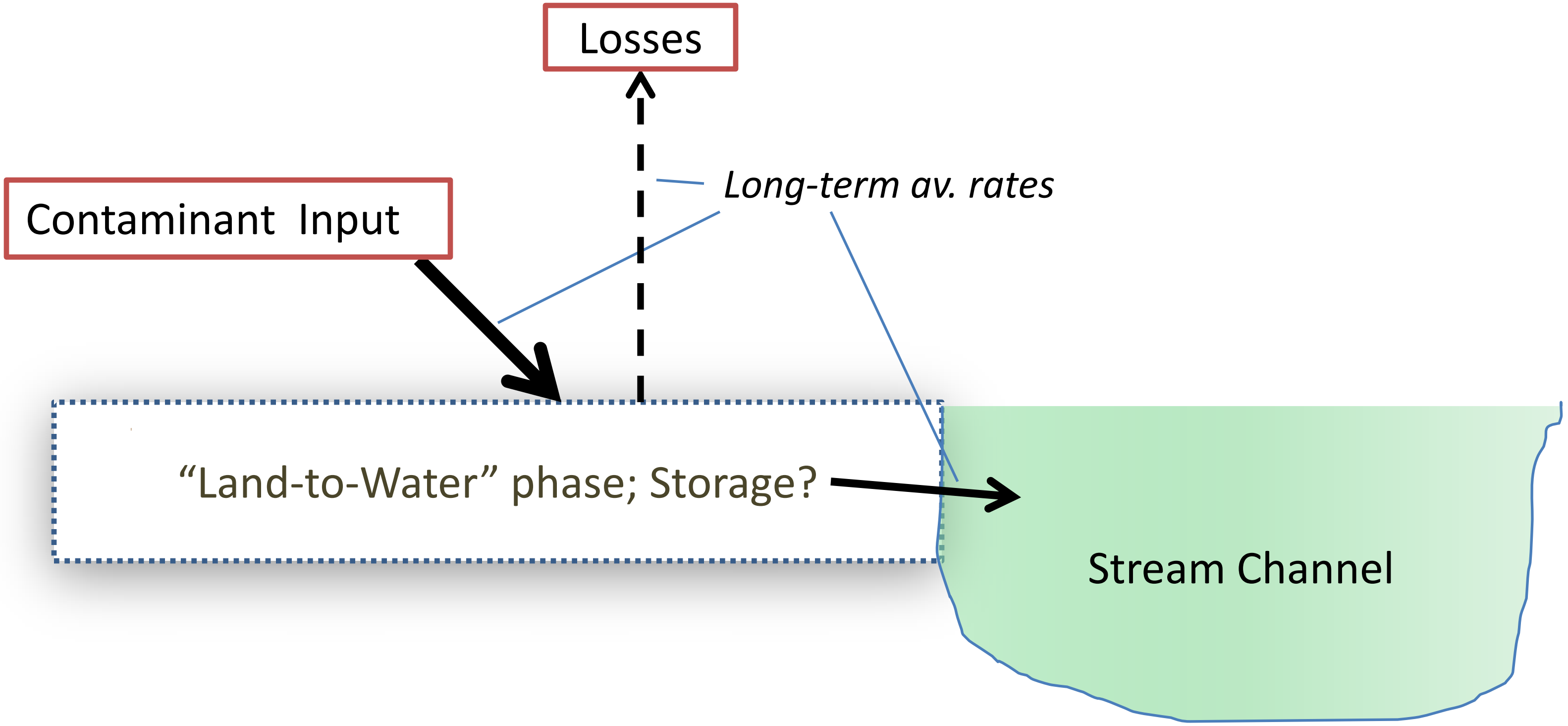


Question: Would it be possible to develop a dynamic version of SPARROW, avoid the space-for-time assumption, and estimate lag-times in nutrient transport?

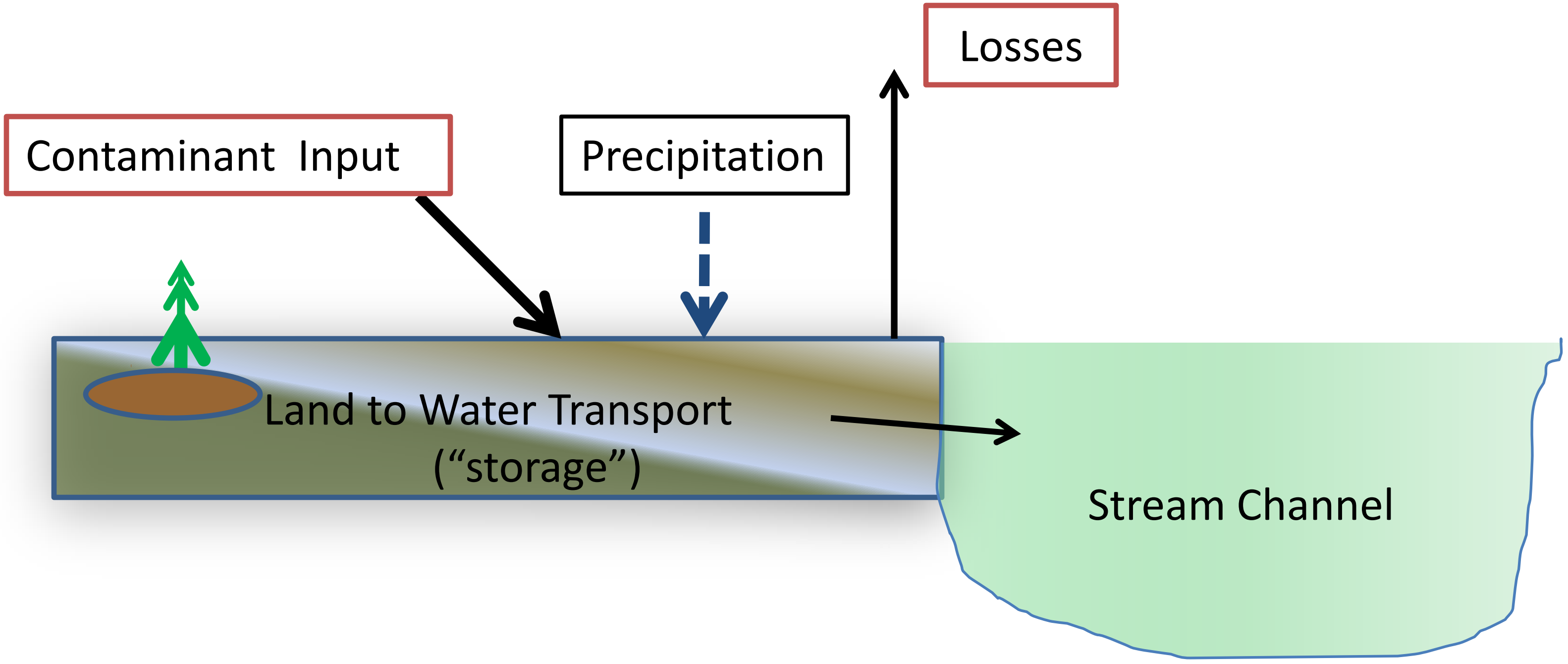
Potential Advantages of a Dynamic SPARROW Model

- Practical (in applications)
  - Interprets and predicts transitory behavior of flux given changing inputs
  - Potential improvement in accuracy by removing certain assumptions and through direct use of hydrologic forcing
  - Potential for calibration of SPARROW models at smaller scale due to increased number of observations.
- Theoretical
  - Based on a more detailed (temporal) specification of mass balance and mass residence time
  - Describes role of hydrologic forcing
  - Avoids "space-for-time" assumption in spatial modeling
  - Introduces concept of "storage" in SPARROW modeling

In a conventional (steady-state) SPARROW model, contaminant material from "sources" has an unknown mass and residence time in the "land-to-water" phase. In short, "storage" is unknown.



An essential mechanism of dynamic behavior in watersheds is temporary "storage". Storage may be either surface or subsurface . Export to stream is a function of amount in storage, hydrologic forcing, and residence time in storage.

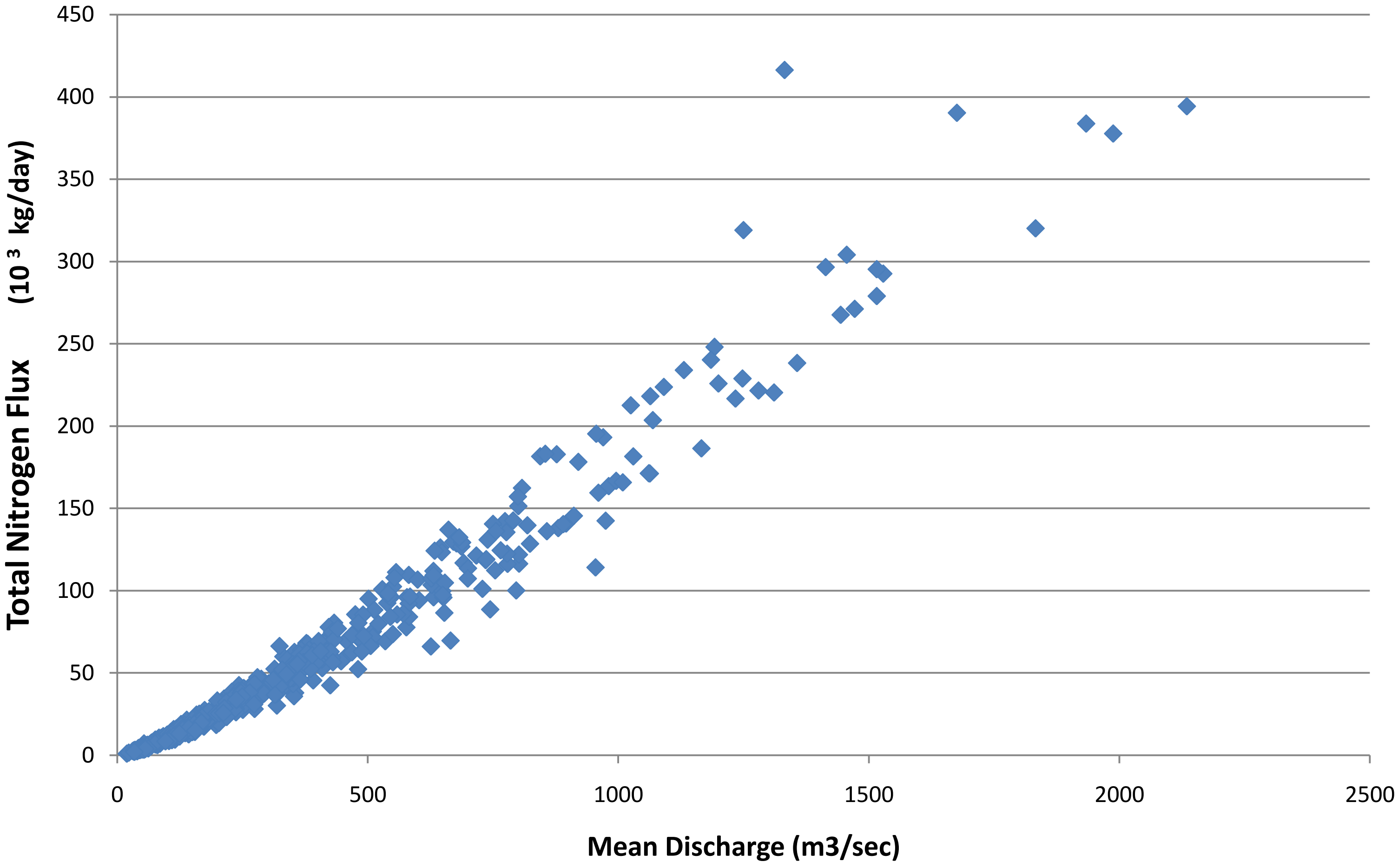


Fundamental Evidence of Importance of Storage:

- Extended periods of time when watershed output (e.g. total nitrogen stream export) exceeds total input.

- Better correlation between time series of watershed export and streamflow than with time series of inputs.

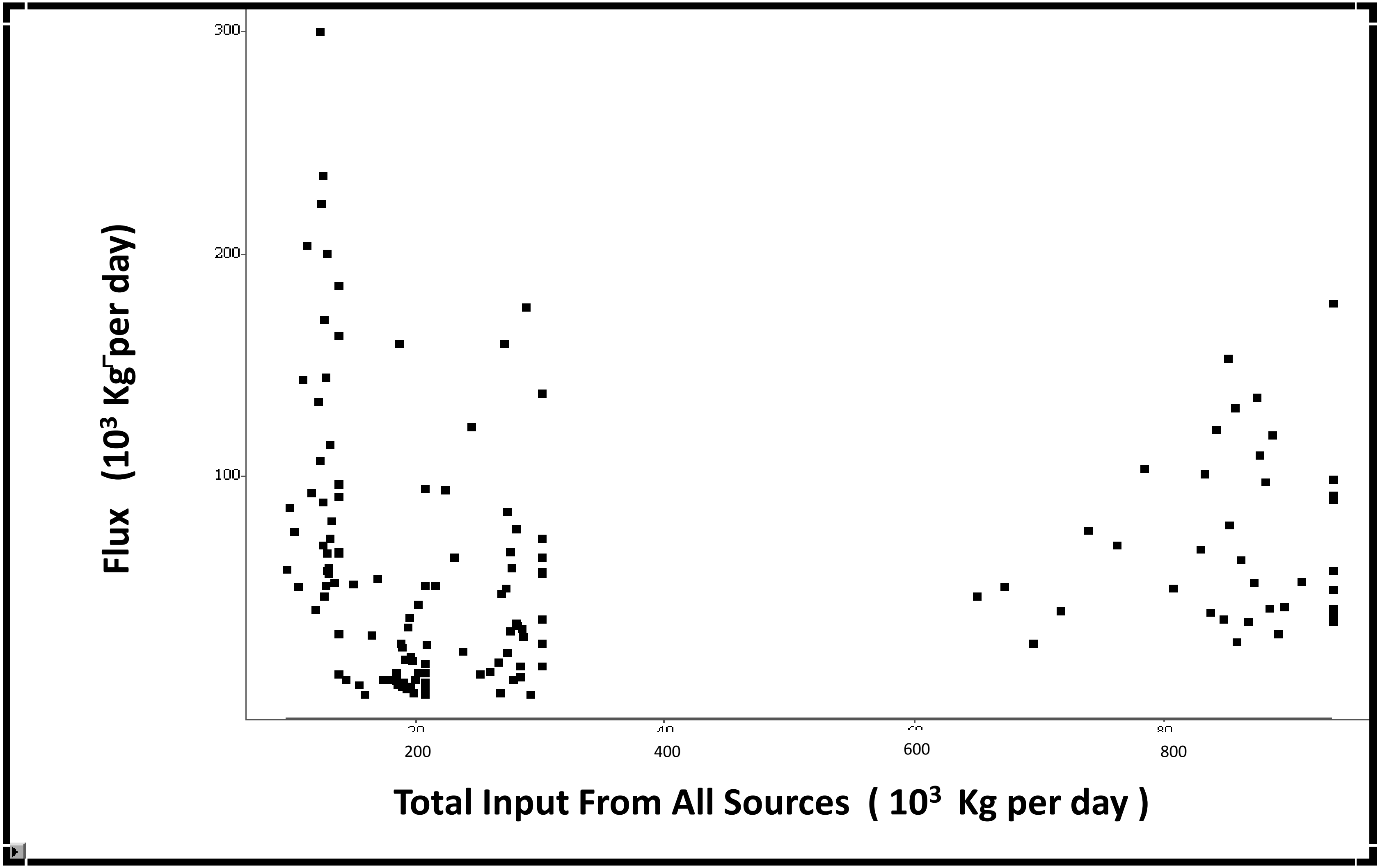
Monthly Total Nitrogen Flux *vs* Mean Discharge:
Potomac River at Chain Bridge, MD
(Based on “WRTDS” estimates)



Data: R. Hirsch, personal comm.

Total Nitrogen in the Potomac Basin

Flux at Chain Bridge *vs* Total Input From All Sources



Brief Derivation of Simple Dynamic "Storage" Model

Define:

I = rate of input of contaminant from a specific source to watershed (m/t)

S = mass of contaminant in "active" land-to-water storage (m)

L = **r S** = contaminant flux from storage to stream (m/t); **r** is 1st-order rate coefficient (1/t)

k S = instantaneous removal rate from storage to all places other than stream (e.g. atmosphere) (m/t) ; **k** is 1st-order rate coefficient (1/t)

Mass balance on storage:

$$dS/dt = I - rS - kS \qquad (1)$$

Integration over time, holding I, r, and k constant gives:

$$S_t = I/(r+k)\ [\,1 - \exp(-(r+k)\Delta t)\,] + S_0 \exp(-(r+k)\Delta t) \qquad (2)$$

Where the subscripts **0** and **t** denote the beginning and end of a time interval **Δt.** Rate coefficients **r** and **k** are average values over the interval Δt.

S, the amount of contaminant in storage, is a “latent” variable - i.e. a state variable that can not be observed or measured.

However, since $\mathbf{S = L/r}$, we can write

$$\mathbf{L_t = I\, r_t/(r+k)_{av}\ [\, 1 - \exp(-(r+k)_{av}\Delta t)\,] + \underbrace{L_0}_{\text{Lag-1 export}} r_t / r_0 \exp(-(r+k)_{av}\Delta t)} \qquad \mathbf{(3)}$$

Definitions:

I = rate of input of contaminant from a specific source to watershed (m/t)

S = mass of contaminant in “active” land-to-water storage (m)

L = **r S** = contaminant flux from storage to stream, where **r** is 1st order rate coefficient

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Subscripts **0** and **t** denote the beginning and end of a time interval **Δt.** Rate coefficients **r** and **k** are average values over the interval Δt.

Parameterization in SPARROW calibration:

r is primarily a function of hydrologic forcing (and possibly other “positive” predictors).

k is expected to be a function of temperature (and possibly other “negative” predictors).

Relationship to Steady-State SPARROW:

When $dS/dt = 0$,

$L^*/I^* = r^*/(r^*+k^*)$

where * denotes long-term, average values.

Another useful relationship (non-steady-state):

$1/(r+k)$ = mean residence time

Mass in storage at a given time:

L/r

SPARROW's Reach-Scale Mass Balance

Reach network relates watershed data to monitored loads

$$LOAD_i = \left\{ \sum_{j\in J(i)} \left[\sum_{n=1}^{N} S_{n,j}\beta_n \exp(-\alpha' Z_j) \right] \prod_m \exp(-\delta_m^s T_{i,j,m}) \prod_l 1/(1+\lambda^r q_{i,j,l}^{-1}) \right\} \exp(\varepsilon_i)$$

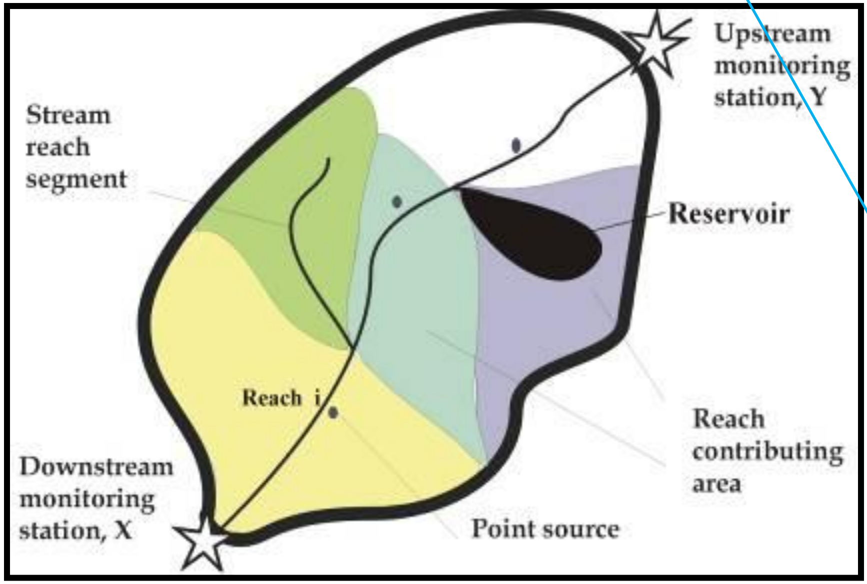
Monitored Stream Load

Sources

Land-to-water transport

Aquatic transport

Error



Required Modification of SPARROW Equation

1. **Addition of runoff, and lag-1 runoff, to Land-to-water transport term**
2. **Addition of lag-1 source term(s) based on observed downstream flux in previous time step.**

Preliminary Calibration of Dynamic SPARROW Model of Total Nitrogen in Potomac Basin

- Based on NHD stream network (16,000$^+$ reaches/catchments)
- 81 water-quality monitoring stations for "observed" flux
- TN sources: point, urban runoff, atmosphere, fertilizer, farm animal waste, catchment "storage"
- Land-to-water drivers: runoff, delta runoff, MODIS vegetation index
- Seasonal time series of all data for fall 2001 through fall 2008

Use of Enhanced Vegetation Index from MODIS

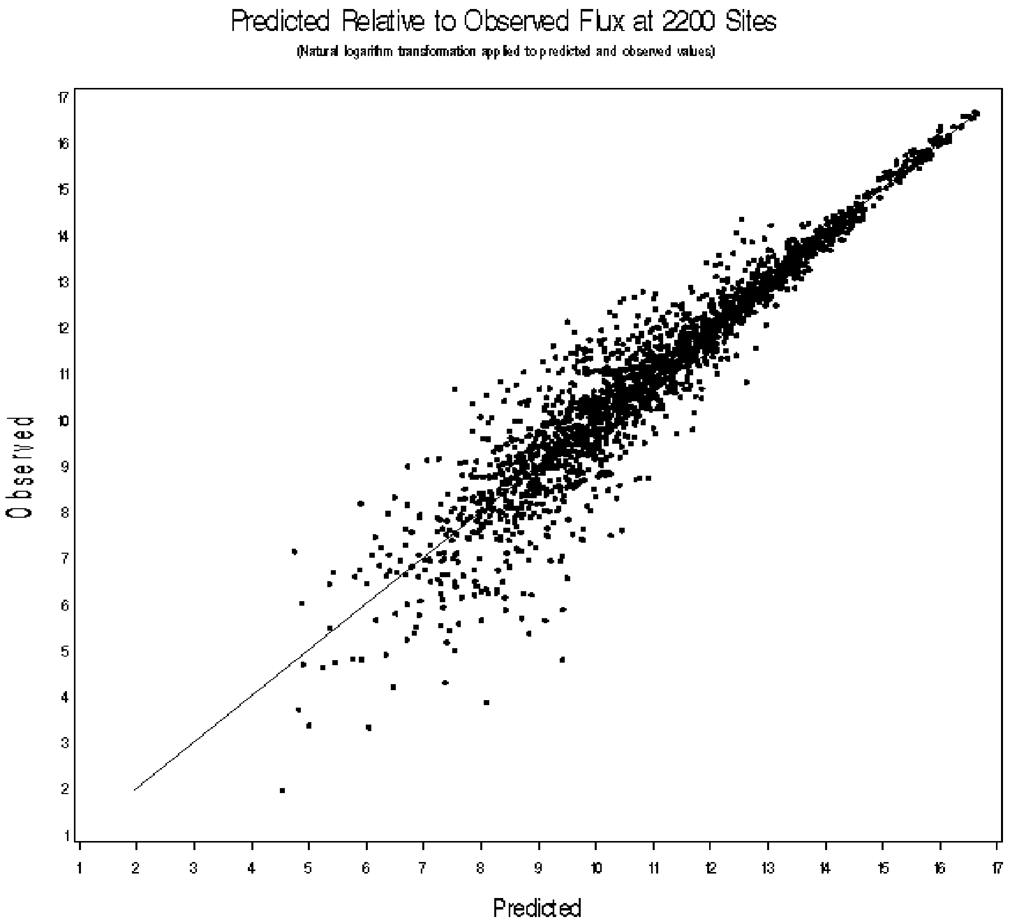
- One challenge in dynamic modeling of reactive nitrogen is obtaining frequently-reported, spatially-detailed input data on the phenology of agricultural production and terrestrial vegetation.
- Used Enhanced Vegetation Index (EVI) data from the MODIS sensor on Terra Satellite to parameterize seasonal uptake and release of nitrogen
- EVI is “enhanced” over NDVI
- 500-meter pixels
- Seasonal data developed from 8-day composite data

Calibration Results (overall)

No. of observations	2268
R^2	90
Yield R^2	68
RMSE	0.69

ln Observed *vs* ln Predicted

(81 sites, 27 seasonal time steps)



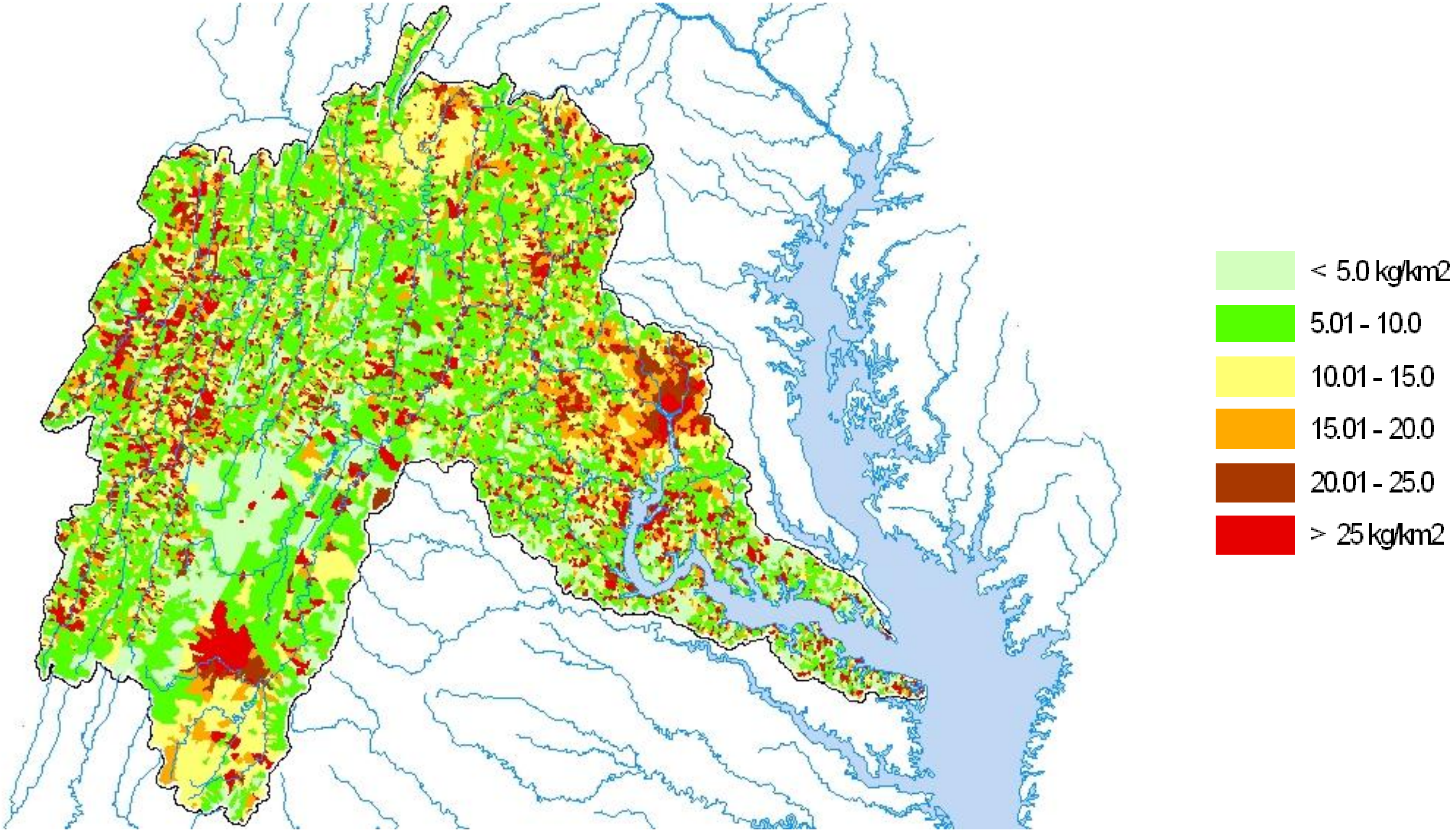
Calibration Results (sources)

Nitrogen source	Units	Coefficient estimate	“t” statistic	Significance (p)
Point sources	kg/yr	0.66	5.9	$< 10^{-4}$
Urban runoff	sq km	427	8.5	$< 10^{-4}$
Atmosphere	kg/yr	0.11	7.5	$< 10^{-4}$
Fertilizer	kg/yr	0.034	4.1	$< 10^{-4}$
Animal waste	kg/yr	0.060	7.7	$< 10^{-4}$
“Storage” (lag-1 flux)	kg/yr	0.35	16	$< 10^{-4}$

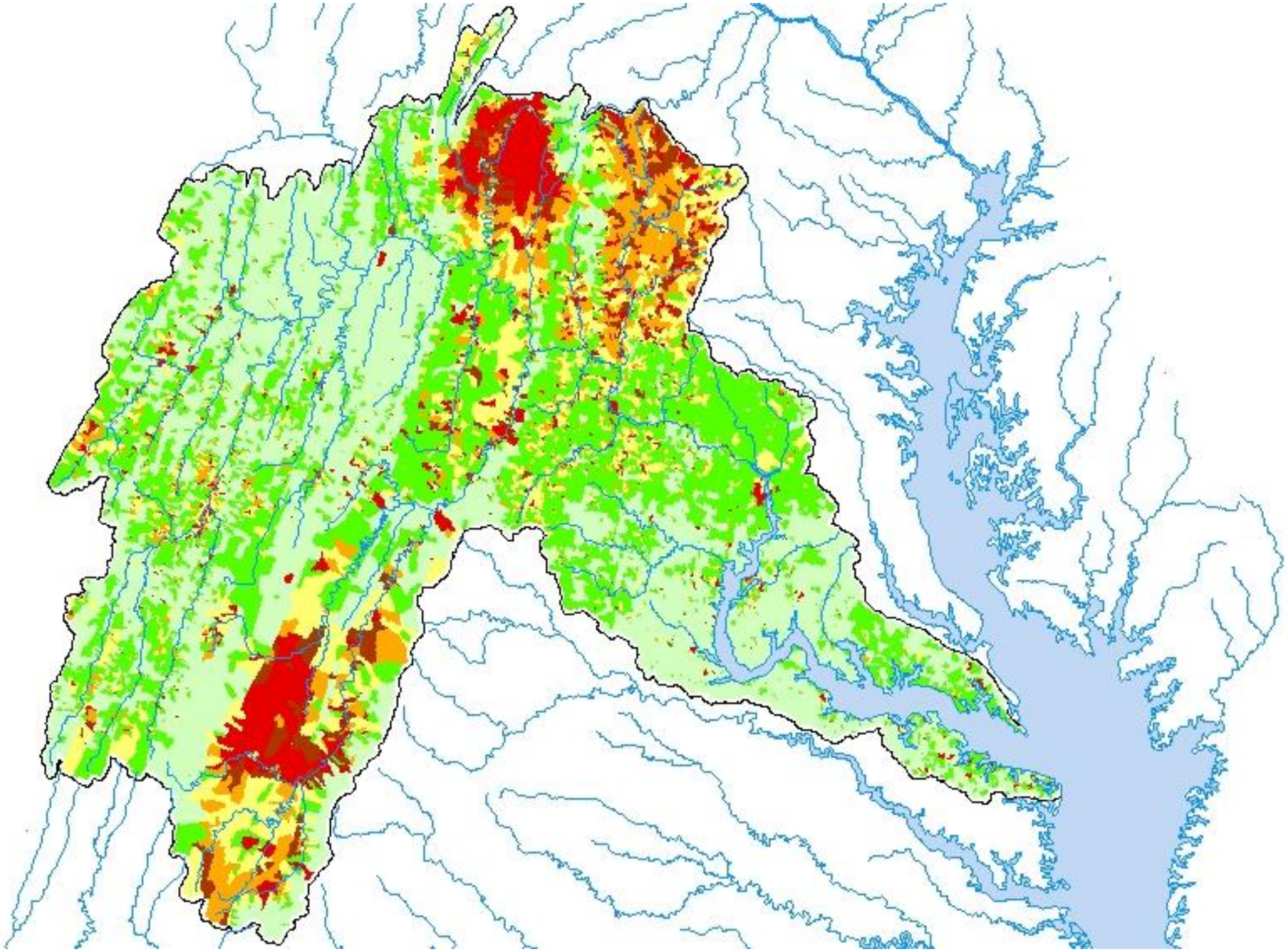
Calibration Results (transport)

Factor/process	Units	Coefficient estimate	“t” statistic	Significance (p)
ln Runoff	ln	0.78	16.6	$< 10^{-4}$
ln delta runoff	ln	0.30	5.1	$< 10^{-4}$
ln EVI	-	-0.90	-10.1	$< 10^{-4}$
In-stream decay	days	0.015	0.56	0.58

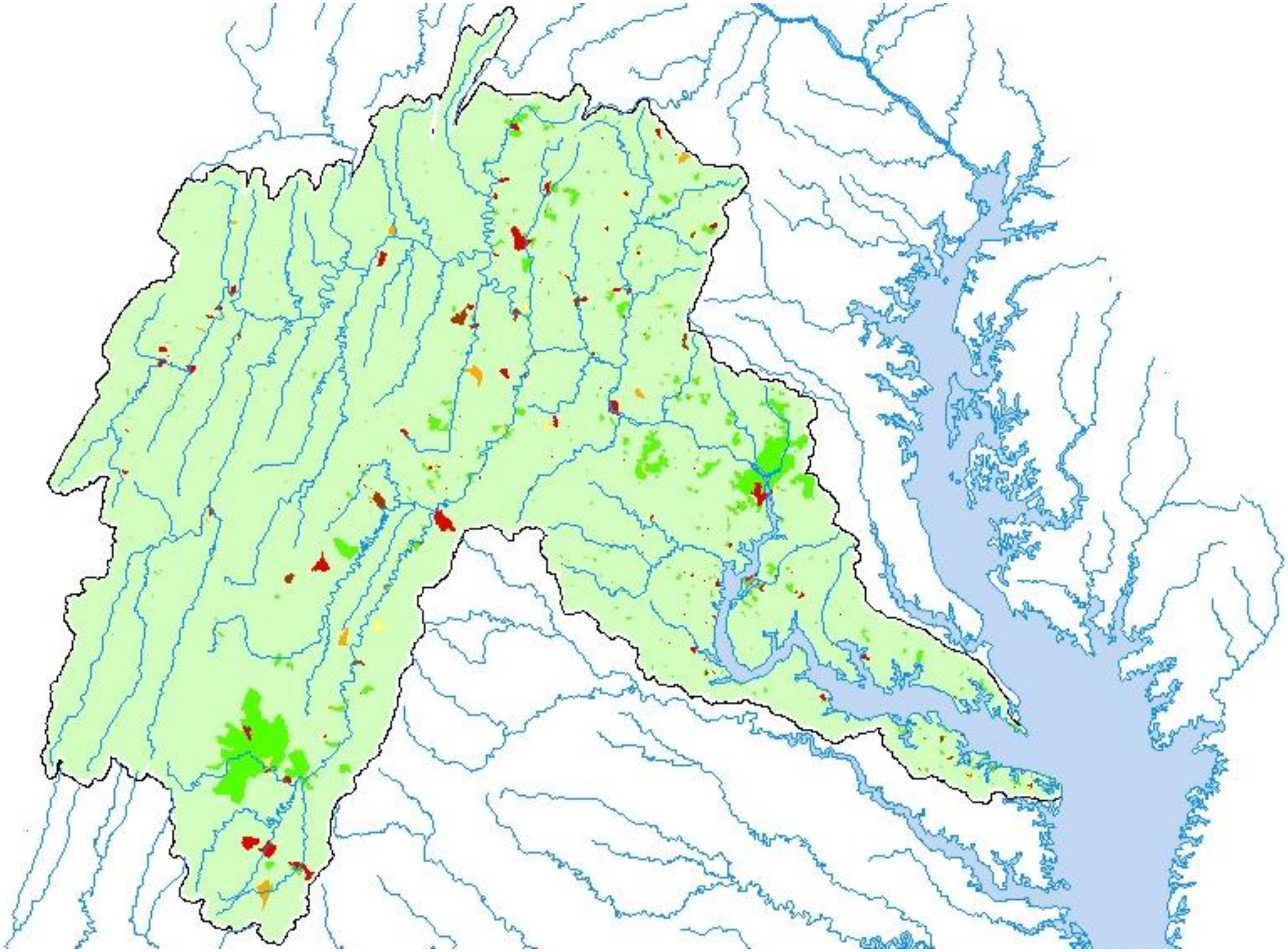
Total Nitrogen Yield (kg km^{-1} day^{-1}); Winter (J, F, M) 2006



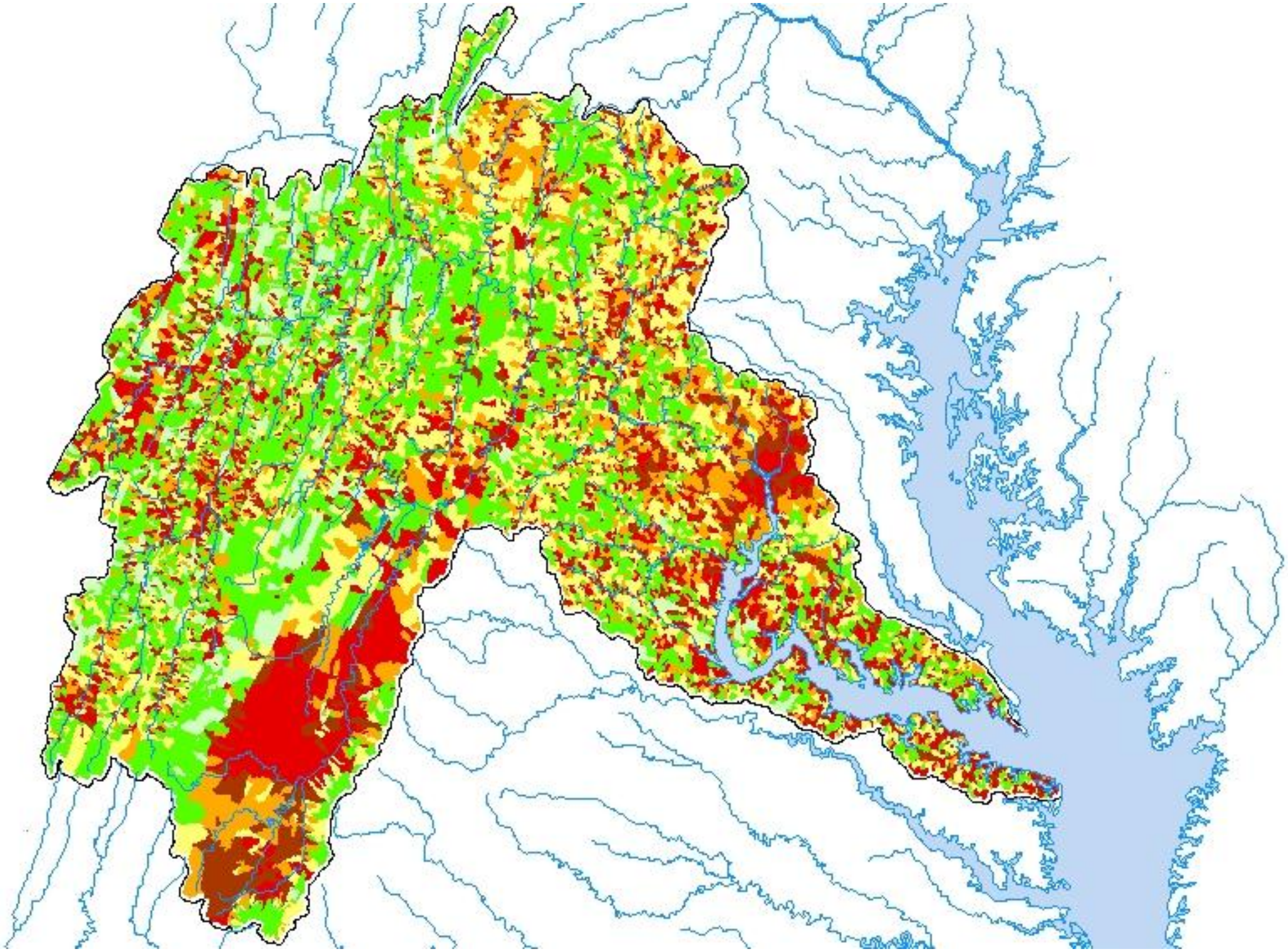
Total Nitrogen Yield (kg km^{-1} day^{-1}); Spring 2006



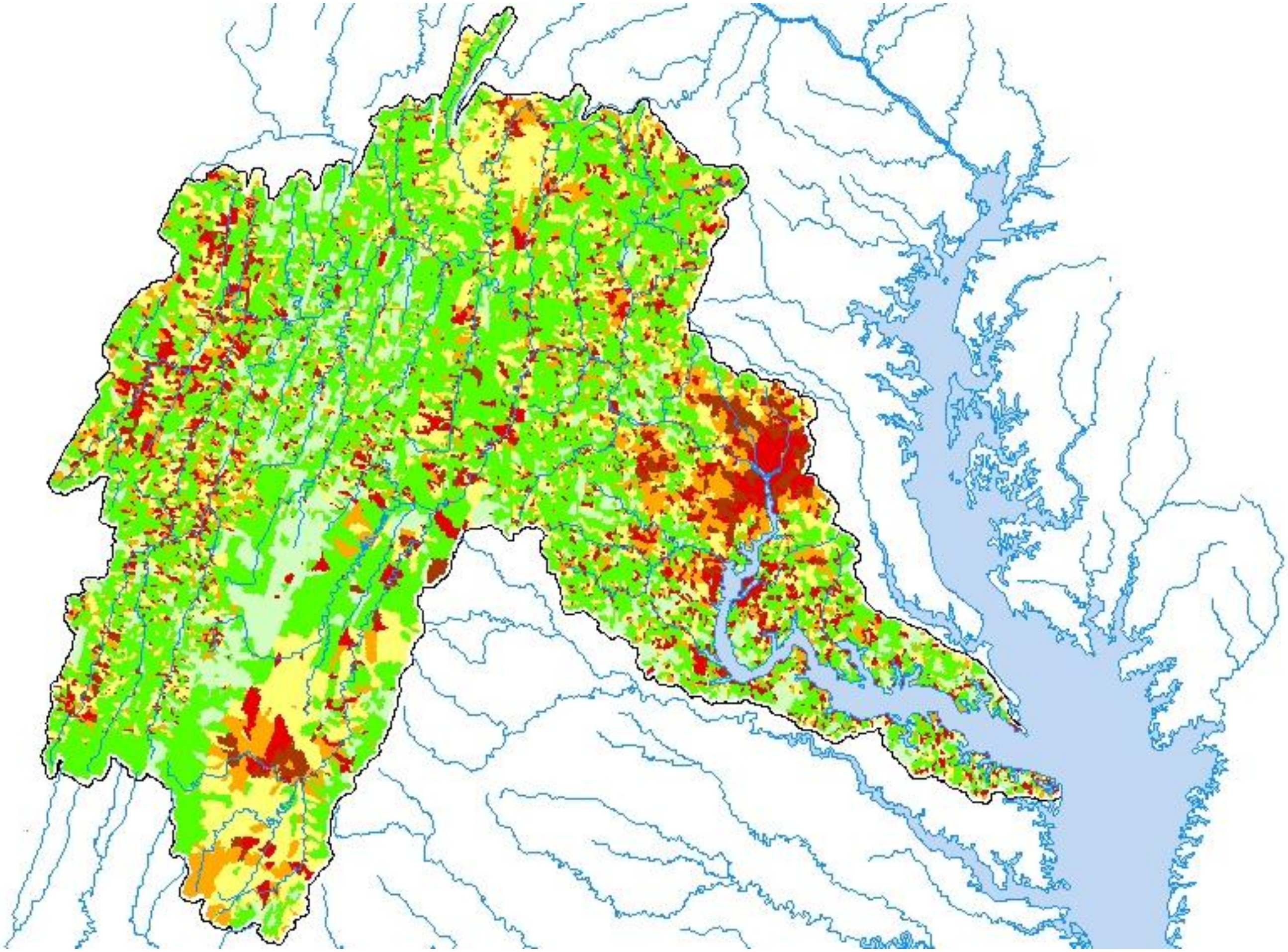
Total Nitrogen Yield (kg km^{-1} day^{-1}); Summer 2006



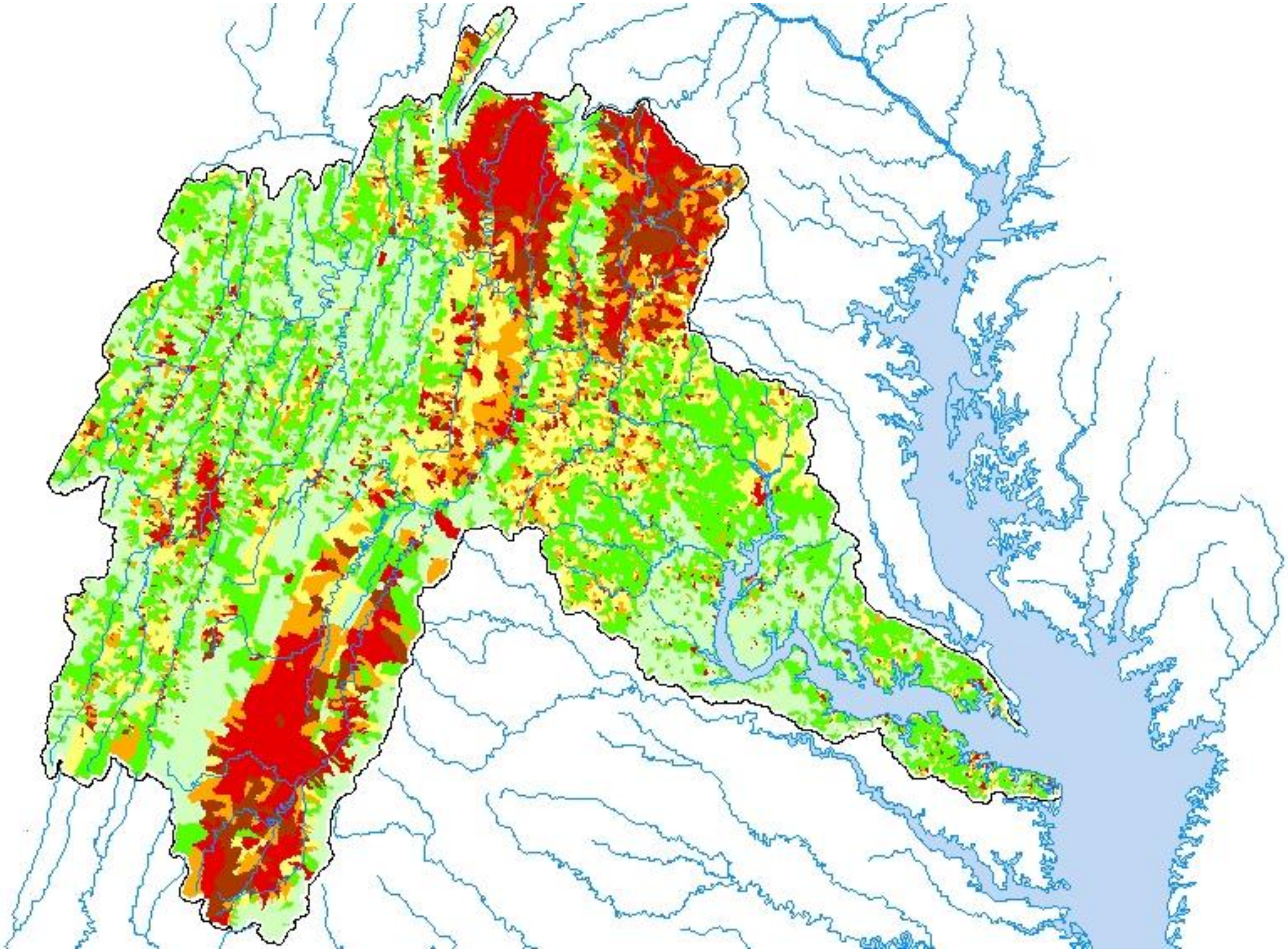
Total Nitrogen Yield (kg km^{-1} day^{-1}); Fall 2006



Total Nitrogen Yield (kg km^{-1} day^{-1}); Winter 2007



Total Nitrogen Yield (kg km^{-1} day^{-1}); Spring 2007



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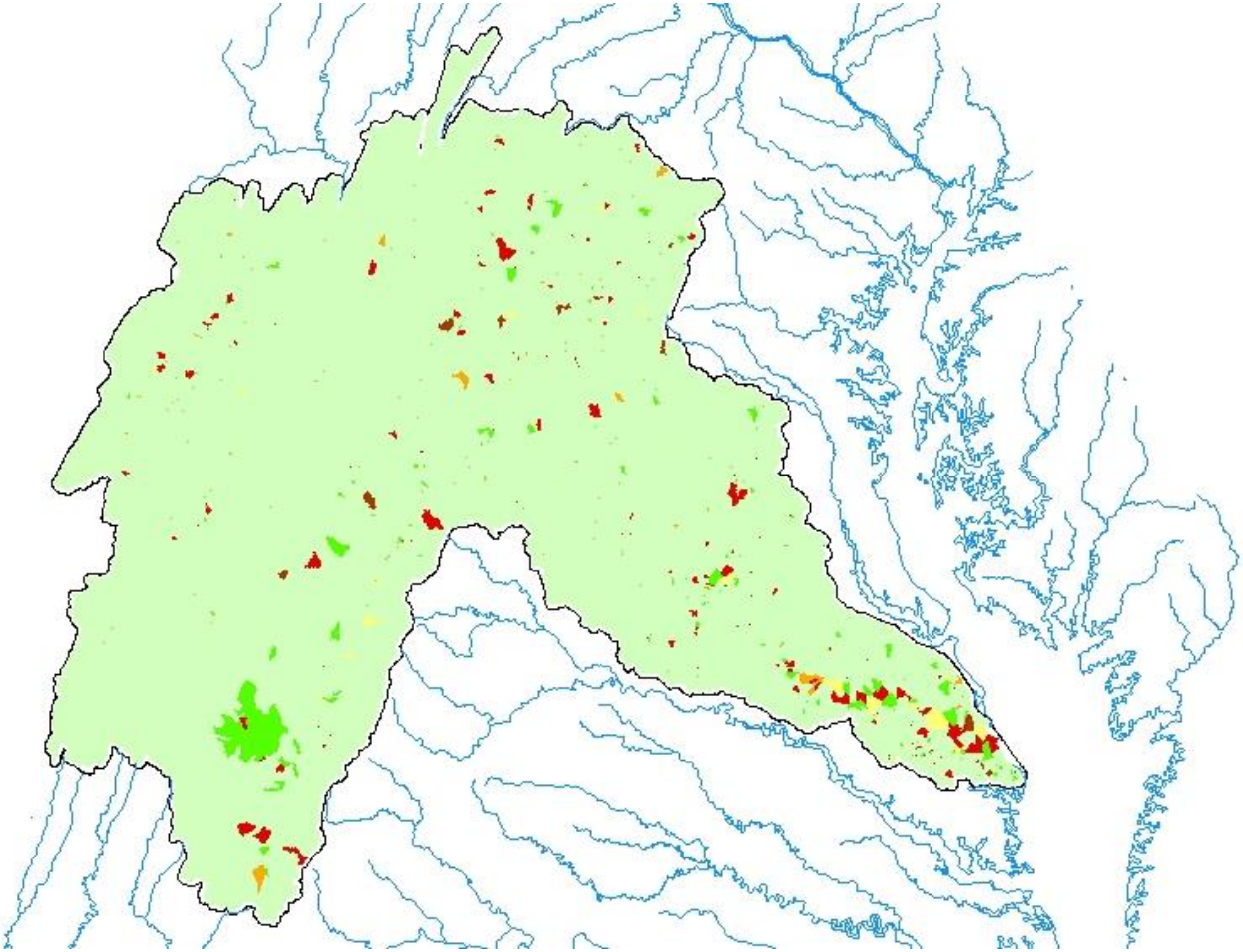
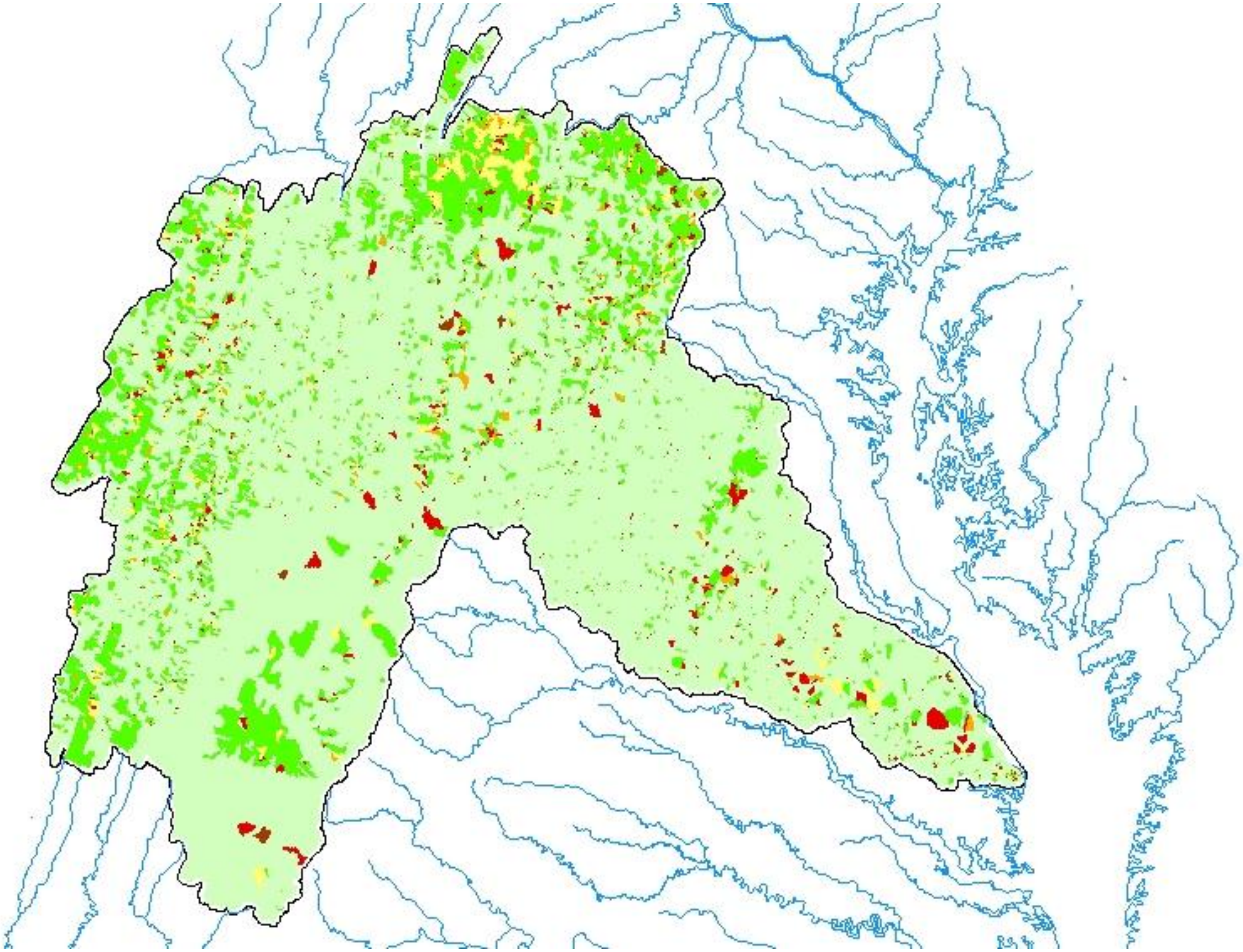
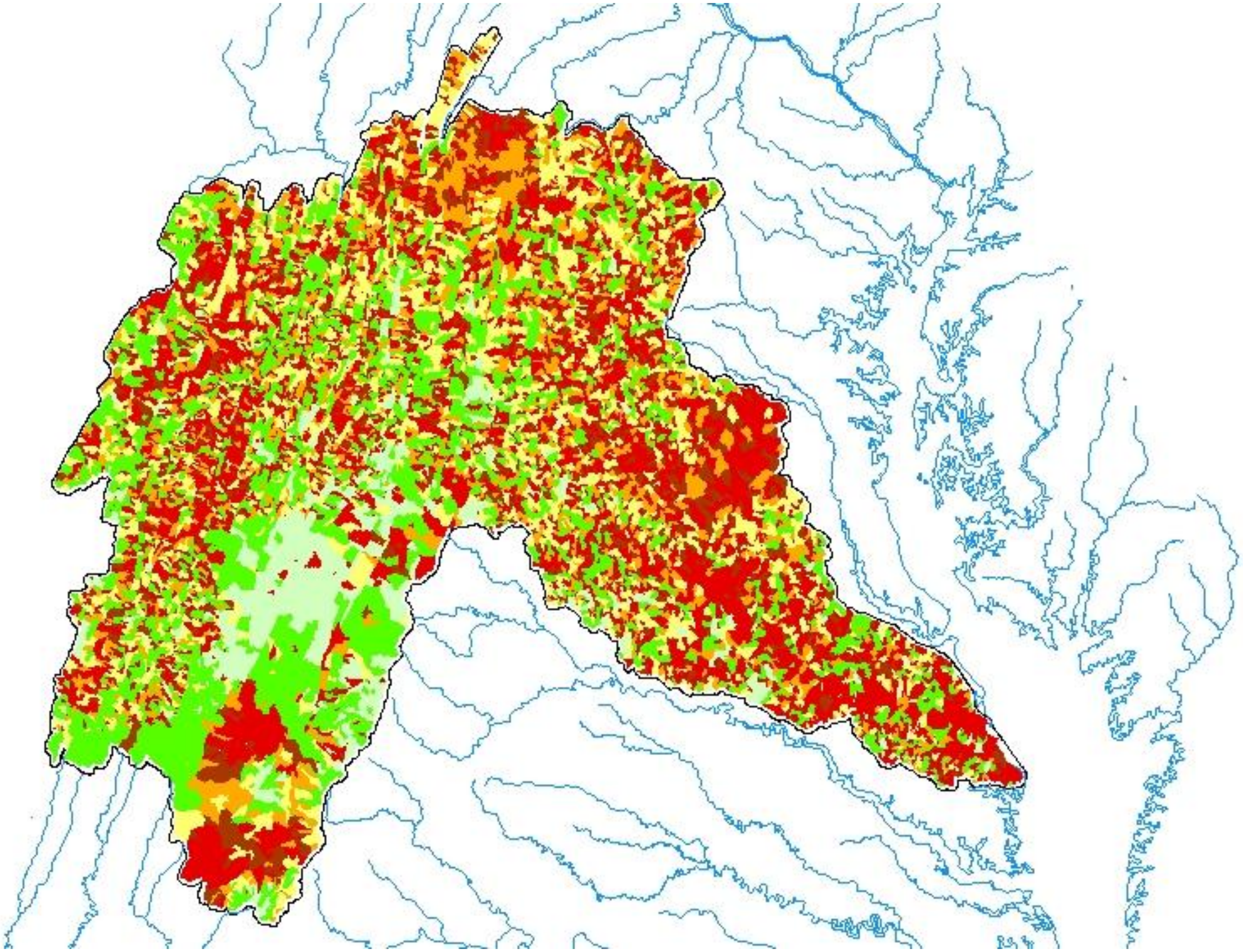


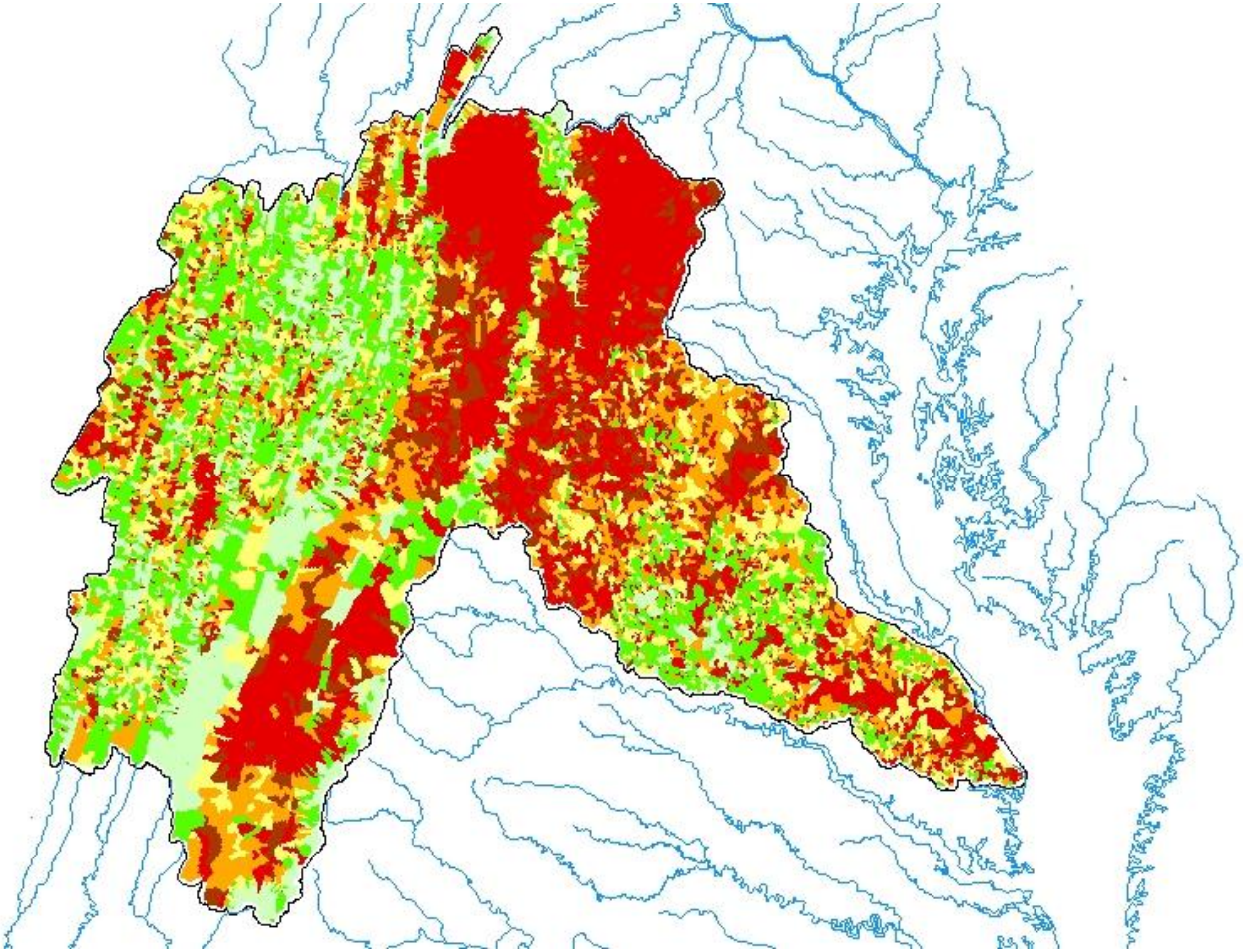
Total Nitrogen Yield (kg km^{-1} day^{-1}); Fall 2007



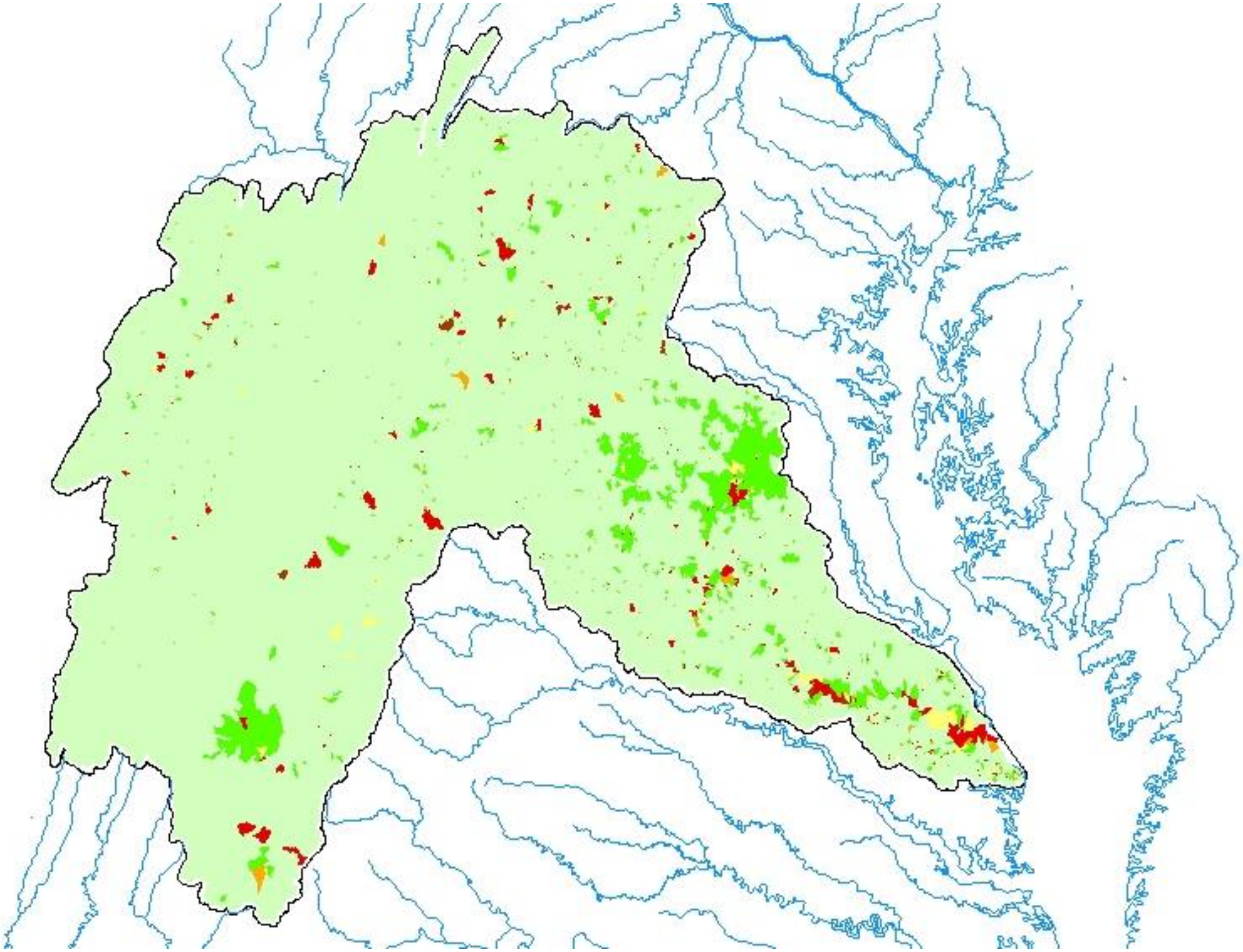
Total Nitrogen Yield (kg km^{-1} day^{-1}); Winter 2008



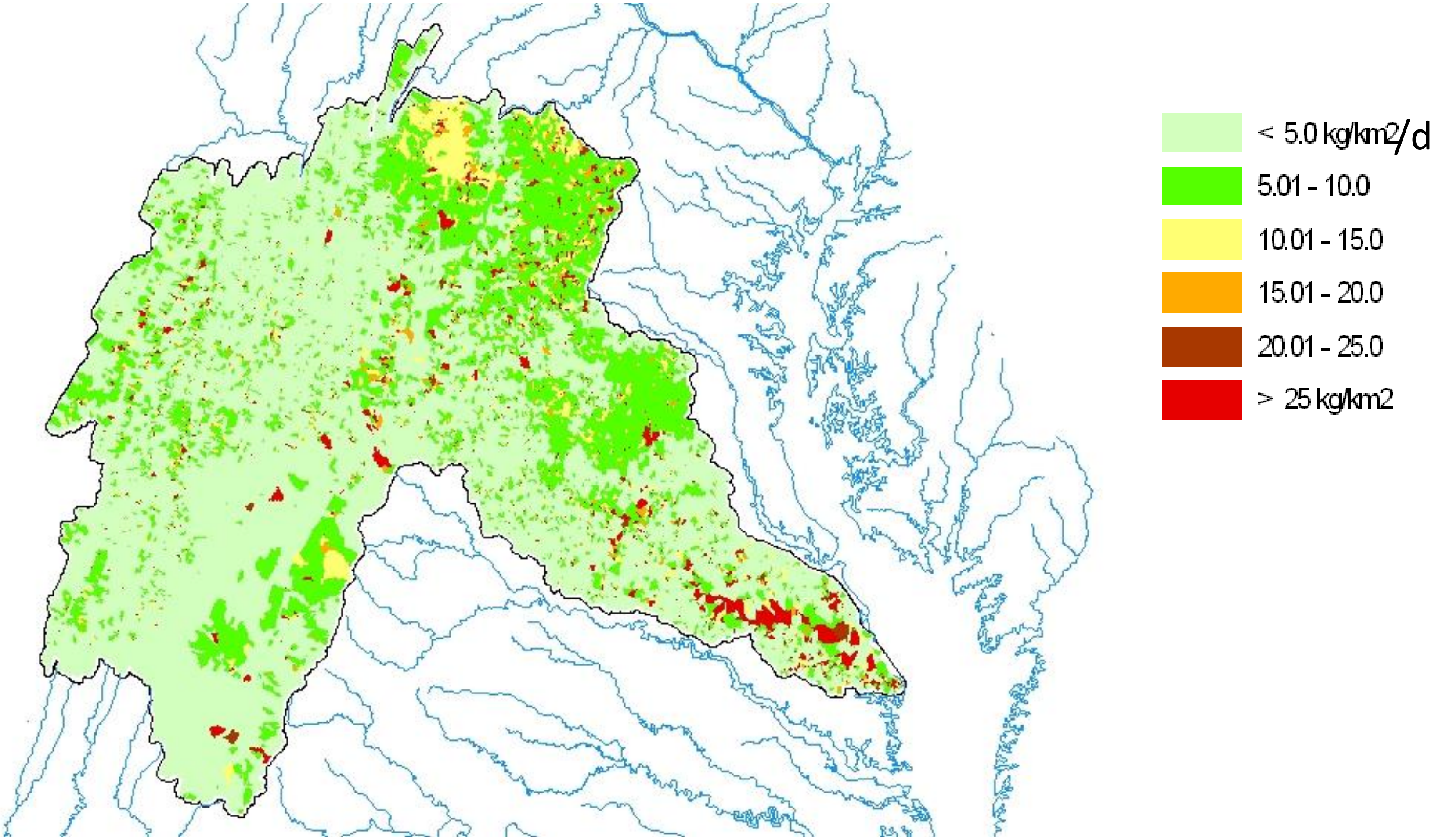
Total Nitrogen Yield (kg km^{-1} day^{-1}); Spring 2008



Total Nitrogen Yield (kg km^{-1} day^{-1}); Summer 2008



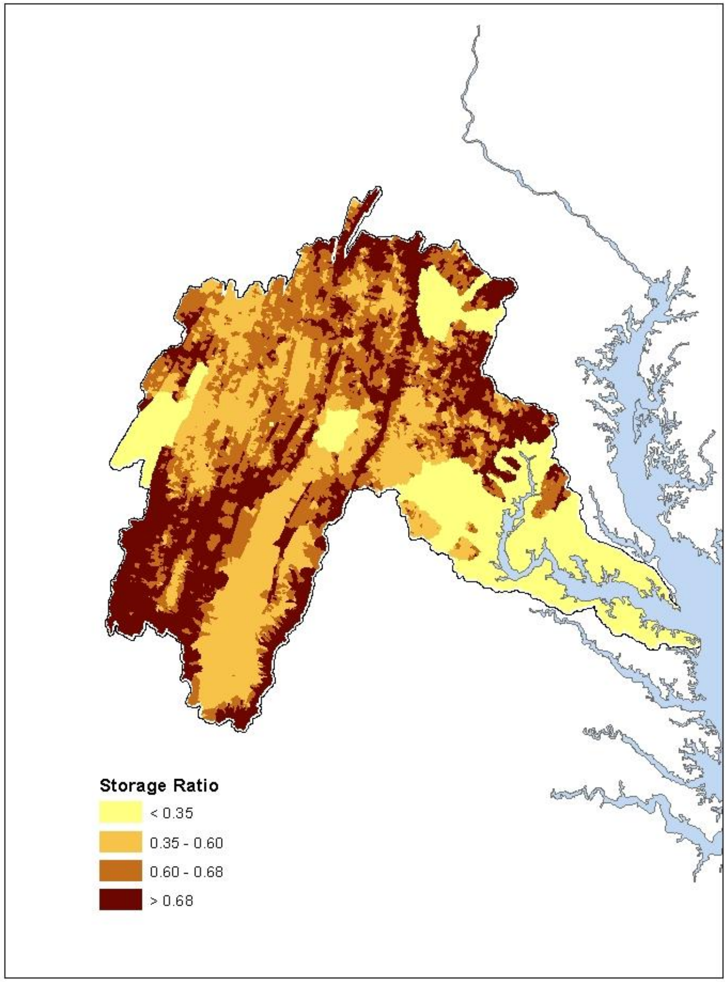
Total Nitrogen Yield (kg km^{-1} day^{-1}); Fall 2008



Distribution of Estimated Mean Residence Time in SPARROW Reach-Scale Watersheds in the Potomac Basin

Percentile	5th	10th	25th	50th	75th	90th	95th
“residence time” (days)	128	142	165	198	252	344	483

Fraction Remaining in “Storage” Per Season After Inputs Are Eliminated



Calibration of Model Equation for Total Potomac Watershed Above Chain Bridge on WRTDS Estimates* of Seasonal TN Flux
1973 - 2010

- Nitrogen inputs estimated from SPARROW dynamic model (2002-2008), Sprague et al, 2000 (1985-98), records of agricultural production !975-85.

- Seasonal temperature pattern based on Chain Bridge records.

- SPARROW equation applied to total inputs for entire basin (Urban runoff, fertilizer, animal waste, N-deposition)

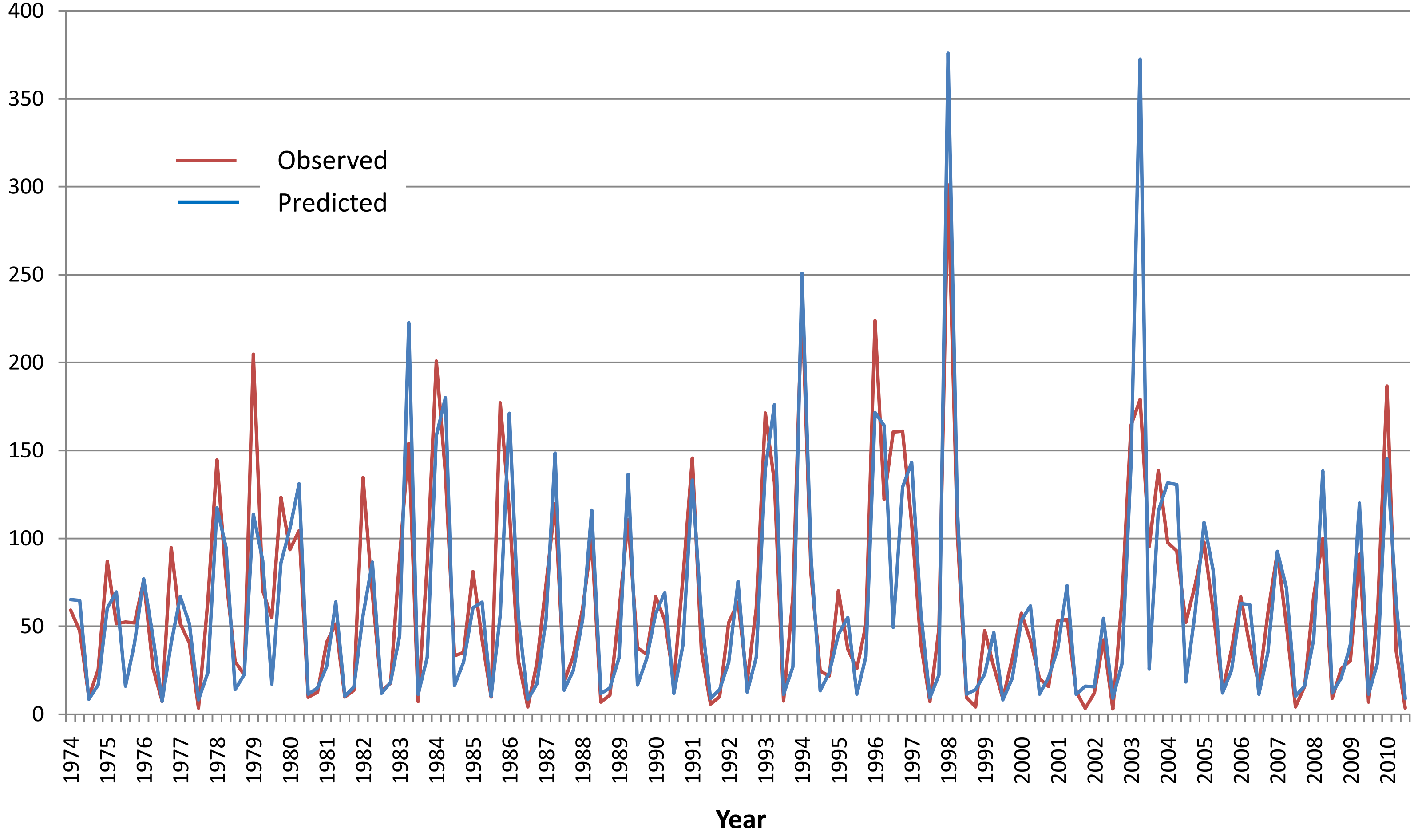
- f(Q, lag-1 deltaQ, temperature, total source inputs).

- $R^2 = 0.77$; all coefficients highly significant.

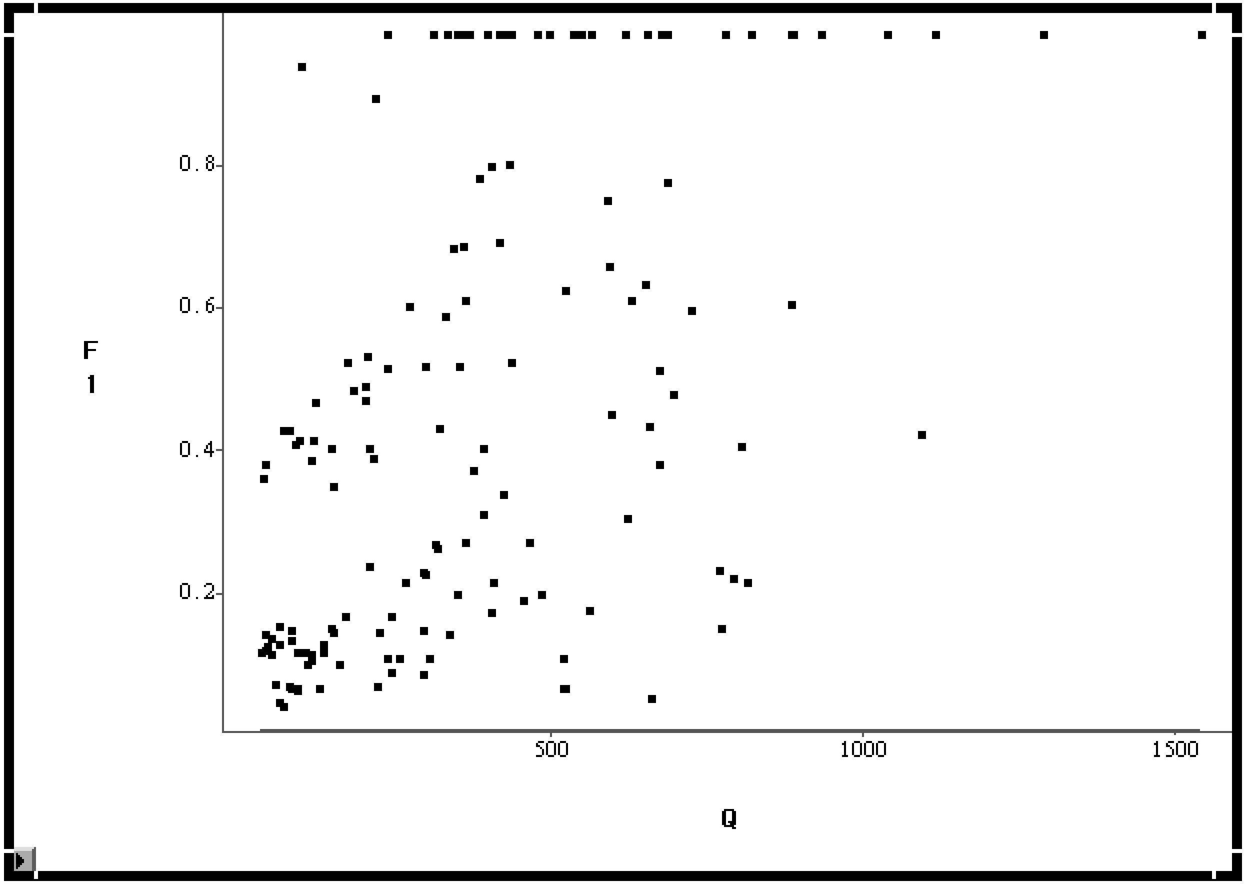
- Implicit mean residence time varies with flow, temperature:

Mean = 120 days
25th percentile = 48 days
75th percentile = 381 days
90th percentile = 24 years

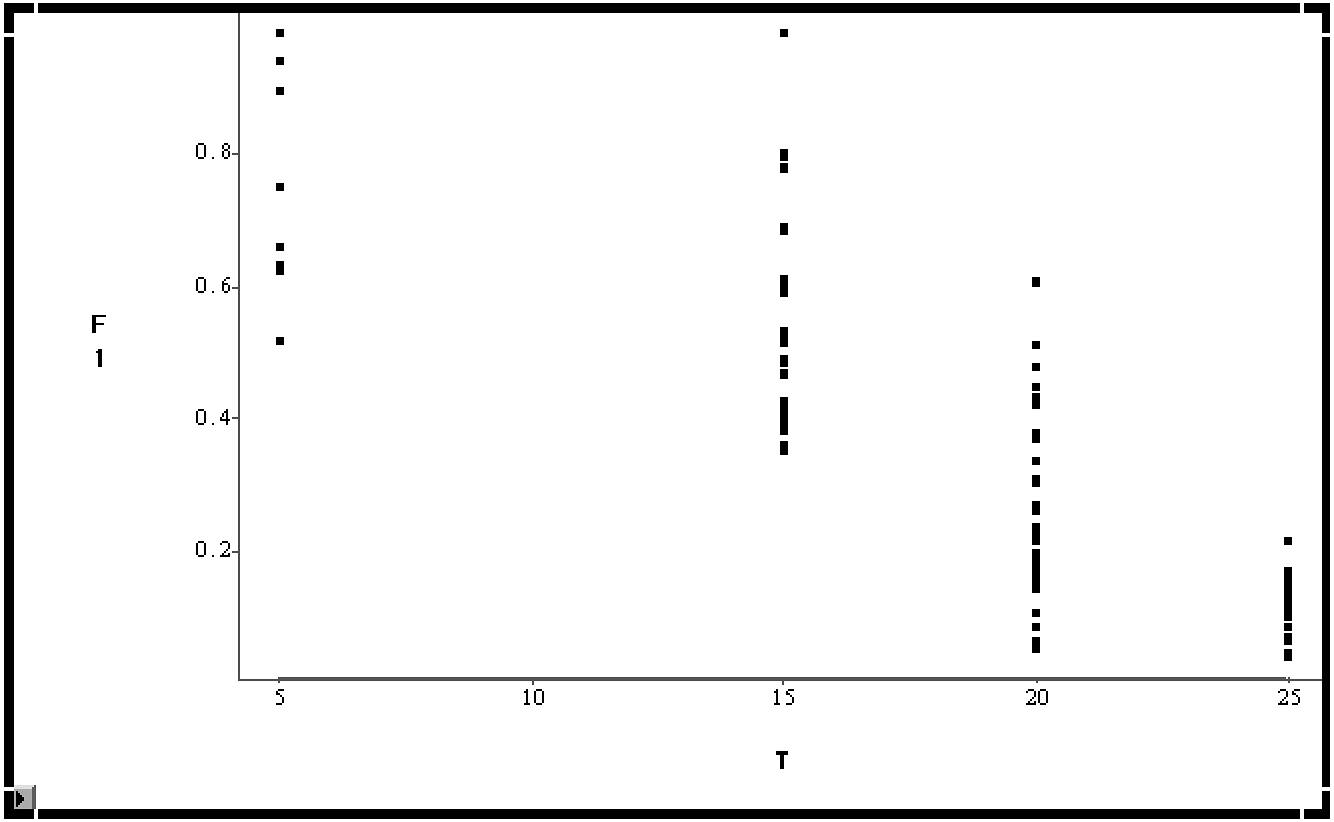
Predicted and Observed TN Flux in the Potomac at Chain Bridge Based on "Total Basin" Model



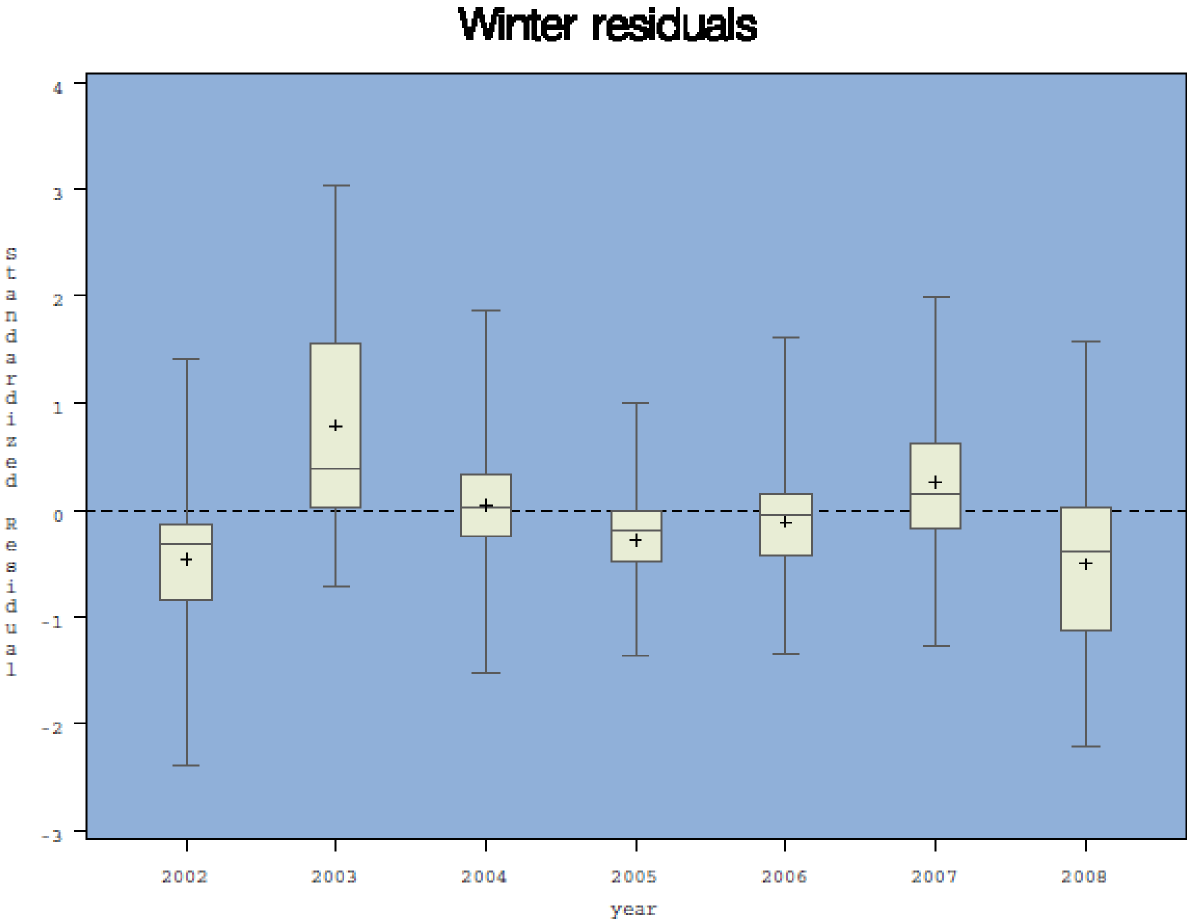
Storage ratio vs streamflow



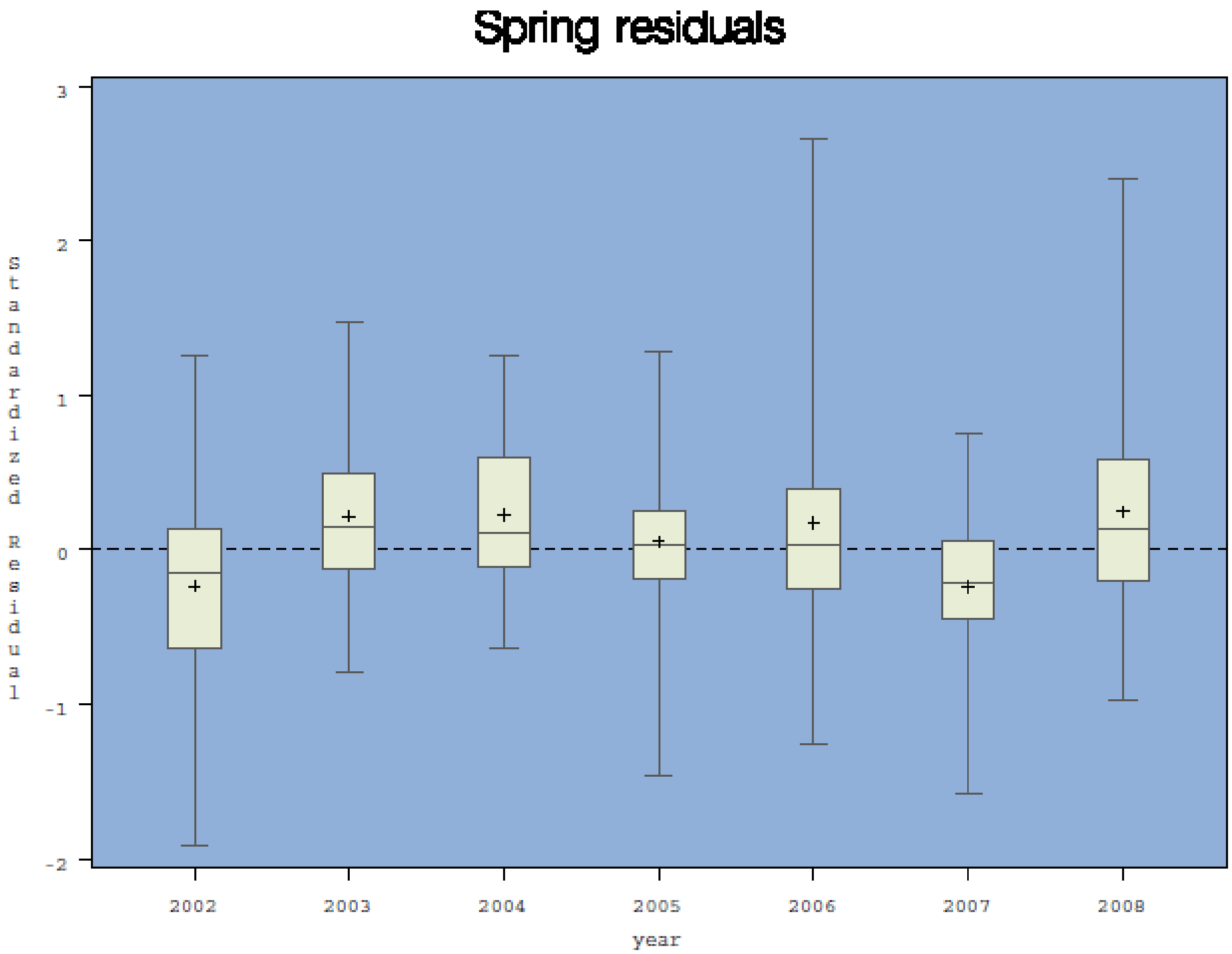
Storage ratio vs temperature



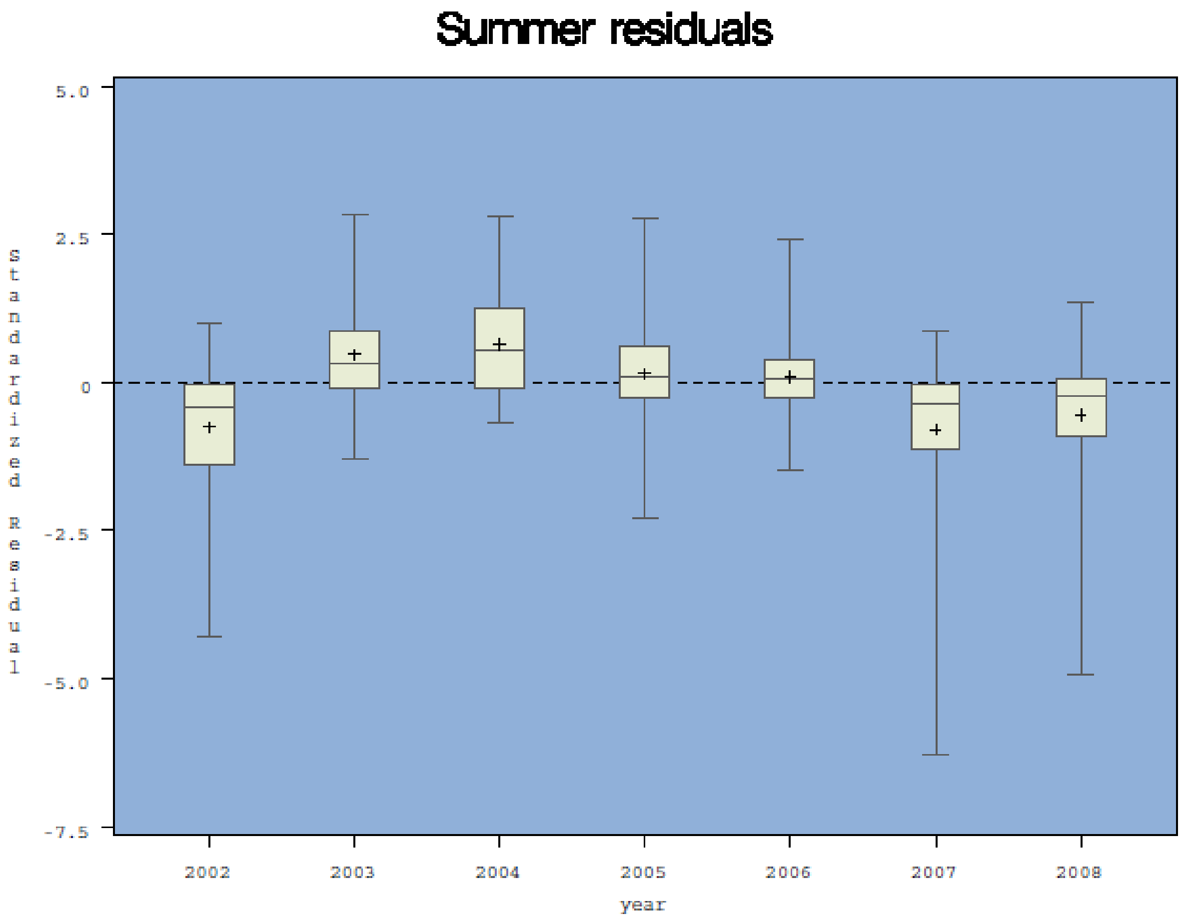
Seasonal Accuracy



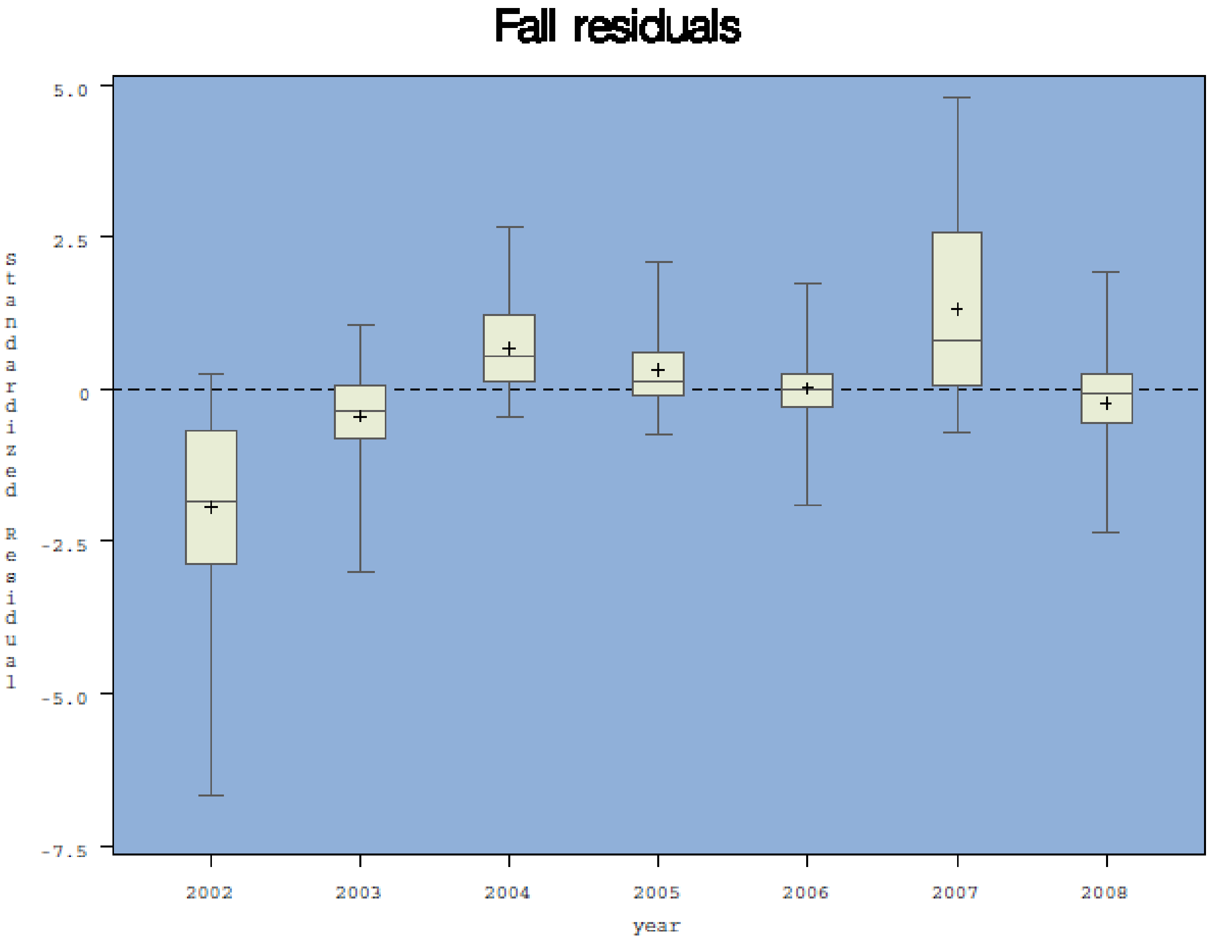
Seasonal Accuracy



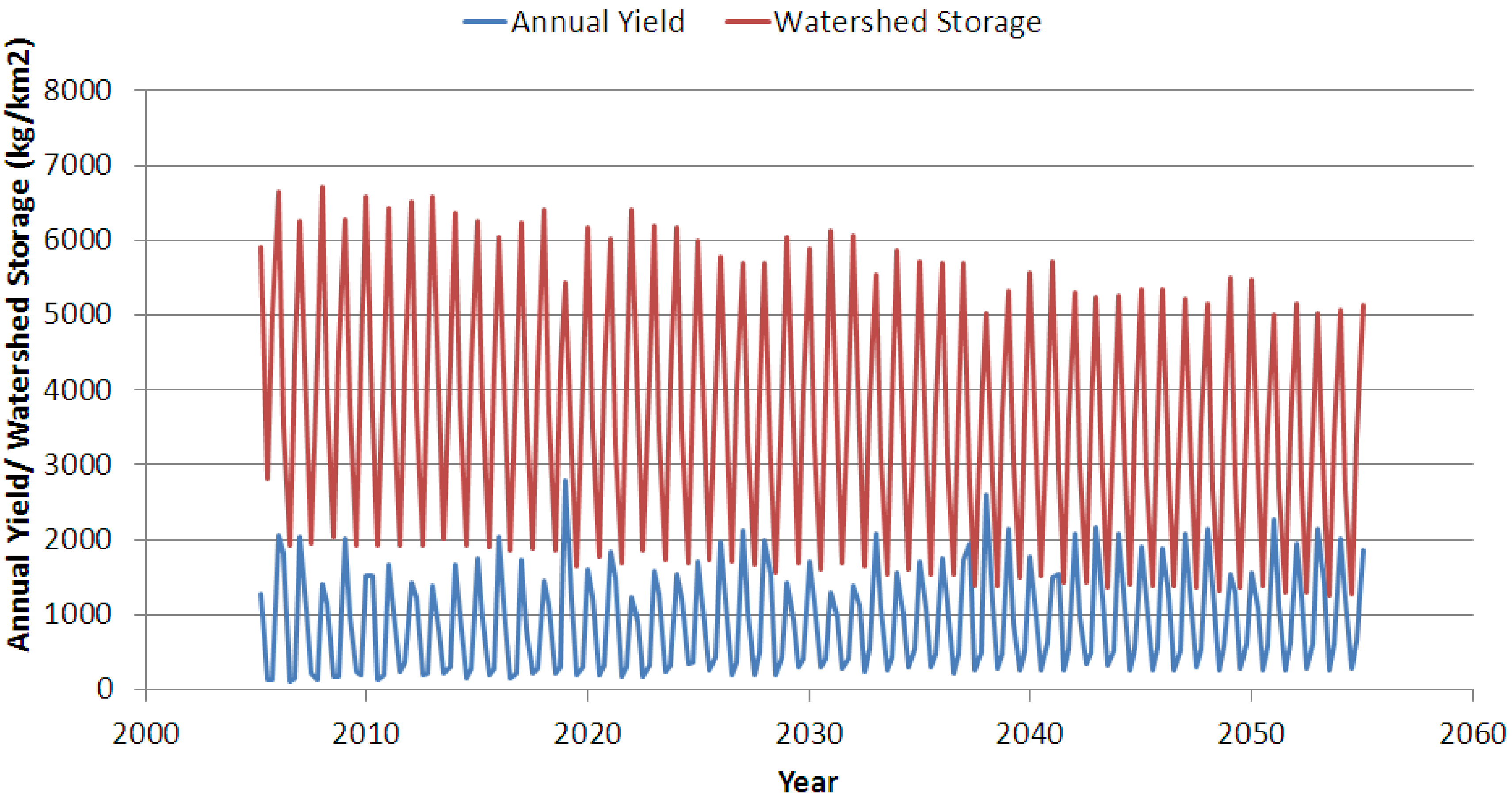
Seasonal Accuracy



Seasonal Accuracy



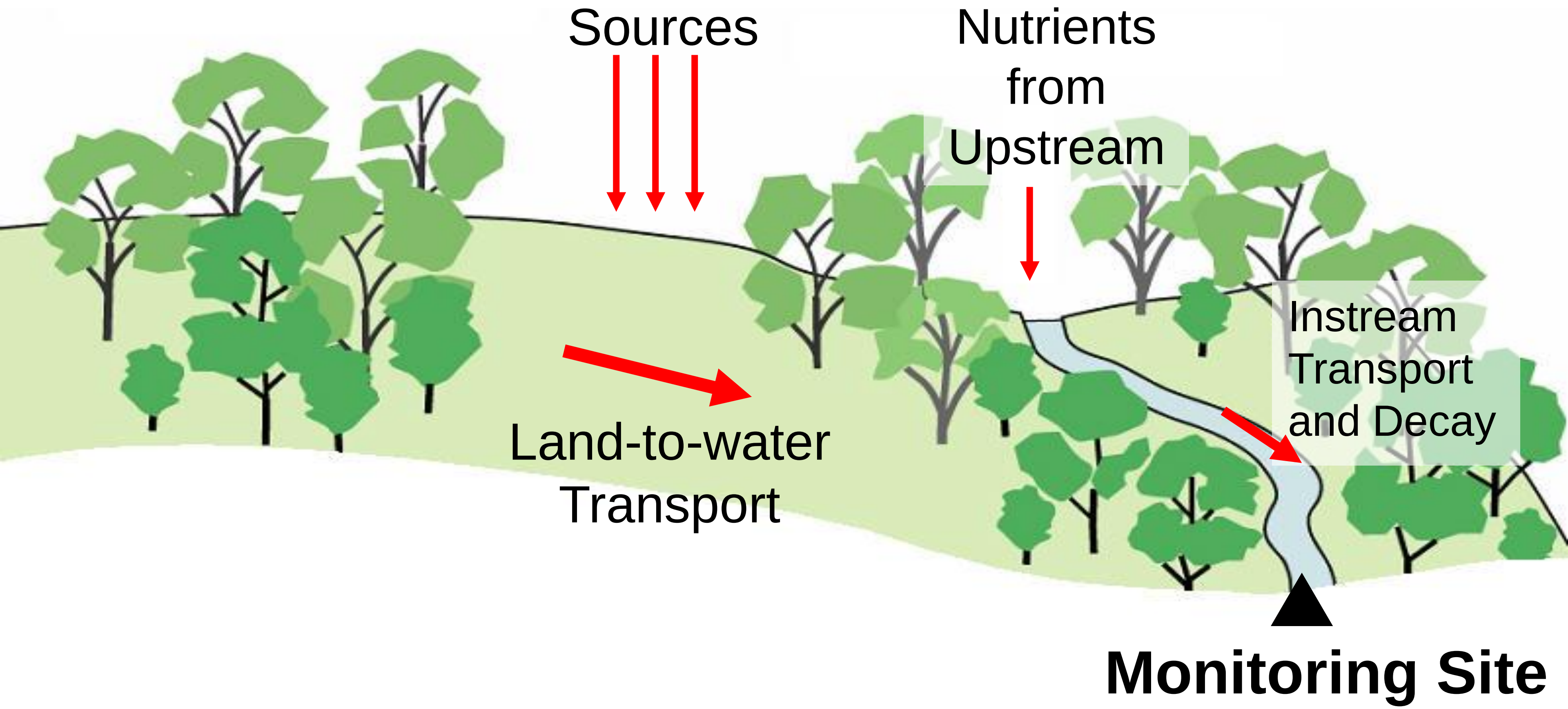
Dynamic “SPARROW” model forecast of seasonal reactive nitrogen yield for the period 2005 to 2055 assuming an annual 1% rise in runoff and 0.08 C rise in temperature.



Conclusions

- The results of an initial attempt to calibrate a dynamic SPARROW model of reactive nitrogen based on seasonal time series of water quality and basin attribute data were highly encouraging.
- EVI was an especially strong predictor, appearing to account for seasonal retention of nitrogen in basin vegetation.
- Model predictions for the entire 16,000-reach stream network show moderately accurate (and seemingly realistic) seasonal and year-to-year variations in yield. Model coefficient estimates were very precise due to many observations.
- Long-term simulation of average Potomac Basin nitrogen yield under the influence of runoff and temperature change suggests that changes in basin storage may play an important role in climate effects on water quality.

Integration of Monitoring Data with Information on Watershed Characteristics and Nutrient Sources



Sources

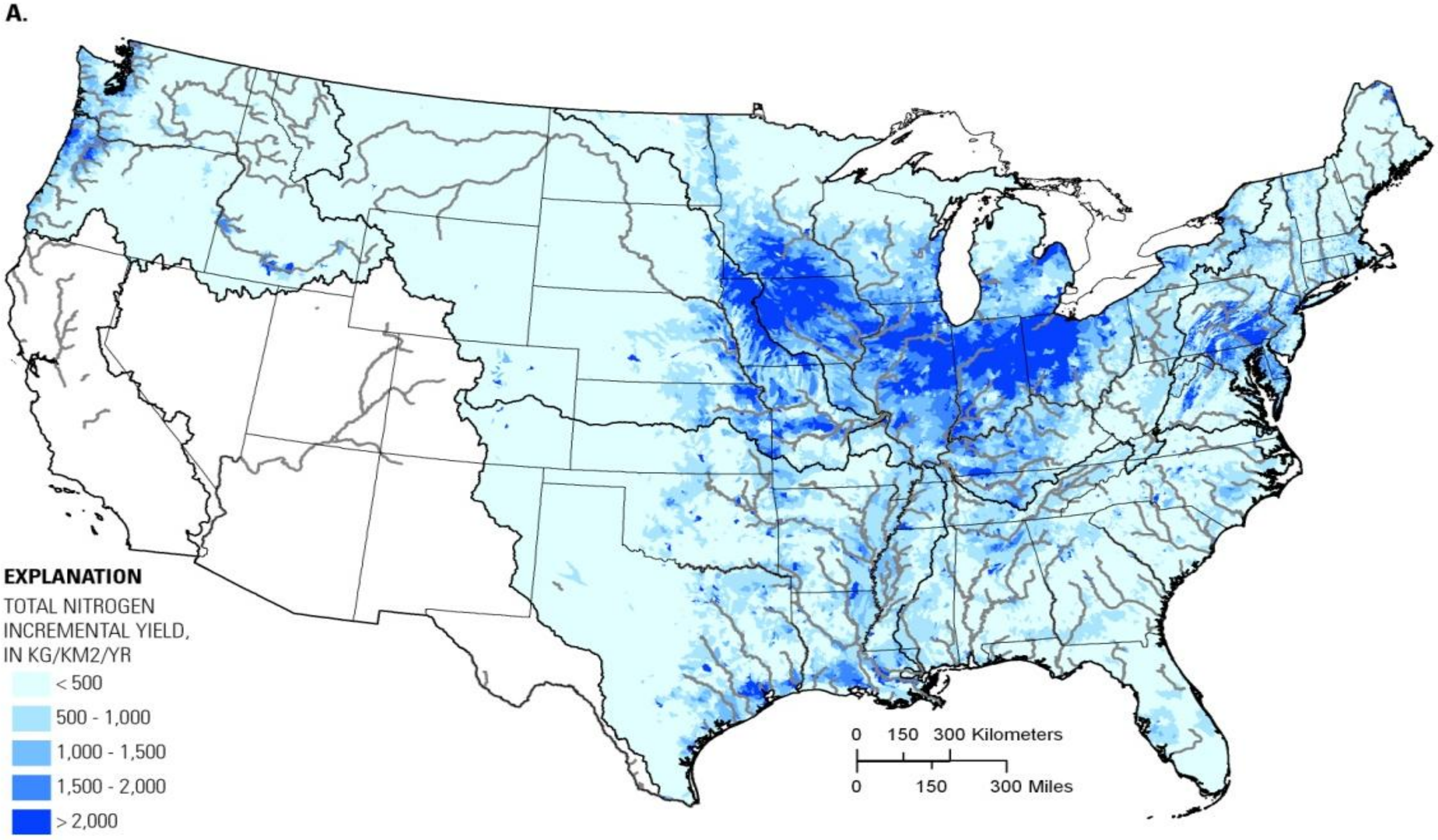
Nutrients from Upstream

Land-to-water Transport

Instream Transport and Decay

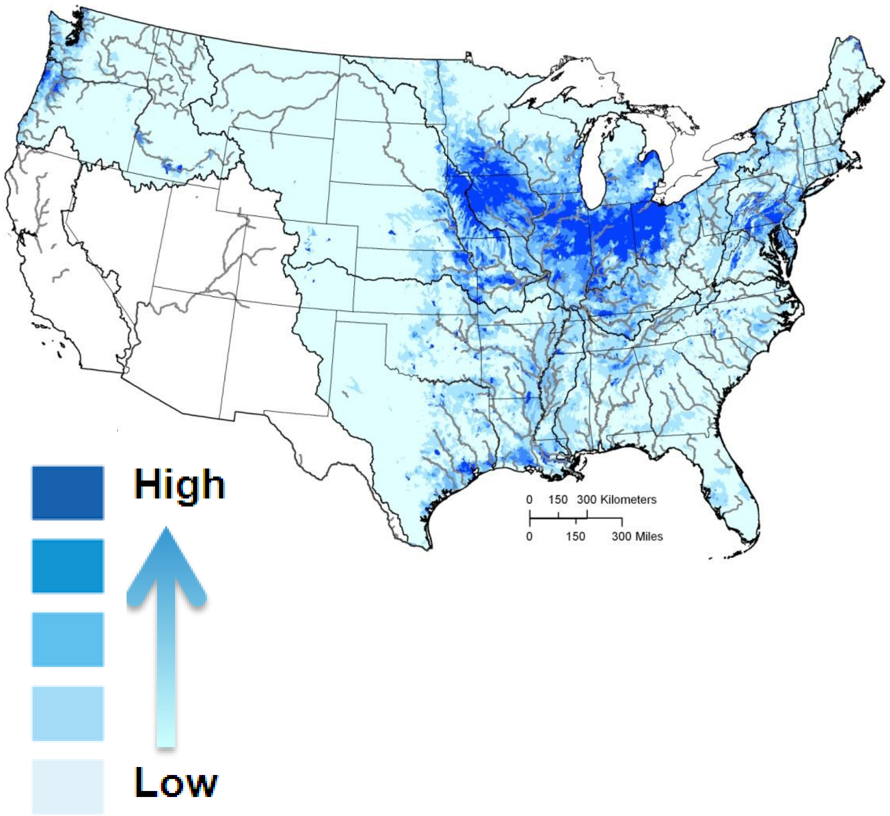
Monitoring Site

The Space-for-Time Problem: Can we use observed spatial gradients to predict temporal trends?

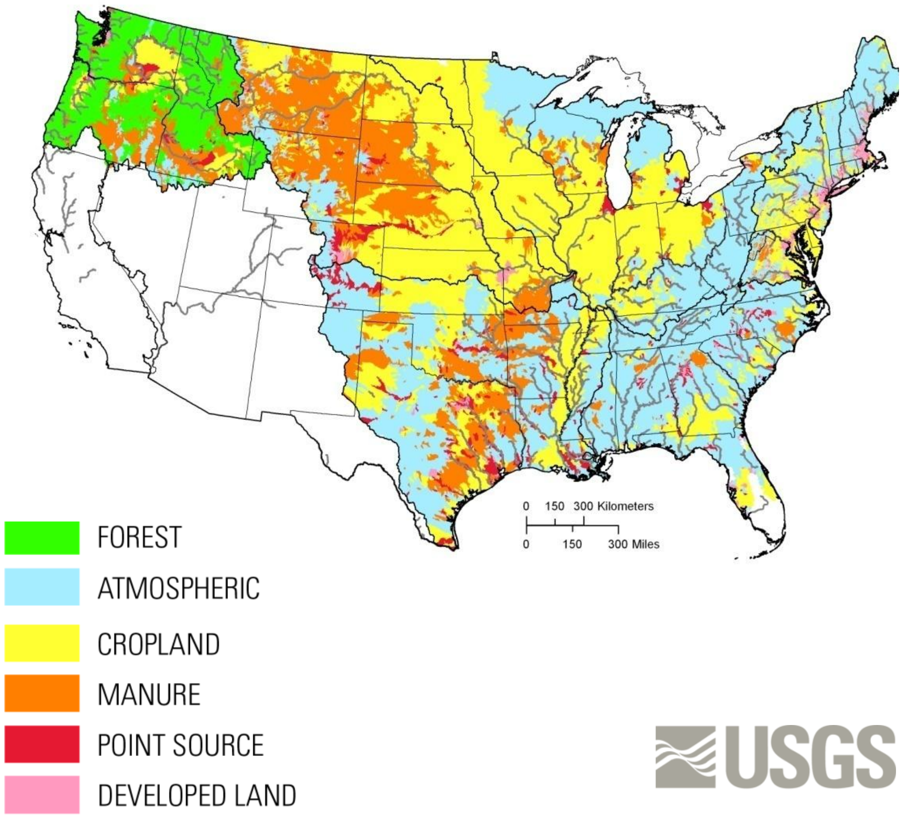


Total Nitrogen Yields and Sources

Yields

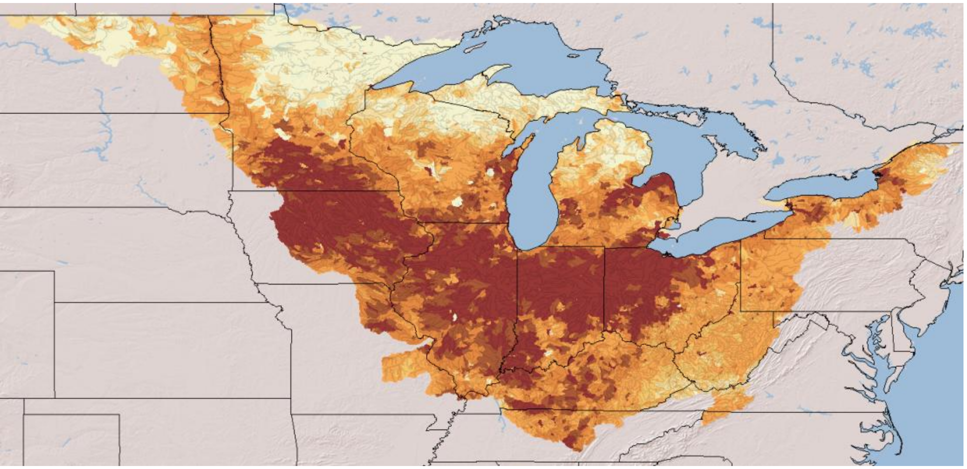


Largest Sources

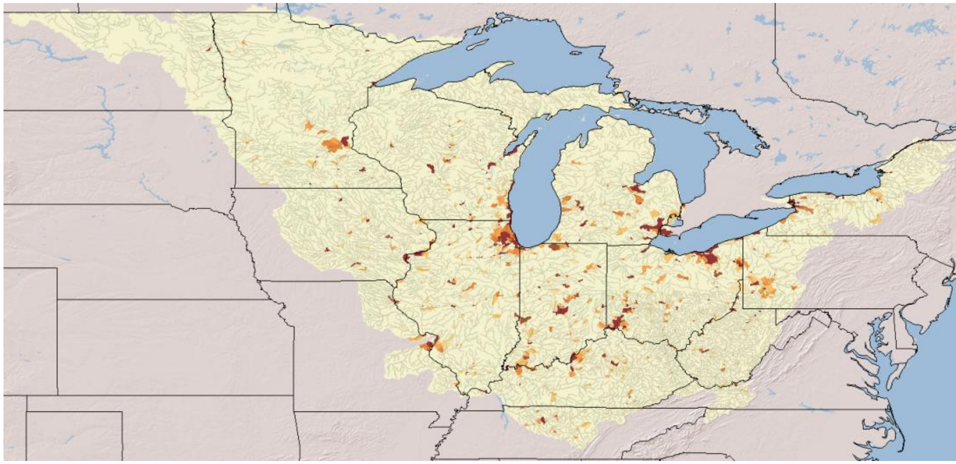


Amounts and Sources of Nitrogen to Streams in the Upper Mississippi/Great Lakes Basin

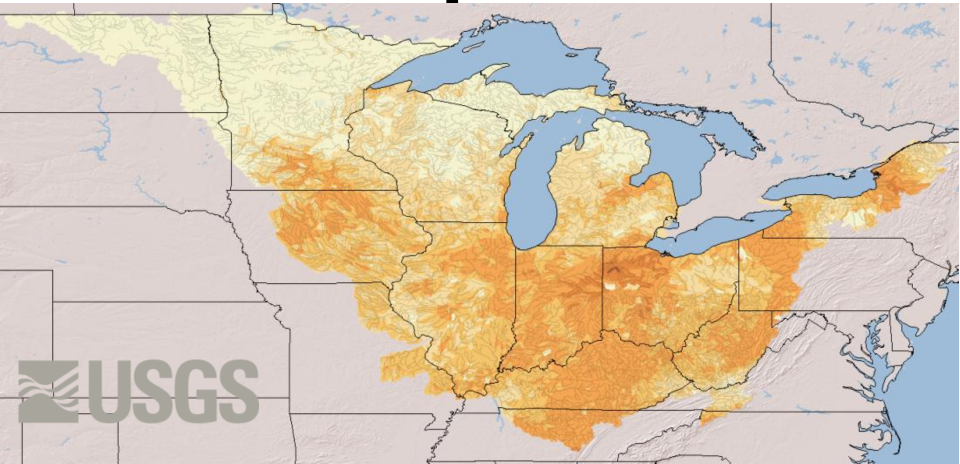
All Sources



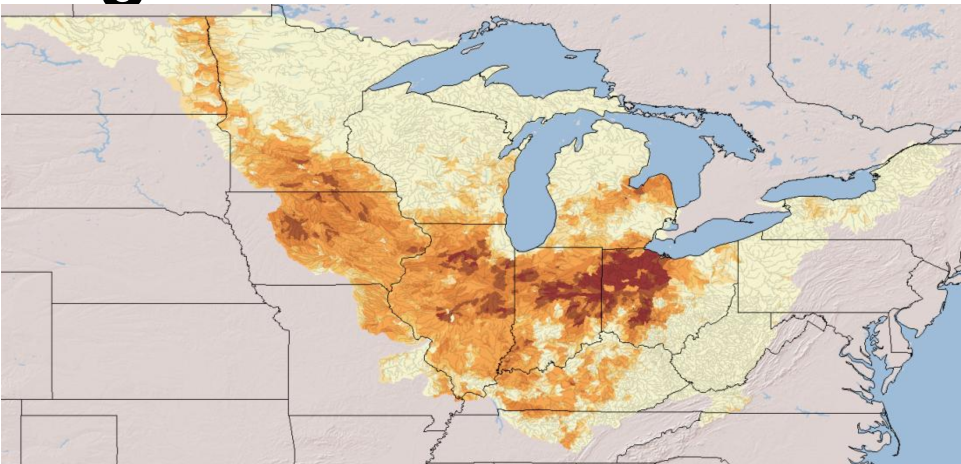
Point Sources



Atmosphere

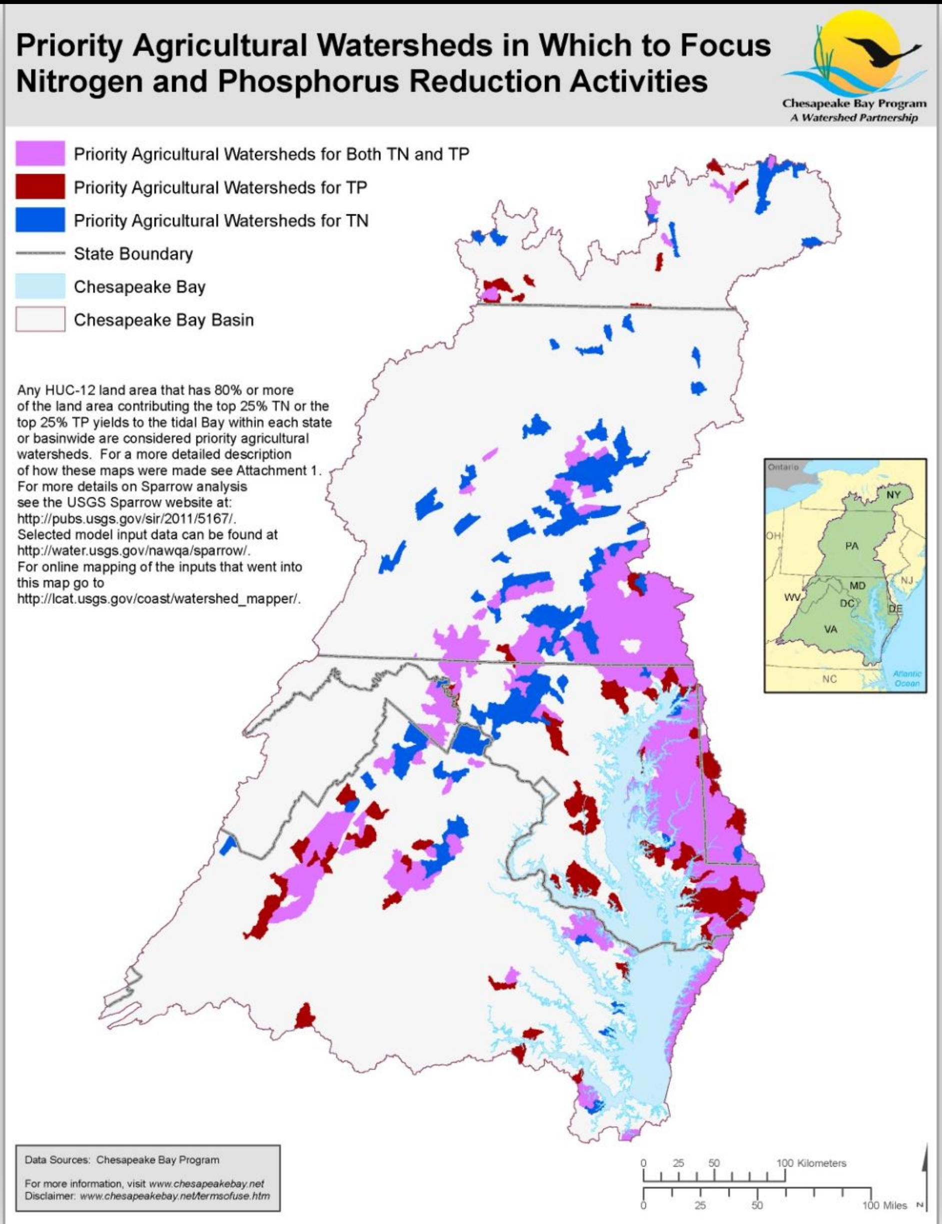


Agricultural Fertilizers



SPARROW Model Applications

Targeting of Management Actions in Chesapeake Bay Watershed



Priority Agricultural Watersheds in Which to Focus Nitrogen and Phosphorus Reduction Activities

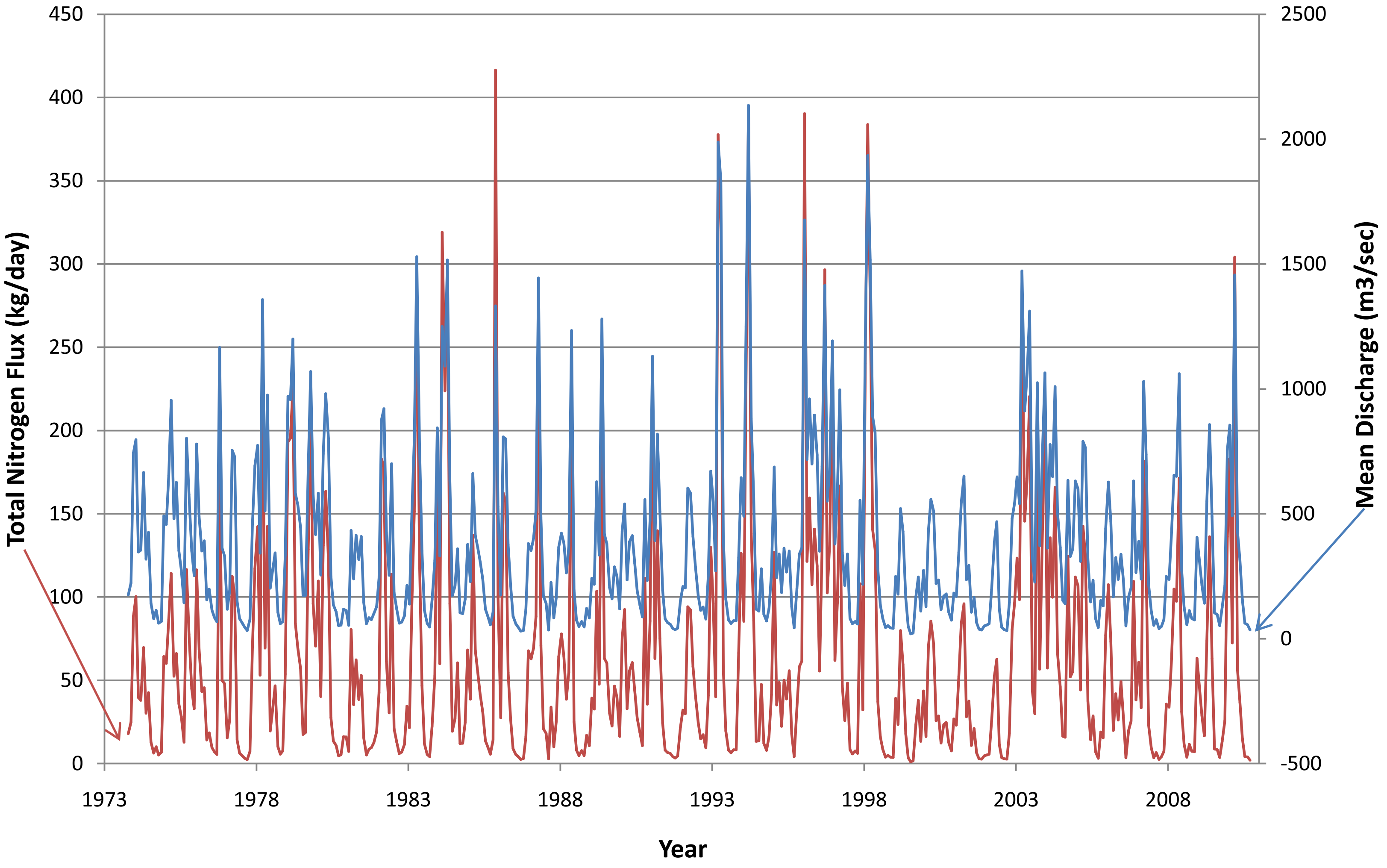
Any HUC-12 land area that has 80% or more of the land area contributing the top 25% TN or the top 25% TP yields to the tidal Bay within each state or basinwide are considered priority agricultural watersheds. For a more detailed description of how these maps were made see Attachment 1. For more details on Sparrow analysis see the USGS Sparrow website at: http://pubs.usgs.gov/sir/2011/5167/. Selected model input data can be found at http://water.usgs.gov/nawqa/sparrow/. For online mapping of the inputs that went into this map go to http://lcat.usgs.gov/coast/watershed_mapper/.

Data Sources: Chesapeake Bay Program

For more information, visit *www.chesapeakebay.net*
Disclaimer: *www.chesapeakebay.net/termsofuse.htm*

Monthly Total Nitrogen Flux and Mean Discharge, 1973 - 2010: Potomac River at Chain Bridge, MD

(Based on “WRTDS” estimates)

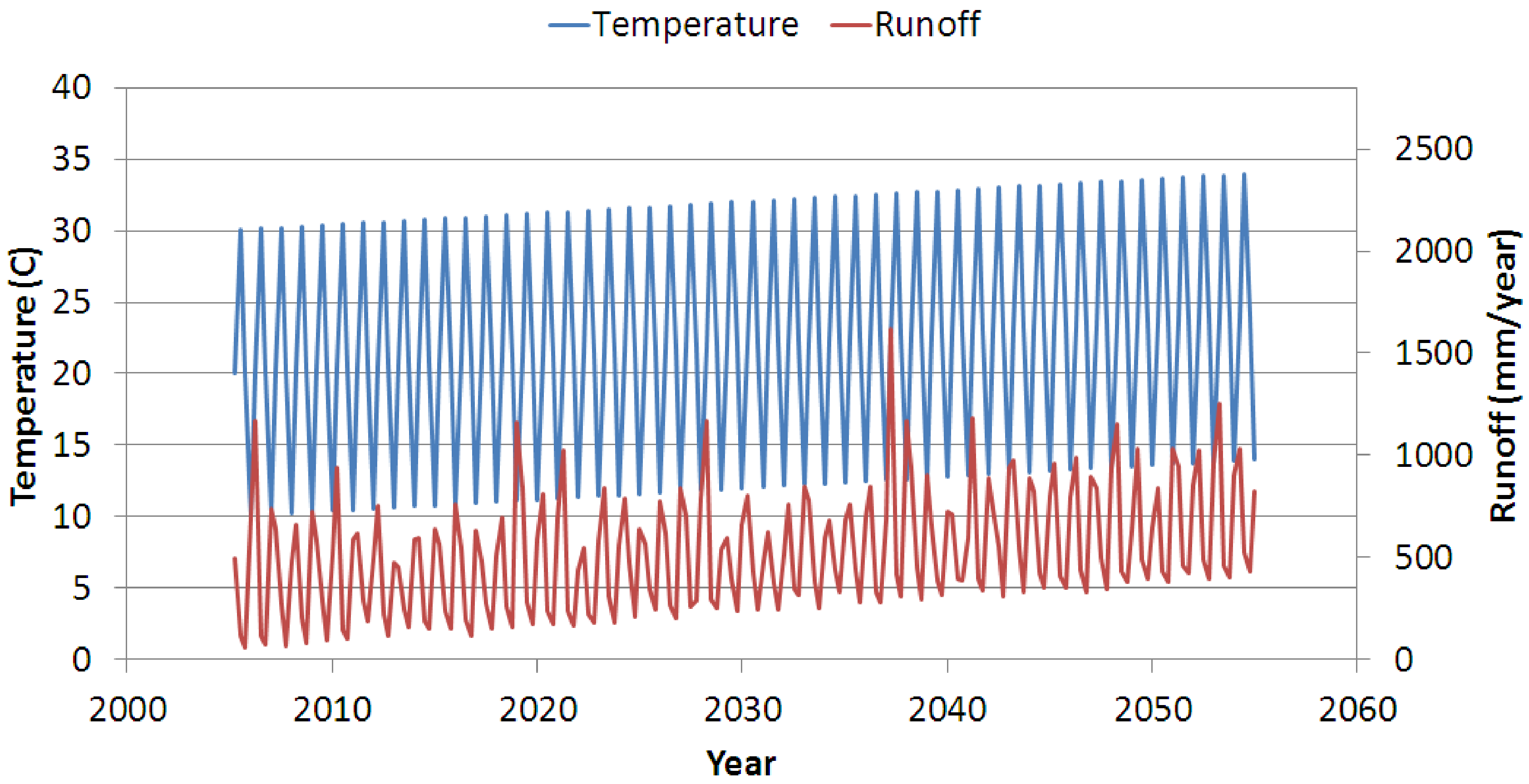


Data: R. Hirsch, personal comm.

SPARROW Model Applications

- Geographic Description of Water Quality - Targeting
- *Forecasting Effects of Changes in Contaminant Sources (e.g. TMDLs) and Other Basin Conditions
- Hypothesis Testing - Research
- Design of Monitoring Networks

Figure 3. **(a) Dynamic SPARROW model forecast of seasonal reactive nitrogen yield for the period 2005 to 2055 assuming (b) an annual 1% rise in runoff and 0.08 C rise in temperature.**



Introduction

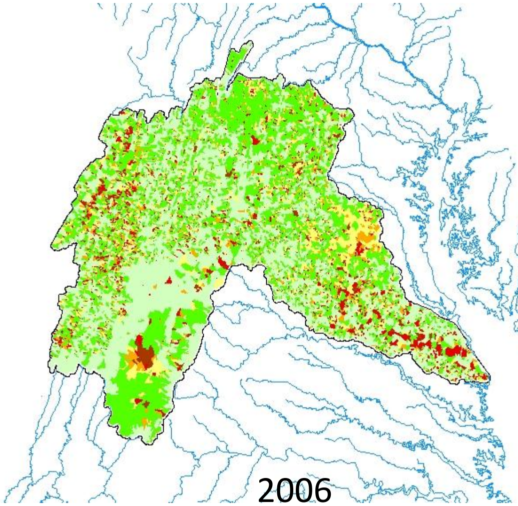
SPARROW models are widely used to identify and quantify the sources of contaminants in watersheds and to predict their flux and concentration at specified locations downstream. Conventional SPARROW models are statistically calibrated and describe the average (“steady-state”) relationship between sources and stream conditions based on long-term water quality monitoring data and spatially-referenced explanatory information. But many watershed management issues stem from intra- and inter-annual changes in contaminant sources, hydrologic forcing, or other environmental conditions which cause a temporary imbalance between watershed inputs and stream water quality. Dynamic behavior of the system relating to changes in watershed storage and processing then becomes important.

Also:

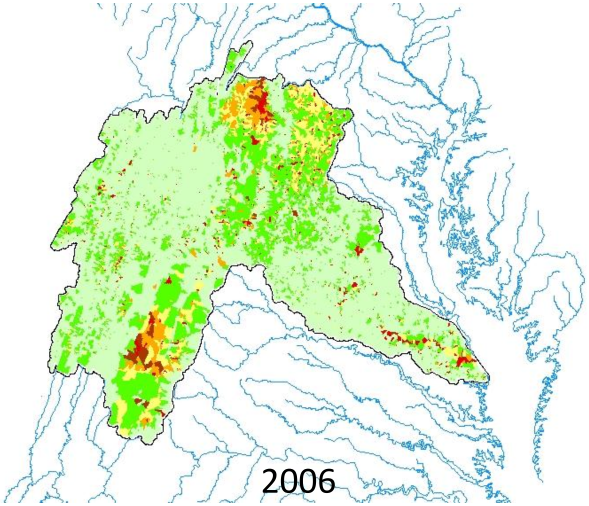
Calibration can be conducted as a multi-year time series (i.e. 36 time steps in the current test), or with seasonally-averaged data.

Multi-year time series have the advantage of displaying wider variations in hydrologic forcing and longer-term storage processes. Would eliminate need for “base year” adjustment.

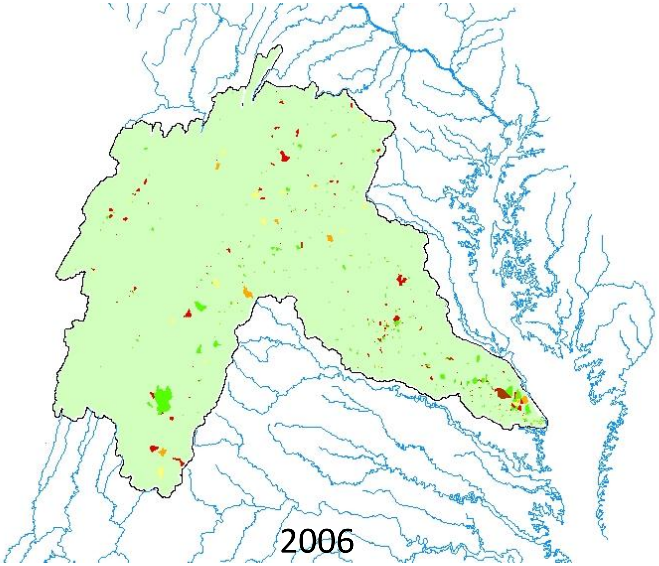
Seasonally-averaged calibrations will emphasize seasonal phenomena, and will better compliment steady-state SPARROW models.



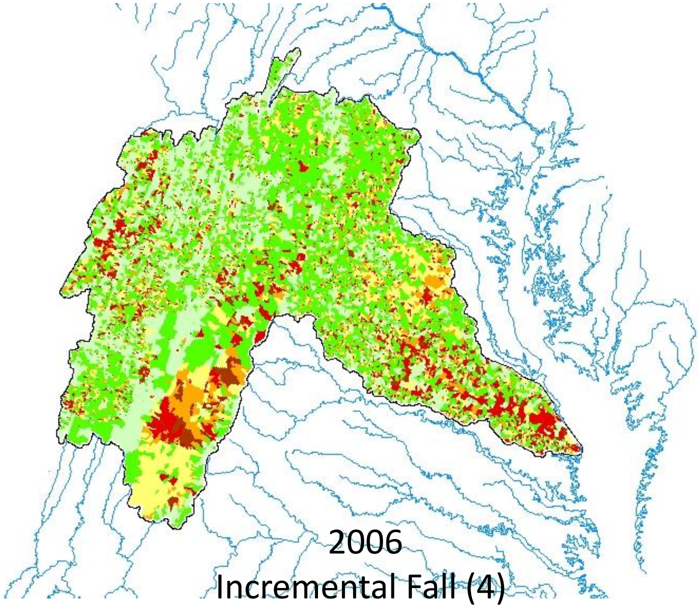
2006
Incremental Winter (1)



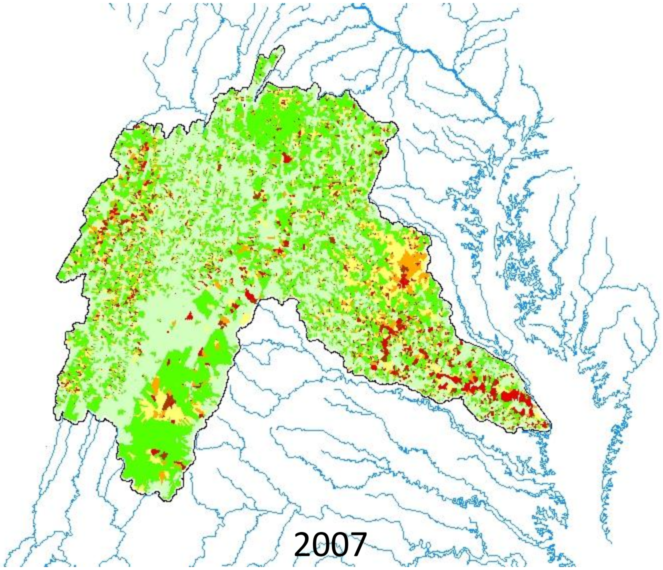
2006
Incremental Spring (2)



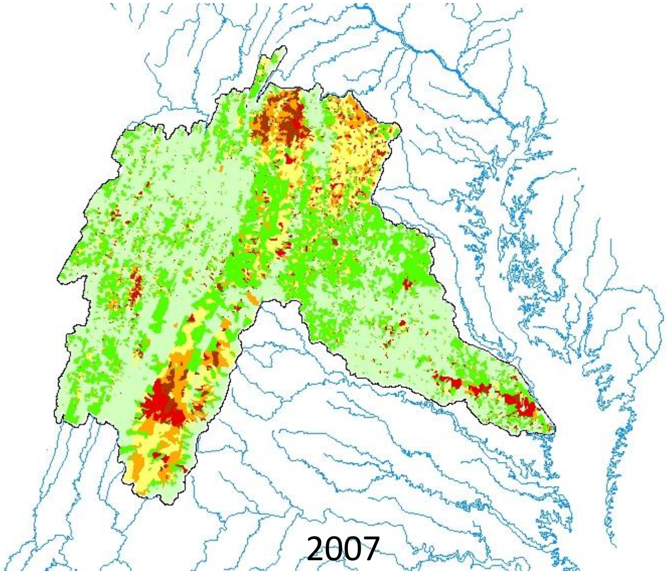
2006
Incremental Summer (3)



2006
Incremental Fall (4)

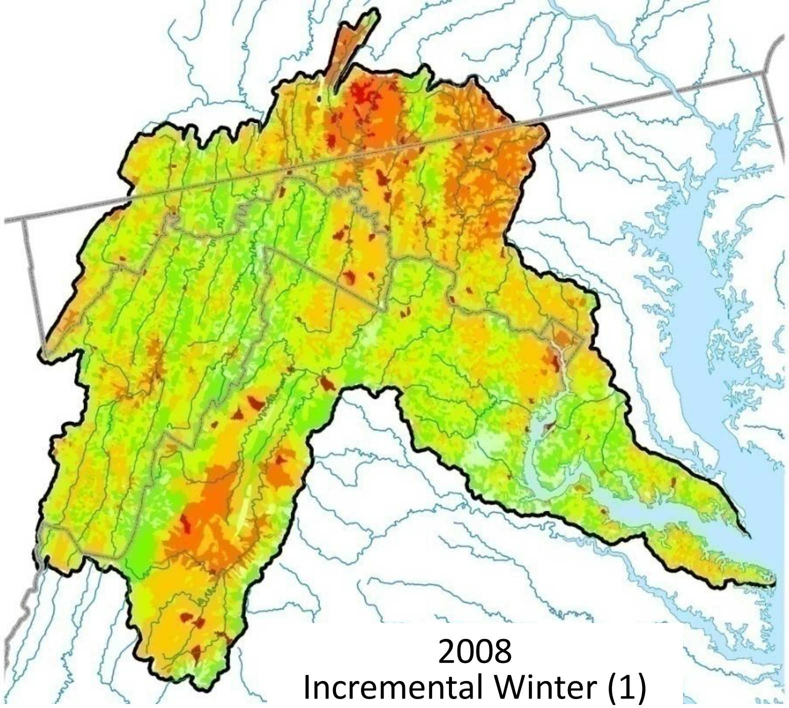


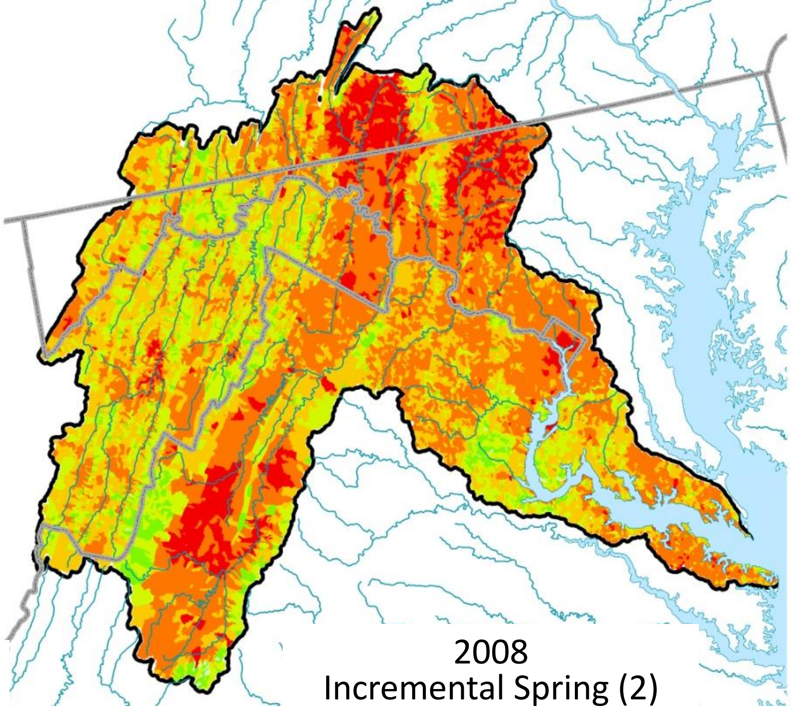
2007
Incremental Winter (1)



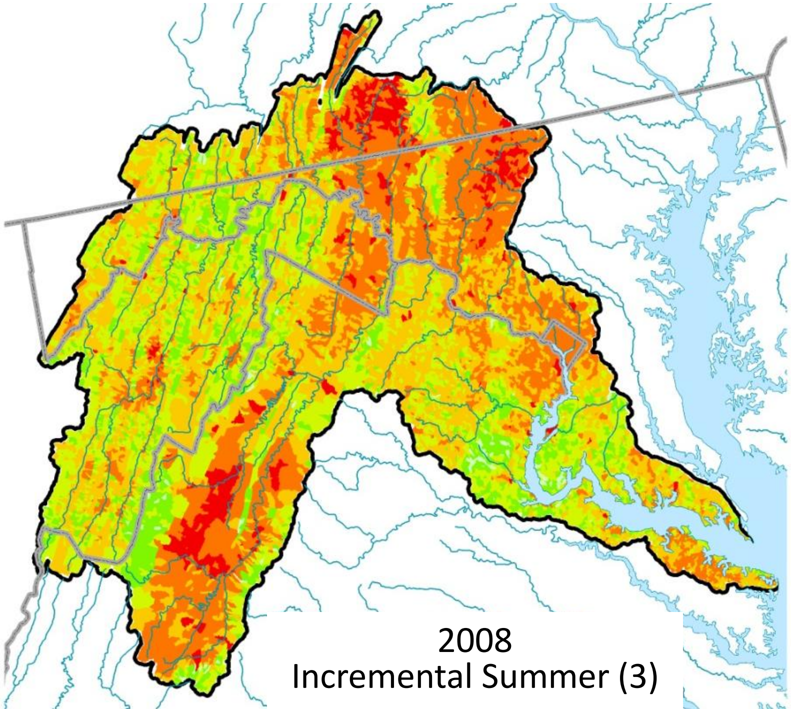
2007
Incremental Spring (2)

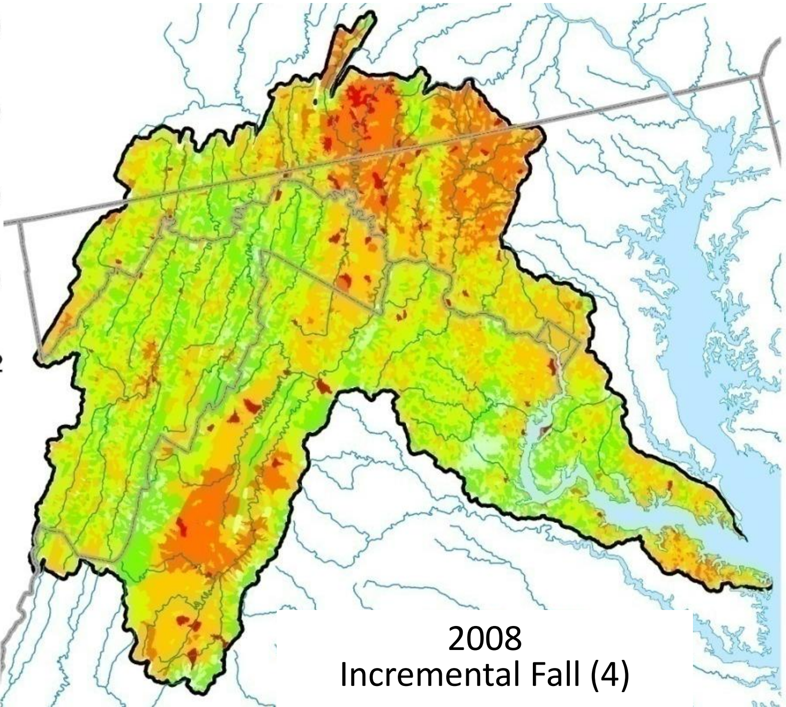
- 🟩 < 5.0 kg/km2
- 🟩 5.01 - 10.0
- 🟨 10.01 - 15.0
- 🟧 15.01 - 20.0
- 🟫 20.01 - 25.0
- 🟥 > 25 kg/km2


2008
Incremental Winter (1)


2008
Incremental Spring (2)

- < 25 kg/km2
- 25.01 - 50.00
- 50.01 - 100.0
- 100.1 - 200.0
- 200.1 - 500.0
- > 500 kg/km2


2008
Incremental Summer (3)


2008
Incremental Fall (4)

Space-time and time-space substitutions in empirical models

Objectives in Developing Dynamic SPARROW Models

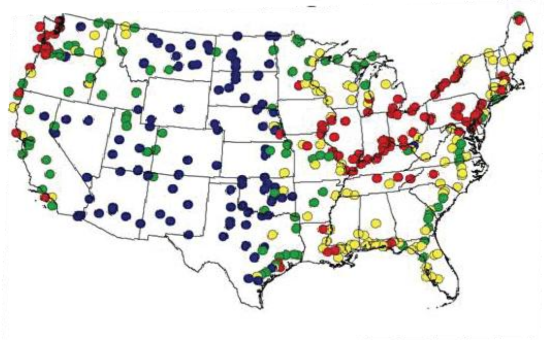
1. Ability to understand and describe seasonal water quality behavior.

2. Ability to forecast longer term transient water quality behavior under anticipated (or hypothetical) changes in climate, land use, economic development, etc.

SPARROW Water-Quality Model

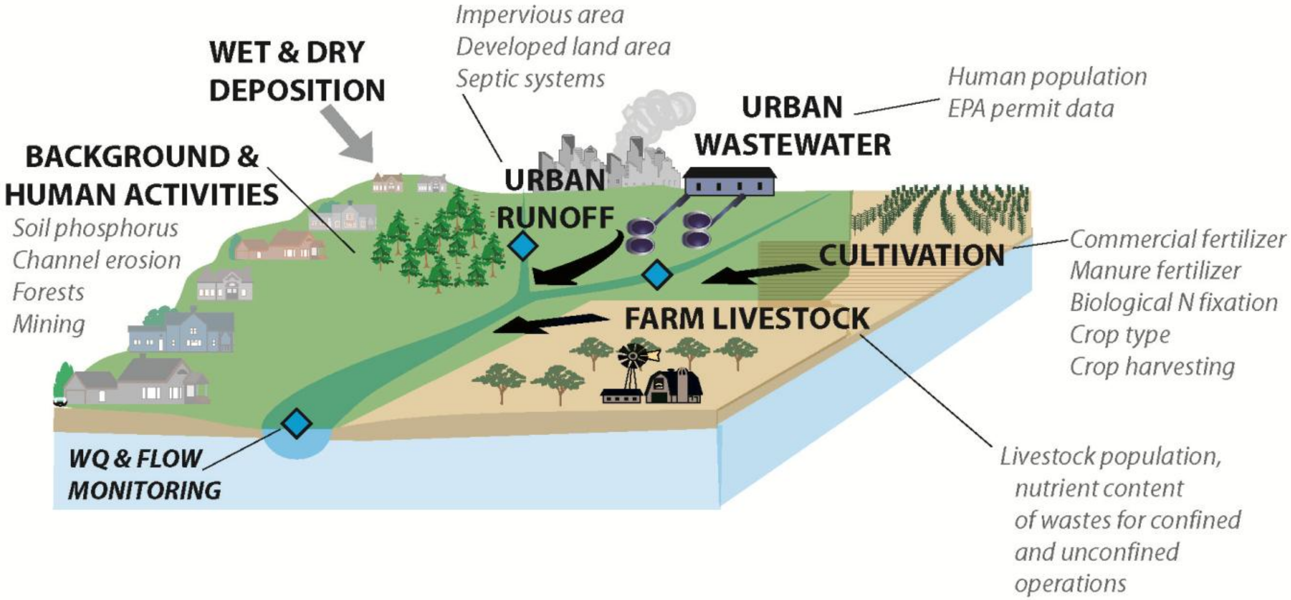
*<u>**SPA**</u>tially <u>**R**</u>eferenced <u>**R**</u>egression <u>**o**</u>n <u>**W**</u>atershed Attributes)*

Monitoring Data



SPARROW: A Spatially-Explicit Mass-Balance Watershed Model

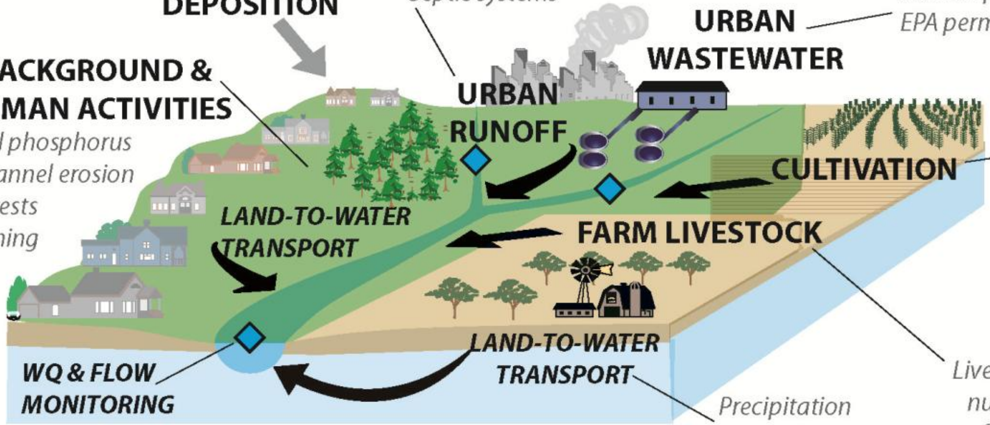
Quantifies nutrient sources and sinks for annual time periods



Examples of sources and processes evaluated in prior SPARROW models

SPARROW: A Spatially-Explicit Mass-Balance Watershed Model

Quantifies nutrient sources and sinks for annual time periods



WET & DRY DEPOSITION

BACKGROUND & HUMAN ACTIVITIES

Soil phosphorus
Channel erosion
Forests
Mining

Impervious area
Developed land area
Septic systems

URBAN RUNOFF

URBAN WASTEWATER

Human population
EPA permit data

CULTIVATION

Commercial fertilizer
Manure fertilizer
Biological N fixation
Crop type
Crop harvesting

FARM LIVESTOCK

Livestock population, nutrient content of wastes for confined and unconfined operations

LAND-TO-WATER TRANSPORT

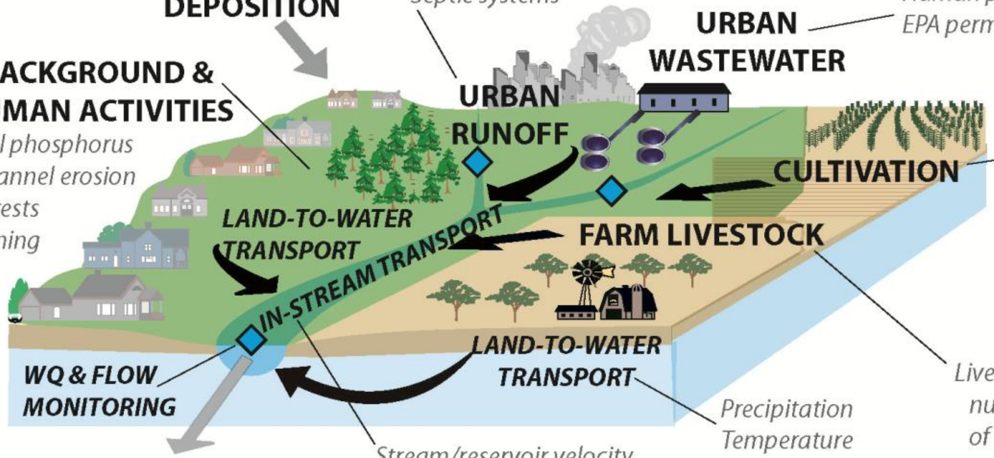
LAND-TO-WATER TRANSPORT

Precipitation
Temperature
Soil permeability
Clay/sand content
Slope
Surface/subsurface flow
Geology
Hydrologic landscape or physiographic region
Drainage density
Wetlands
Artificial drainage

WQ & FLOW MONITORING

SPARROW: A Spatially-Explicit Mass-Balance Watershed Model

Quantifies nutrient sources and sinks for annual time periods



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IN-STREAM TRANSPORT

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Temperature
Soil permeability
Clay/sand content
Slope
Surface/subsurface flow
Geology
Hydrologic landscape or physiographic region
Drainage density
Wetlands
Artificial drainage

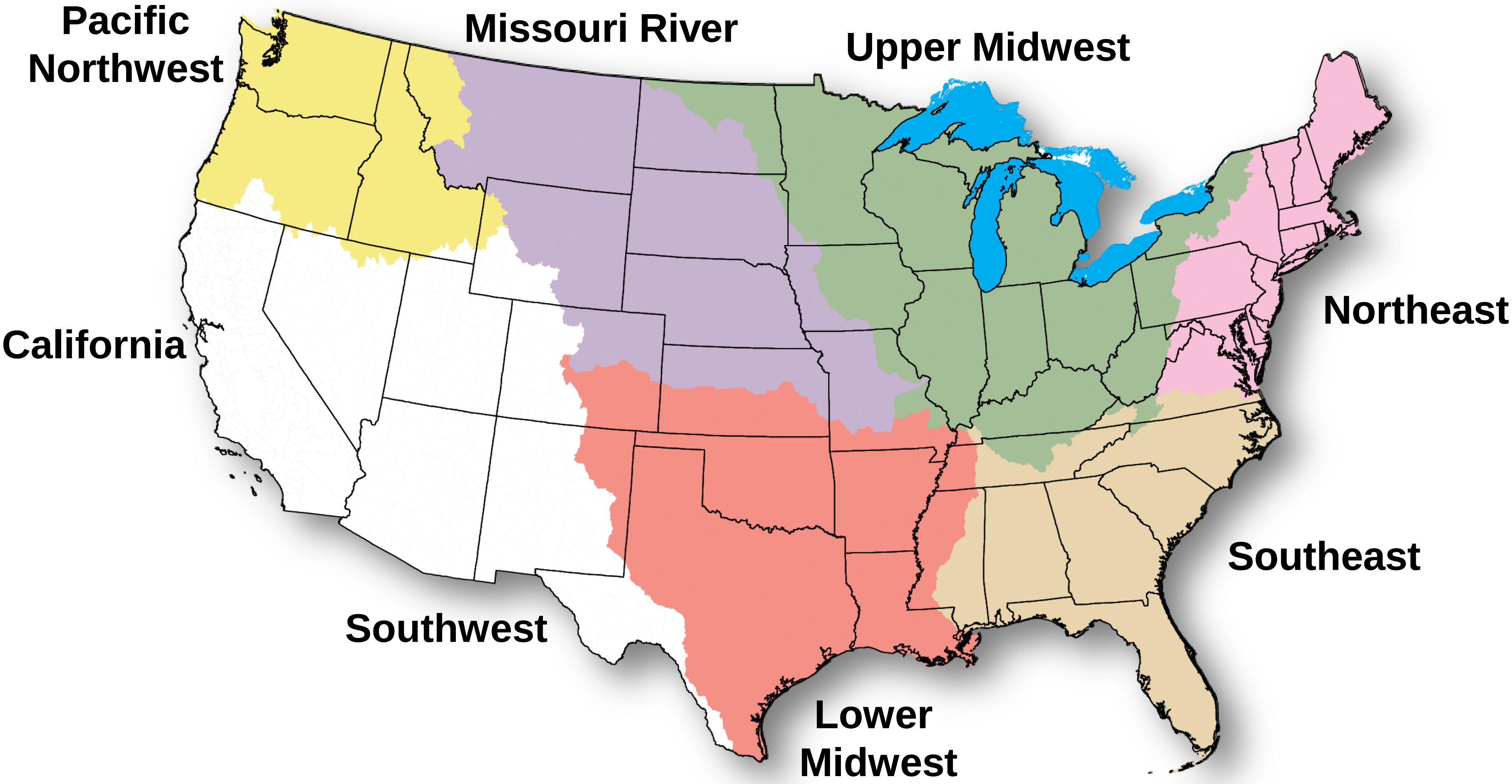
WQ & FLOW MONITORING

Stream/reservoir velocity
First-order decay reflects denitrification and multi-year storage

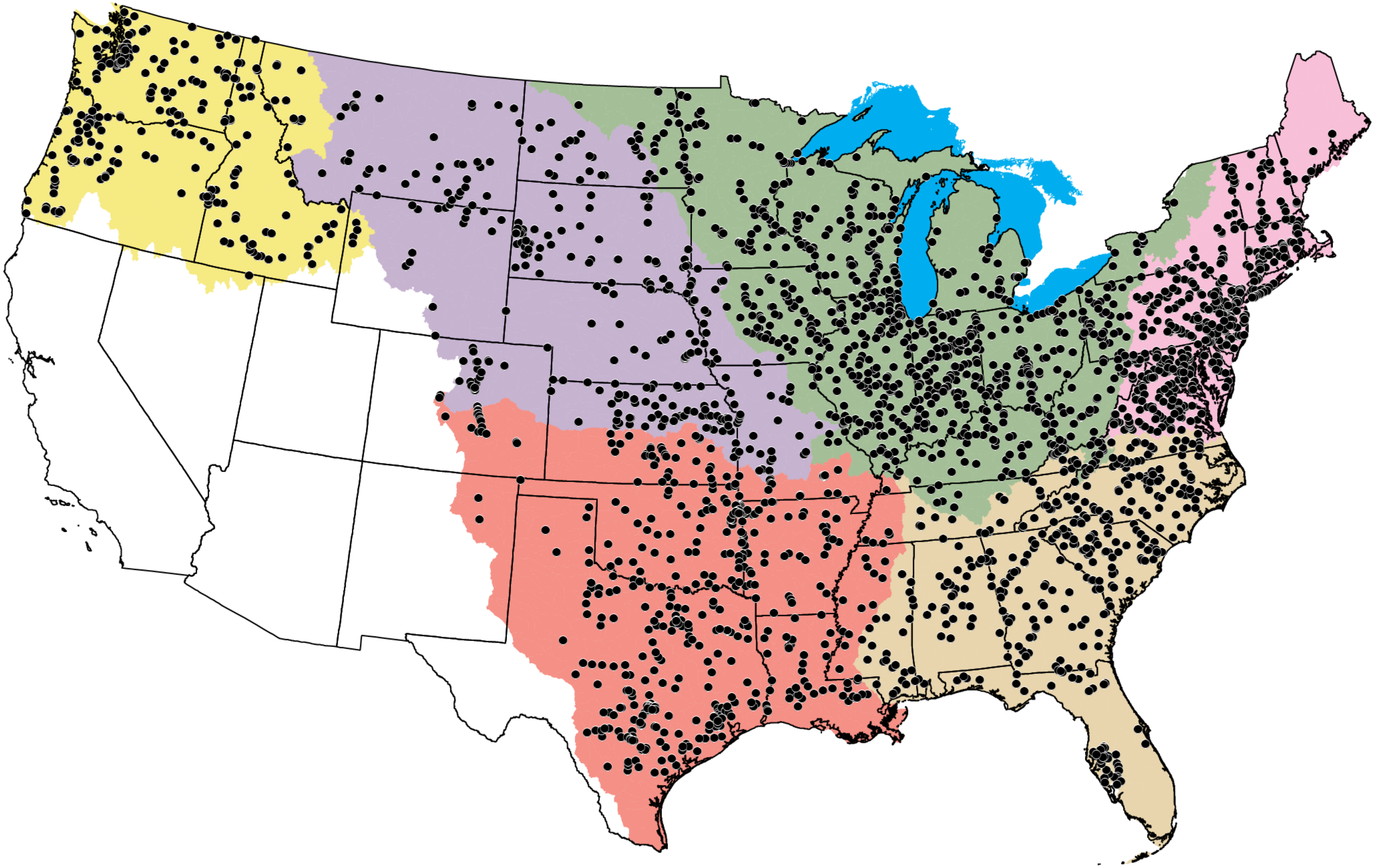
DOWNSTREAM TRANSPORT & COASTAL DELIVERY

National Water Quality Assessment Program

Surface Water Status and Trends Regions

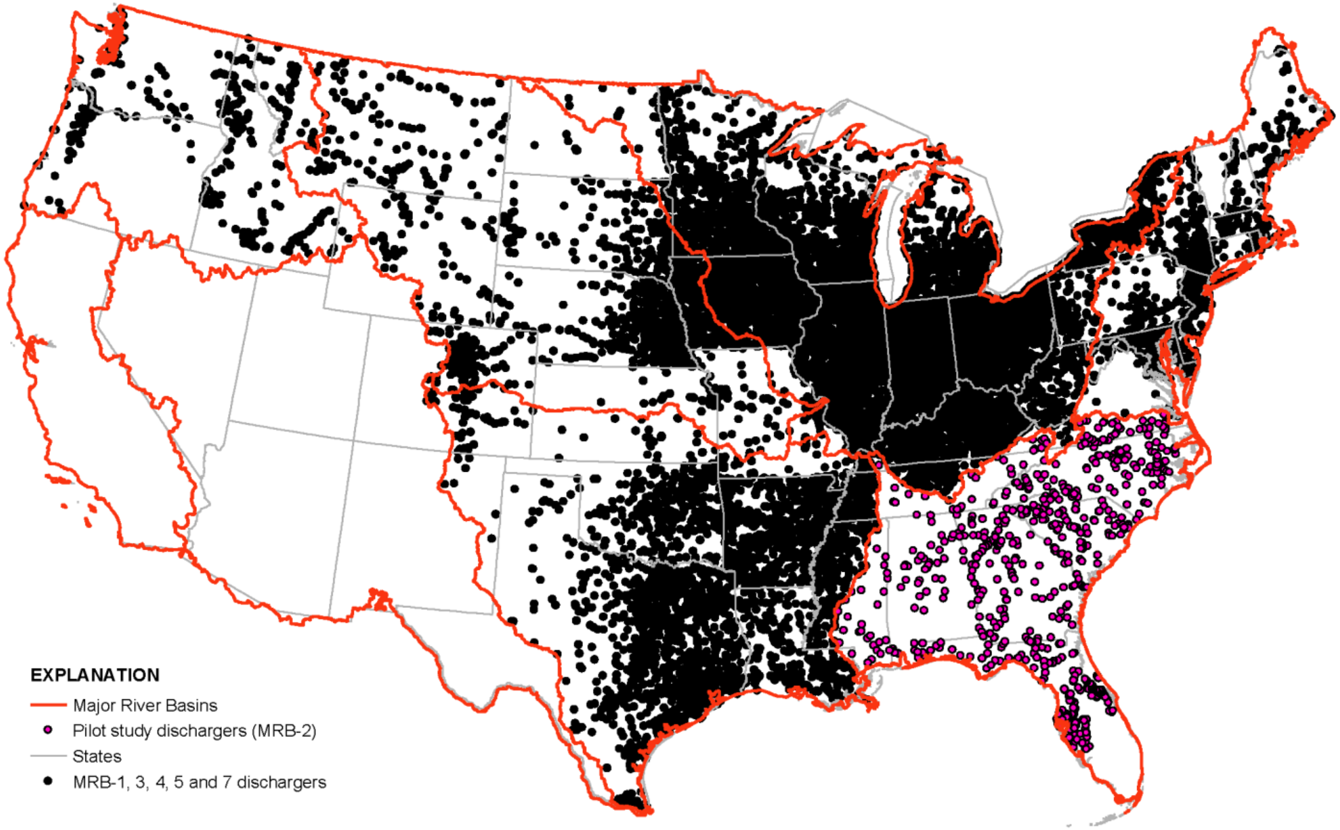


Monitoring Data Are Critical for Modeling



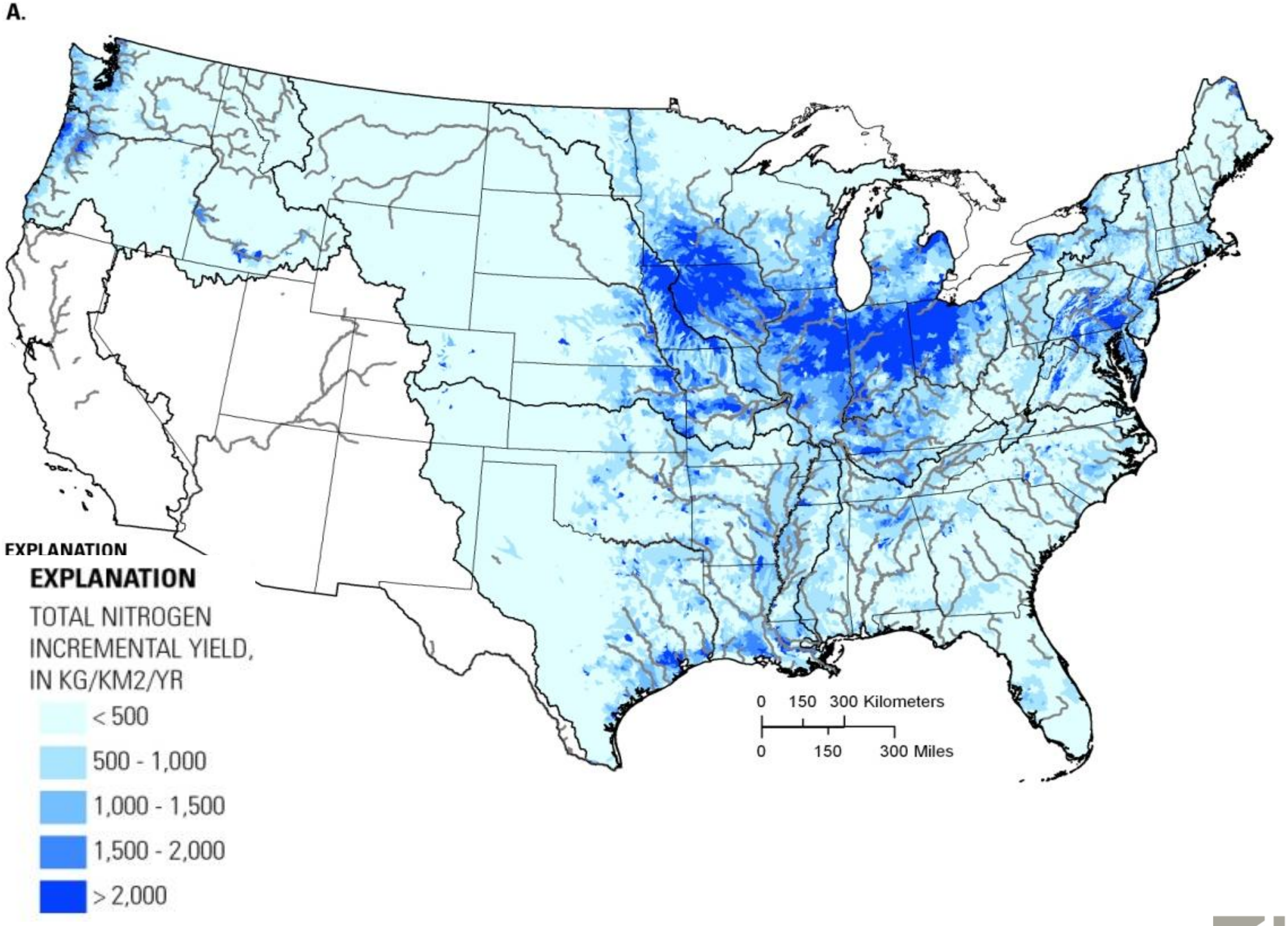
2,700 calibration sites with data from 73 agencies

Nutrient Source Data – Point Sources



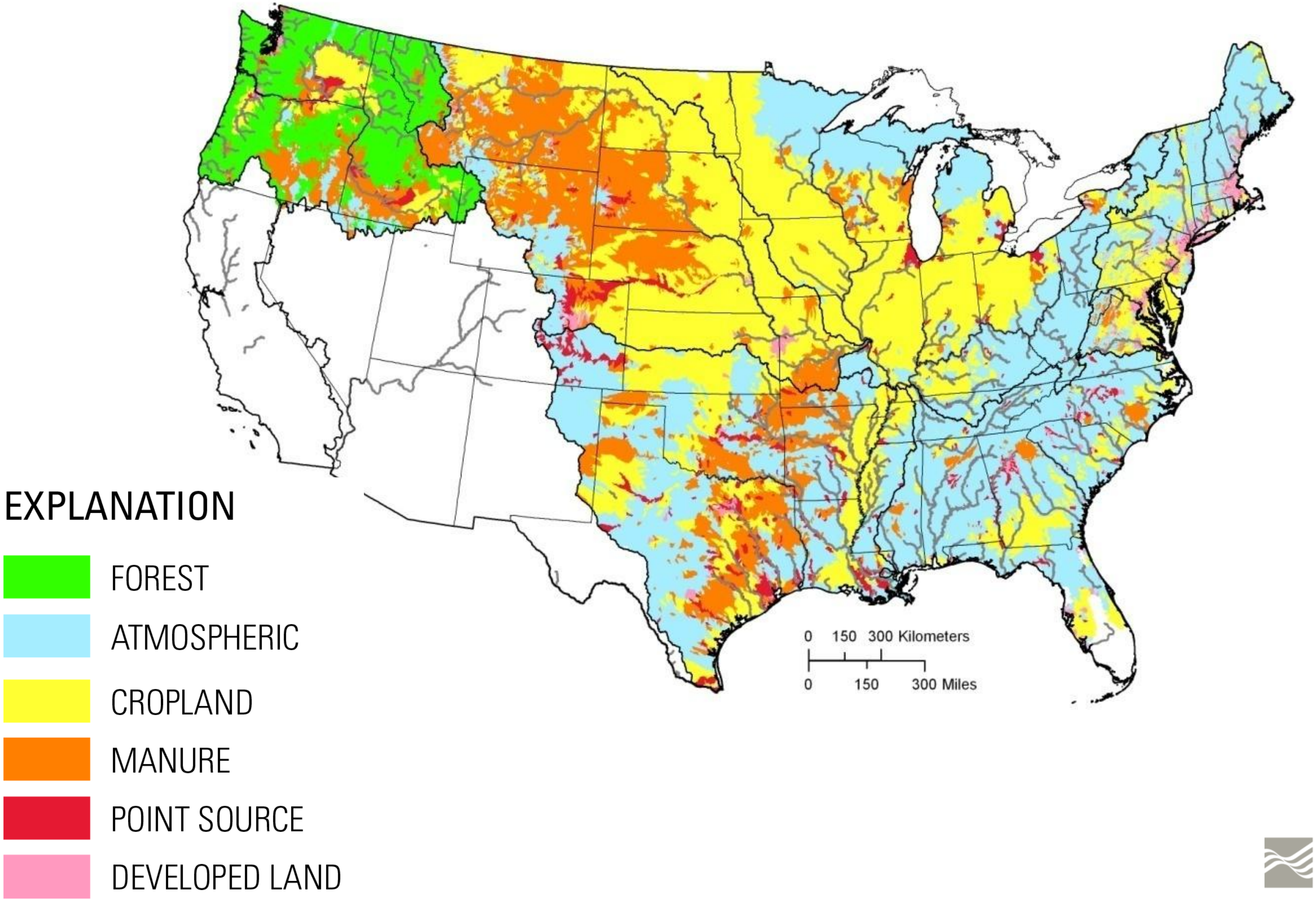
Molly Maupin, USGS

Total Nitrogen Yields



USGS

Largest Nitrogen Sources



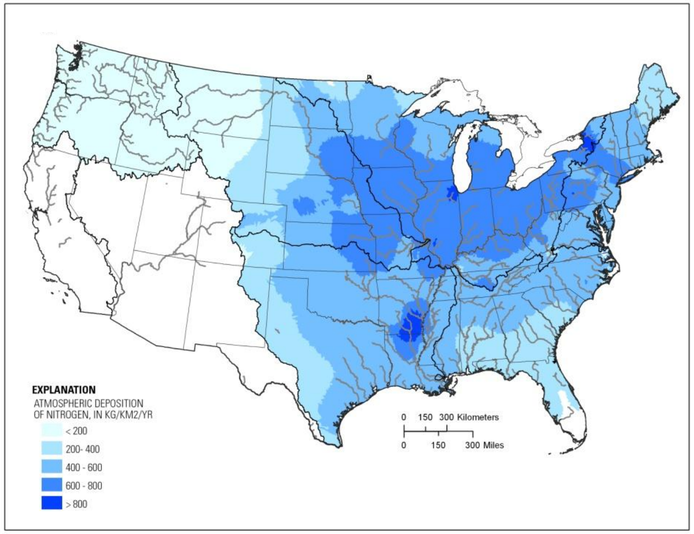
USGS

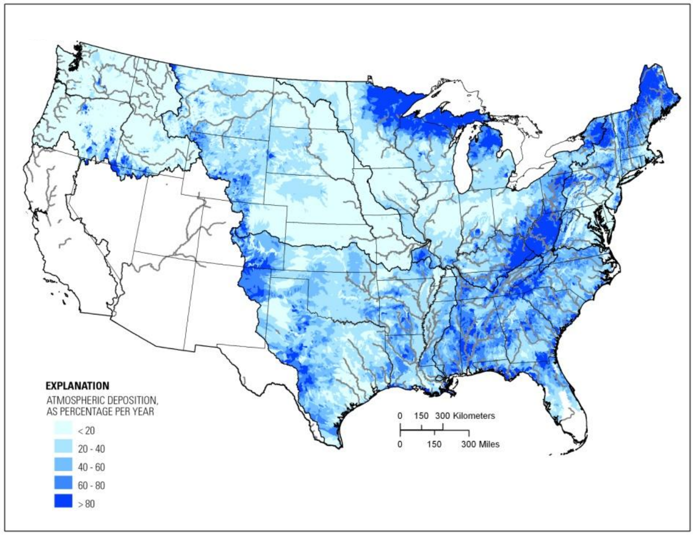
SPARROW Perspectives on Source Input

Atmospheric Deposition Example

Nitrogen Deposition to the Land Surface

(kg/km^2/yr)



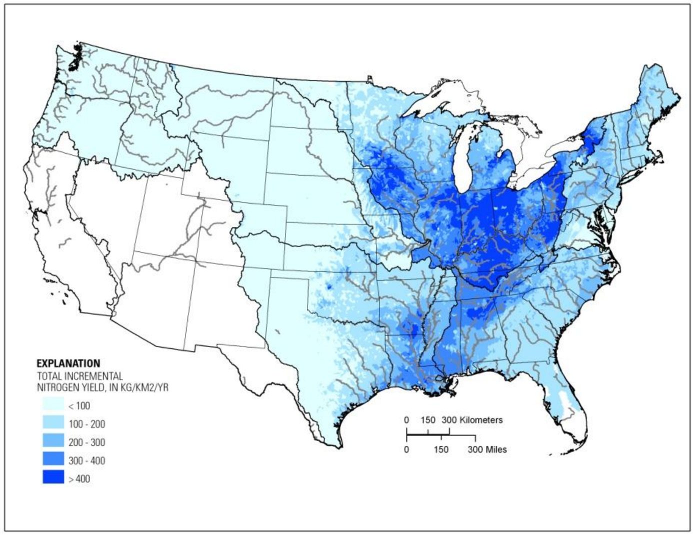


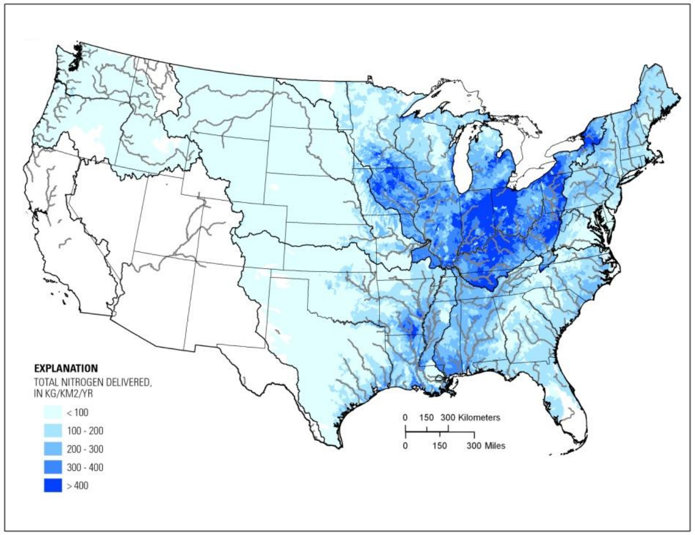
Percentage of Nitrogen Source Input from Deposition

(%)

Nitrogen Yield from Incremental Catchments

(kg/km^2/yr)





Nitrogen Yield from Delivered Downstream

(kg/km^2/yr)