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

Presented By

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Workshop:

"Management Effects on Water Quality Trends"

Scientific and Technical Advisory Committee, Chesapeake Bay Program

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Presentation Outline

- **Project objectives**
- **Dynamic SPARROW modeling**
  - Role of MODIS data
- **Model calibrations and results**
  - South Carolina estuaries
  - Potomac River/Chesapeake Bay
  - Long Island Sound
- **Simulating the effects of source reductions**
- **Exploring the role of groundwater**
- **Conclusions**

Project Objectives

SPARROW models are now widely used for investigating spatial aspects of water quality (conditions, processes, and management); however…..

***Limitations of the steady state "assumption" in SPARROW modeling*:**

1. **In calibration:** requires long-term averaging and load adjustments for changes in flow and sources.
2. **In interpretation:** contaminant storage and residence time in the watershed are unknown.
3. **In application:** can't predict the response of contaminant flux to changes in precipitation, temperature, sources, etc (seasonal or longer term). Also, requires "space for time" assumption.

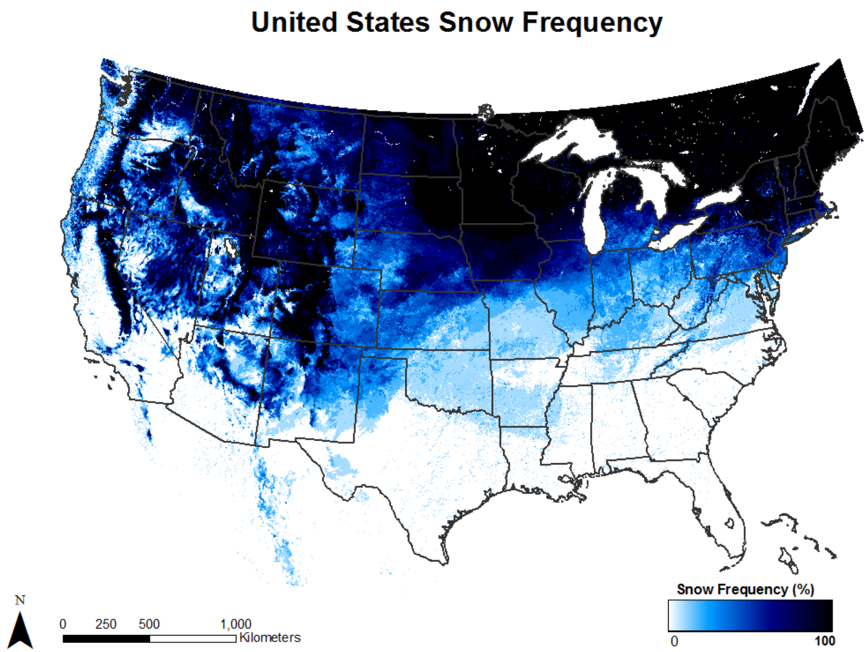
***Research Questions*:**

1. **Can dynamic SPARROW models be constructed by calibration with time series data?**
2. **Can dynamic SPARROW models be constructed with "memory" so that they account for storage and time lags in contaminant flux using a recursive form?**

3*. Does use of earth observation data facilitate dynamic SPARROW modeling?

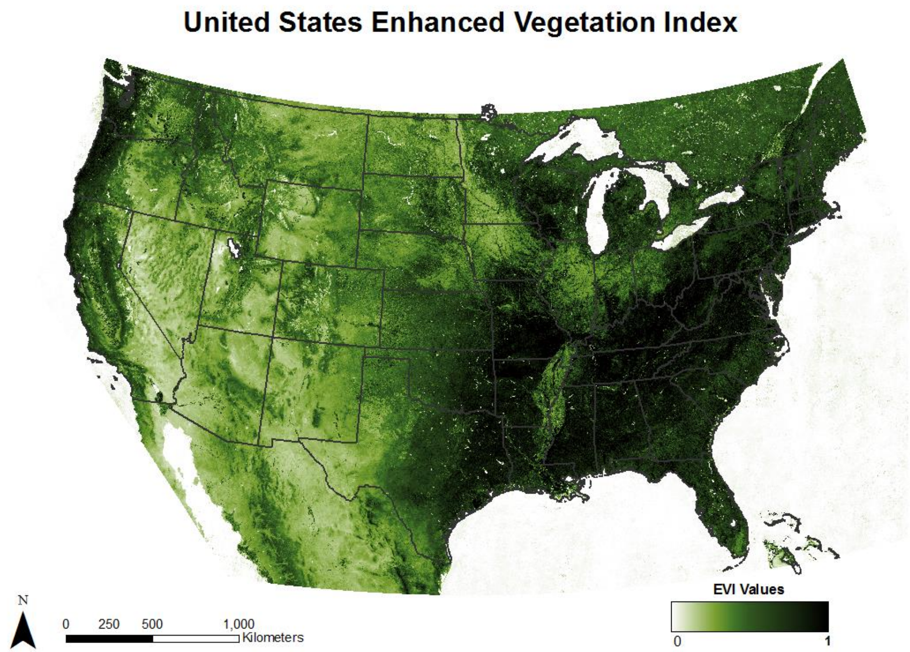
- NASA supported research

New seasonal data sets derived from MODIS 8-day 500-m surface reflectance (2001-2009)



Seasonal snow cover frequency

$$\text{snow freq} = N_{snow}/N_{observations}$$



Median Enhanced Vegetation Index (EVI)

$$EVI = G\frac{r_{NIR} - r_{red}}{r_{NIR} + (C_1 r_{red} - C_2 r_{blue}) + L}$$

Also: Gross Primary Productivity and Land Surface Water Index

SPARROW's Reach-Scale Mass Balance

Reach network relates watershed data to monitored loads

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

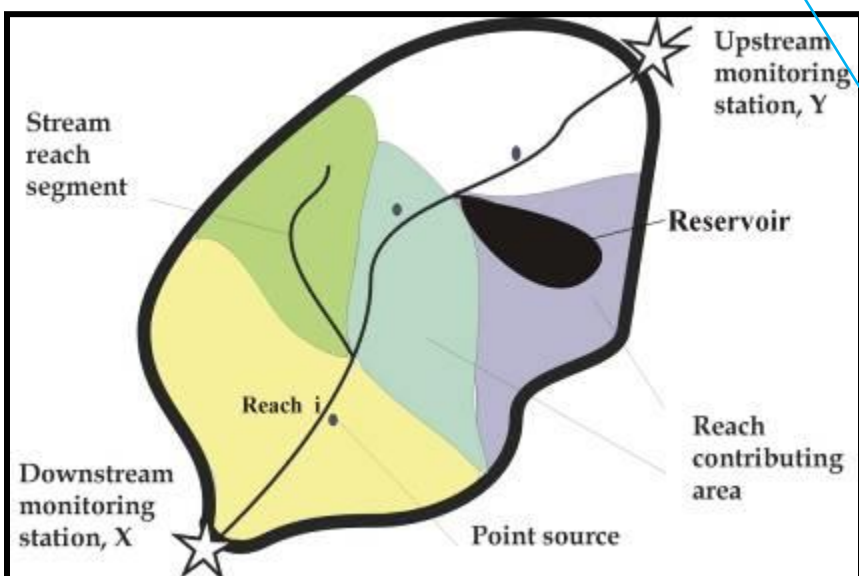
Monitored Stream Load

Sources

Land-to-water transport

Aquatic transport

Error



Required Modification of SPARROW Equation for dynamic modeling

1. **Addition of runoff, and lag-1 runoff, to Land-to-water transport term**
2. **Addition of lag-1 source term(s) based on predicted "concentration" in previous time step.**
3. **Operates recursively**

Recursive Form

The procedure for dynamic calibration requires specifying the "source" and "land-to-water" terms for individual reach-level catchments as follows:

$$\mathbf{E_t} = \Sigma_i \boldsymbol{f_t} \mathbf{S_{t,i}} + \boldsymbol{f_0} \mathbf{E_0}$$

where

$\mathbf{E_t}$ is export (m/t) of N_R from the catchment during the current time step;

$\mathbf{E_0}$ is export (m/t) of N_R from the catchment during the previous time step;

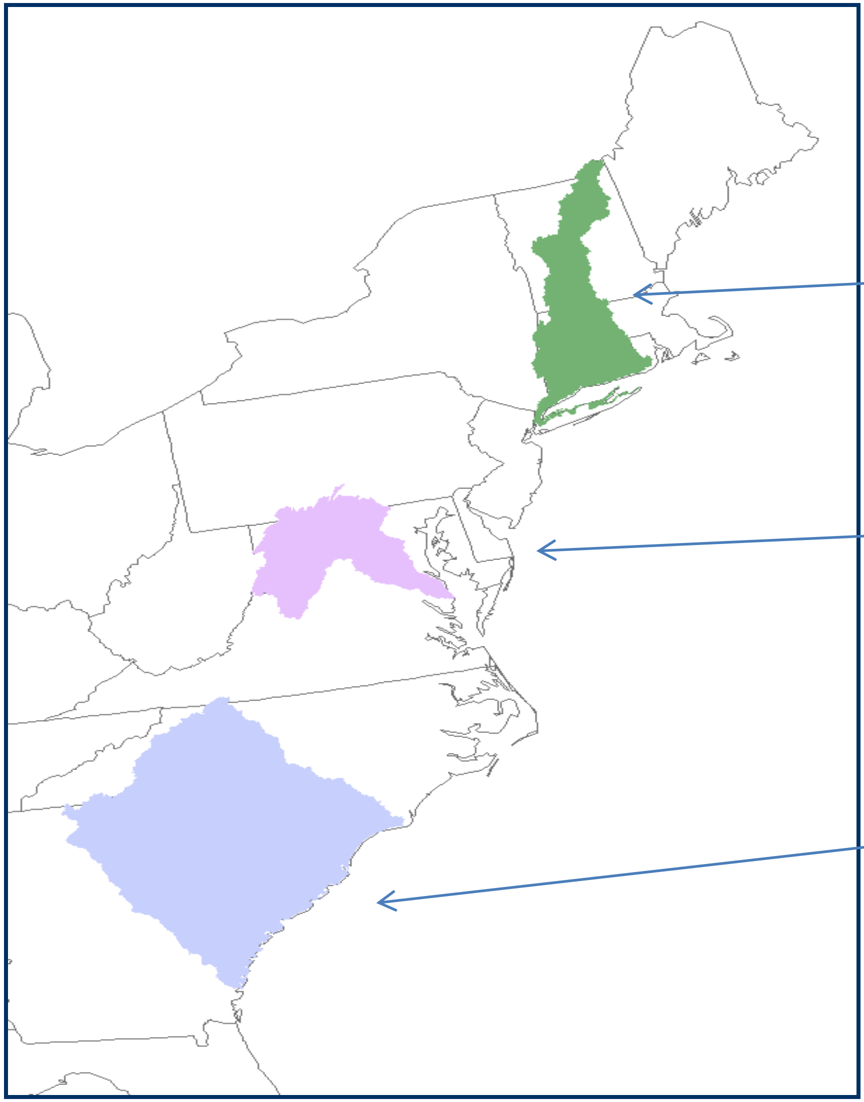
$\Sigma \boldsymbol{f_t} \mathbf{S_t}$ is the sum of sources of new N_R to the catchment during the current time step;

$\boldsymbol{f_t}$ and $\boldsymbol{f_0}$ are functions of catchment characteristics (e.g. precipitation, temp, runoff, etc).

When sources of N_R are zero, catchment export falls exponentially according to the recursive relation: $\mathbf{E_t / E_0 = \boldsymbol{f_0}}$. Assuming the export rate of material from transient storage at a given point in time is proportional to the quantity in storage, the exponential decay rate can be used to estimate the mean residence time of stored material: $\mathbf{E_t / E_0 = exp[-(r+k)\,\Delta t}\,]$ and mean residence time is $\mathbf{1/[ln(r+k)\,\Delta t]}$
Where r and k are rate coefficients for stream export and watershed loss, and Δt is time step length.

The contribution to export of transient storage relative to "quick" runoff (CTS) is estimated as $\boldsymbol{f_0} \mathbf{E_0} \;/\; (\Sigma_i \boldsymbol{f_t} \mathbf{S_{t,i}} + \boldsymbol{f_0} \mathbf{E_0})$

Basin locations for three dynamic SPARROW models.



Independent Variables

N sources (4 or 5)

Precipitation

Temperature

Runoff

Delta runoff

Enhanced vegetation index*

Snow/ice % cover (LIS only)*

In-stream decay

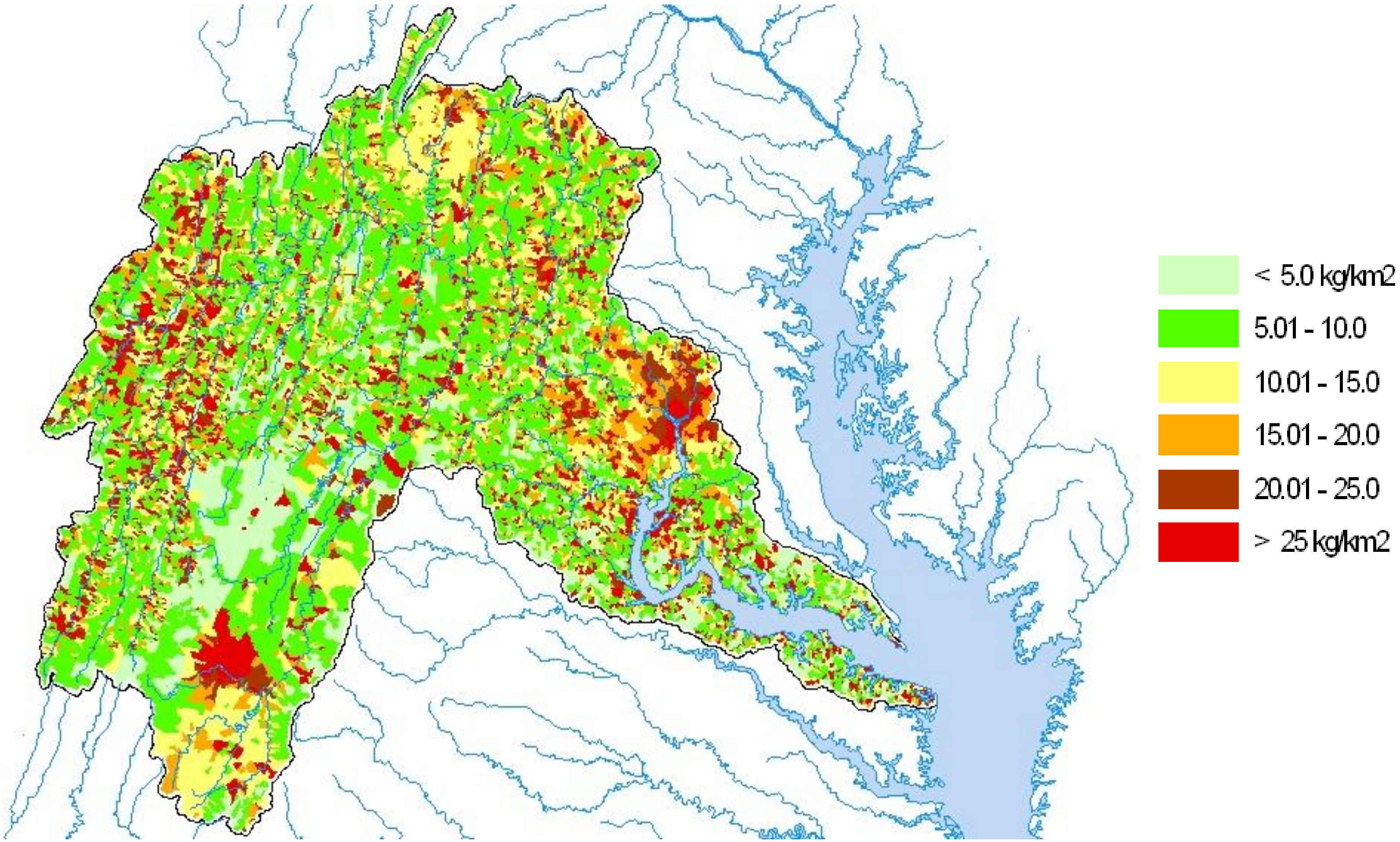
Other (slope, base flow index, depth to gw, carbonate %)

* MODIS data

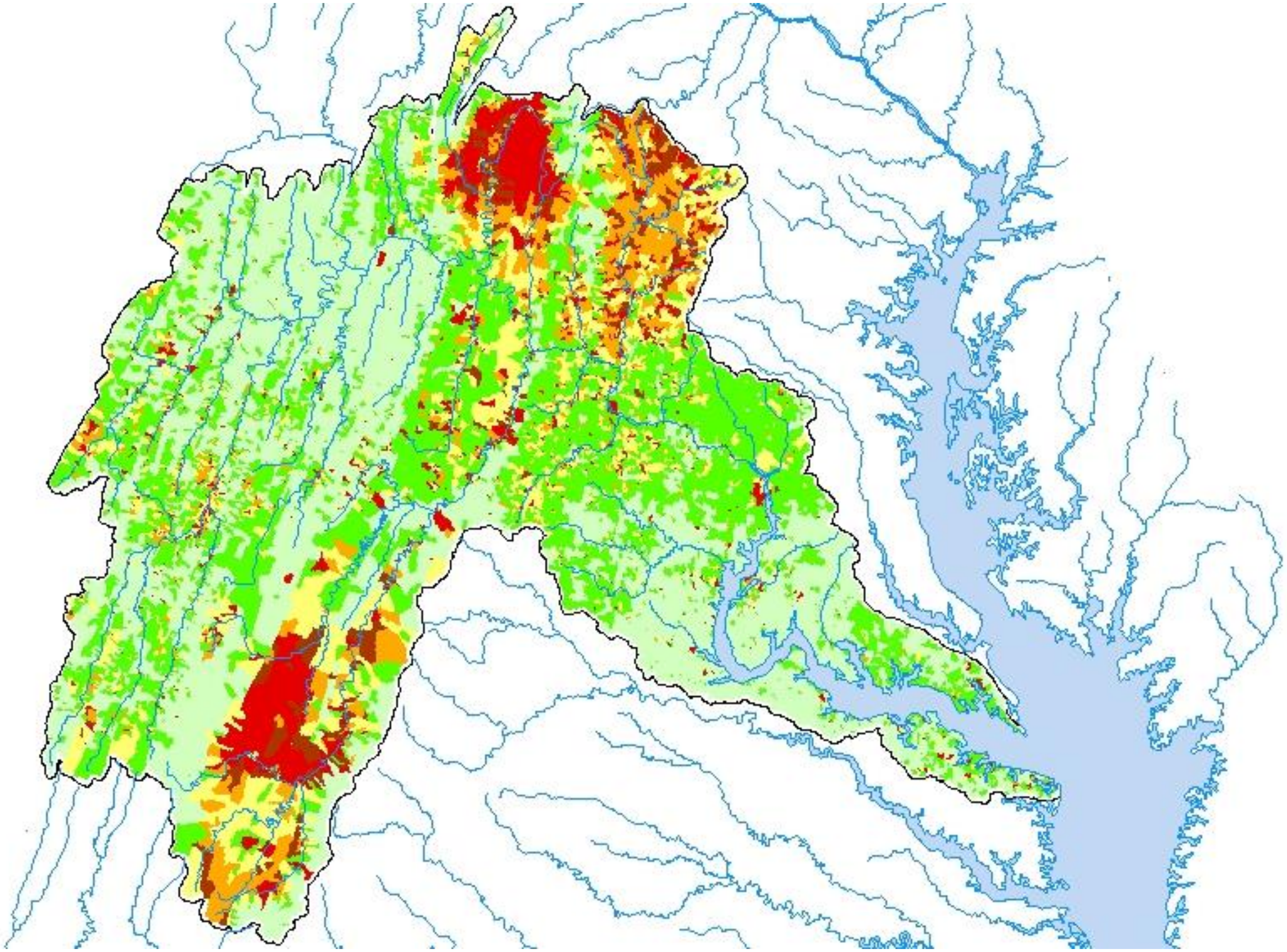
Calibration Results for Three Dynamic SPARROW Models

Drainage Basin	Area (km^2)	Storage Processes	Model r^2 (RMSE)	Estimated Mean Residence Time (yr)	Contribution of Storage to Export (CTS in %)
South Carolina	134,300	Plant/Soil Uptake	0.90 (0.64)	1.1	72
Potomac River	30,100	Plant/Soil Uptake	0.90 (0.69)	1.5	79
Long Island Sound	22,059	Plant/Soil Uptake Snow/Ice Cover	0.94 (0.44)	0.27	40 22

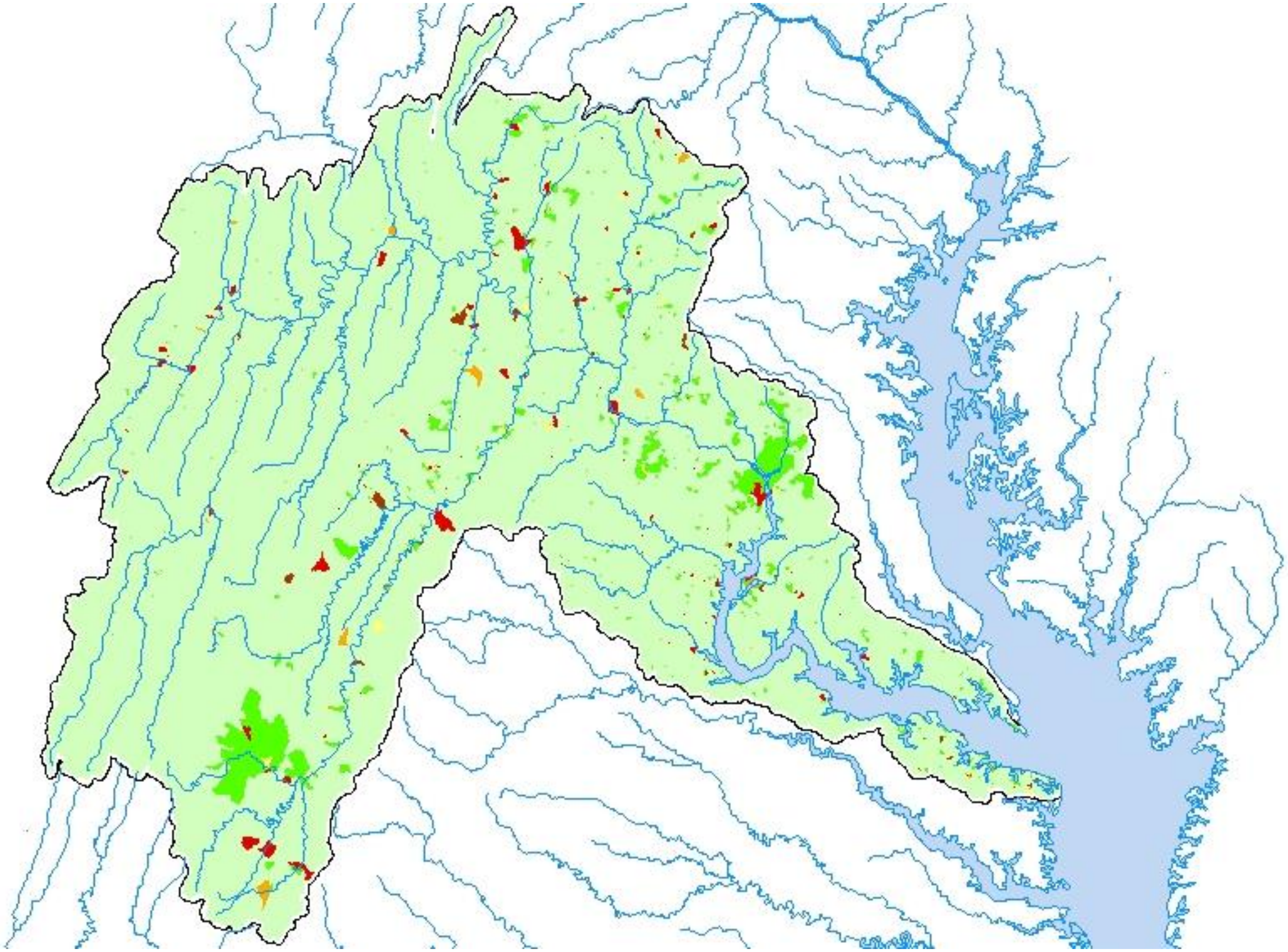
Total Nitrogen Yield (kg km^{-2} day^{-1})
Winter (J, F, M) 2006



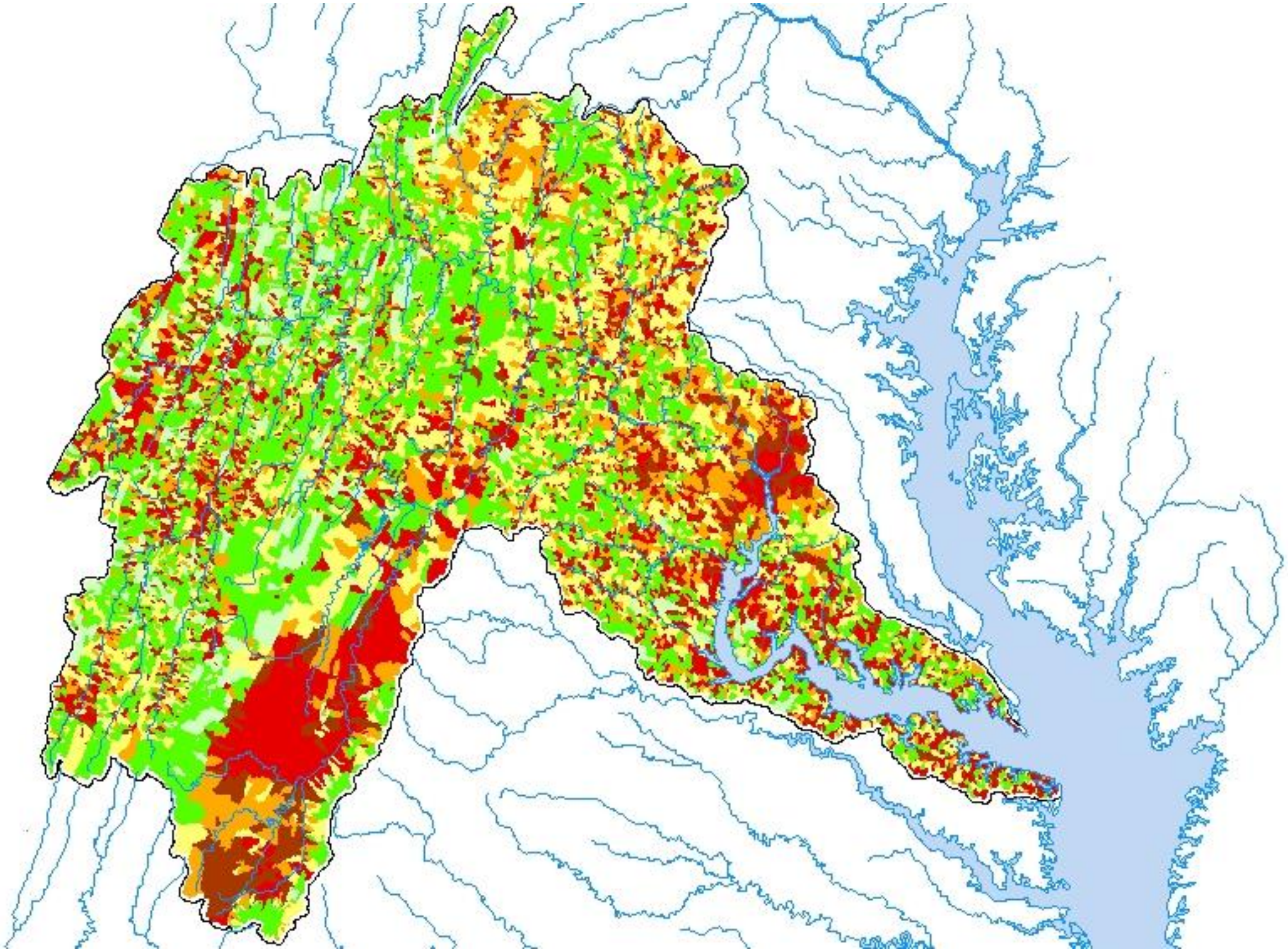
Total Nitrogen Yield (kg km^{-2} day^{-1})
Spring 2006



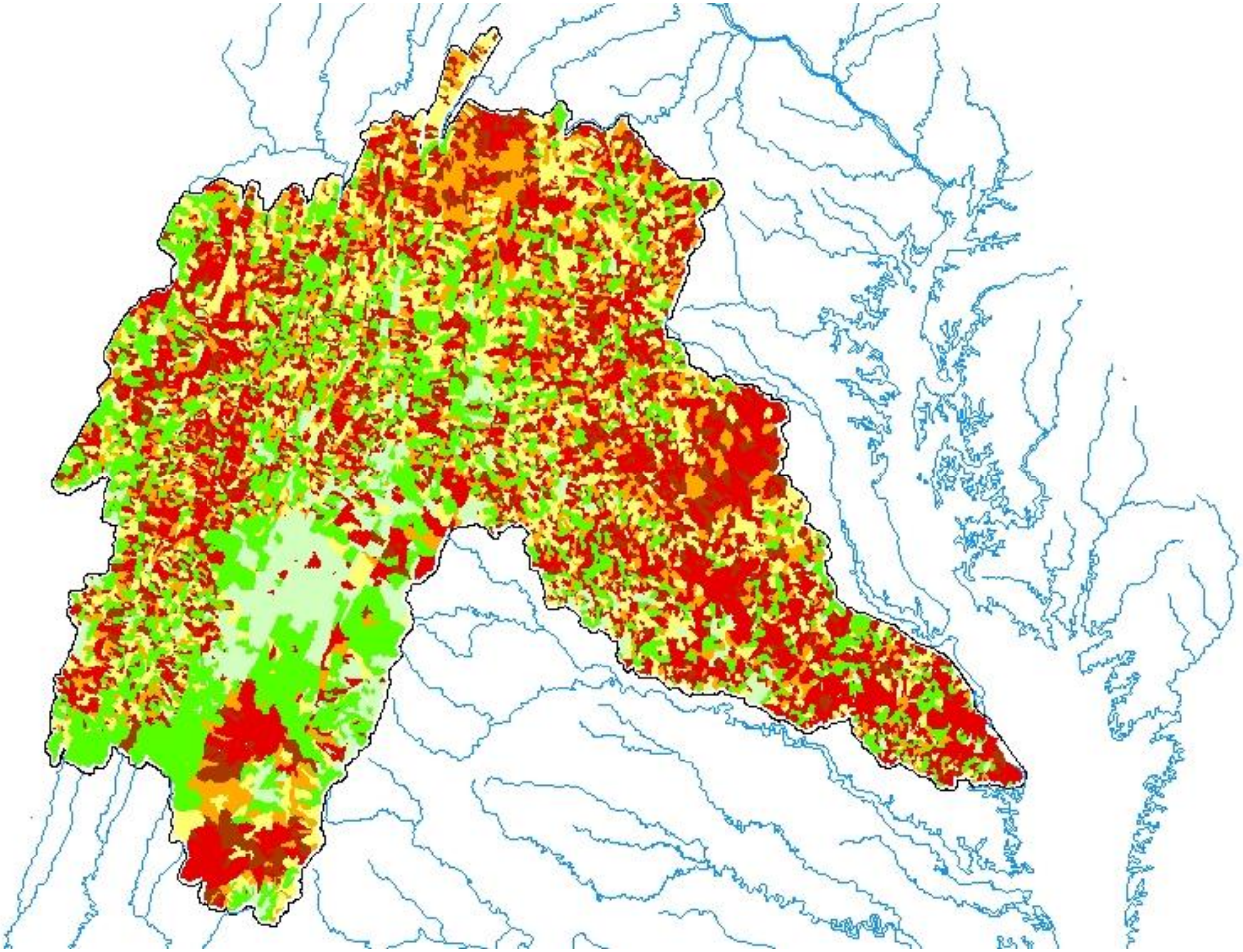
Total Nitrogen Yield (kg km^{-2} day^{-1})
Summer 2006



Total Nitrogen Yield (kg km^{-2} day^{-1})
Fall 2006



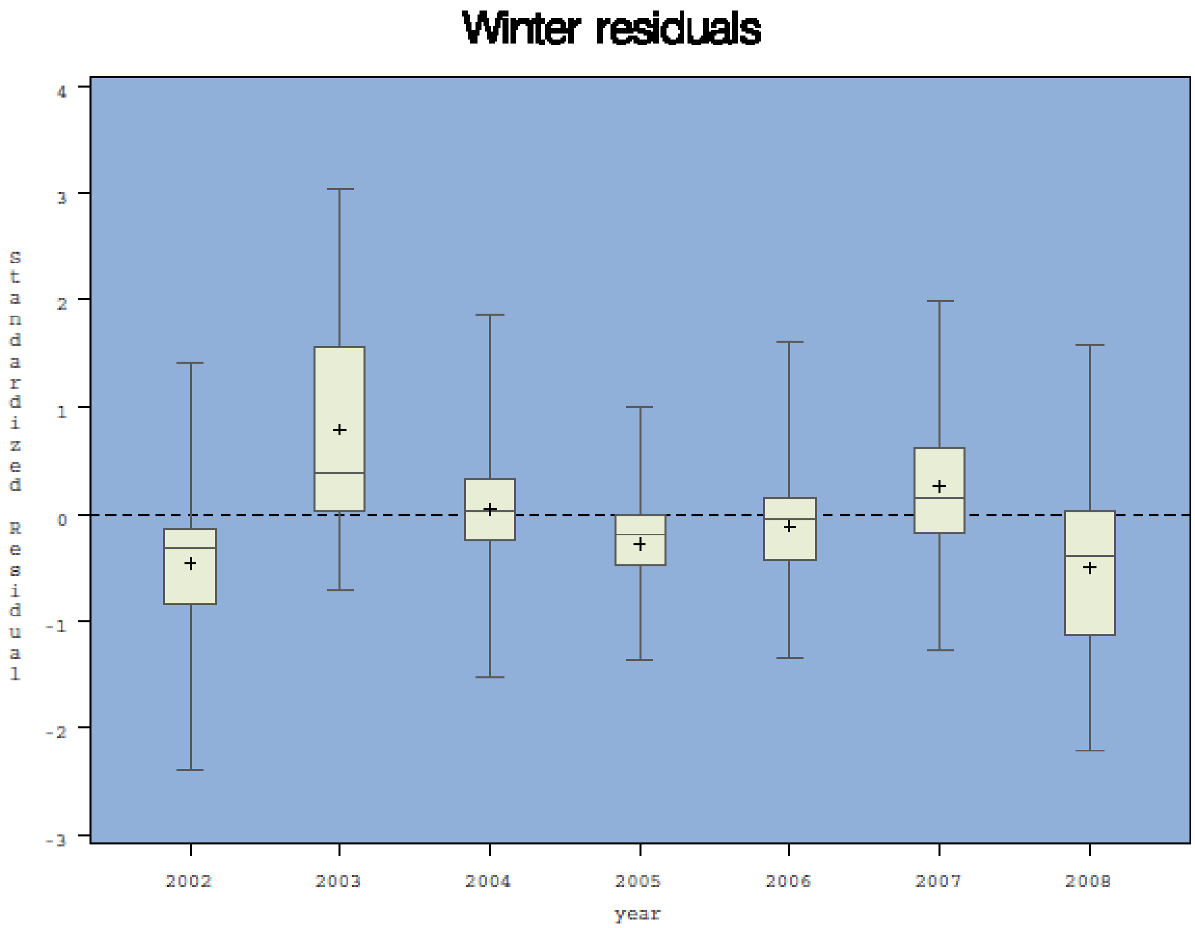
Total Nitrogen Yield (kg km^{-2} day^{-1}) Winter 2008



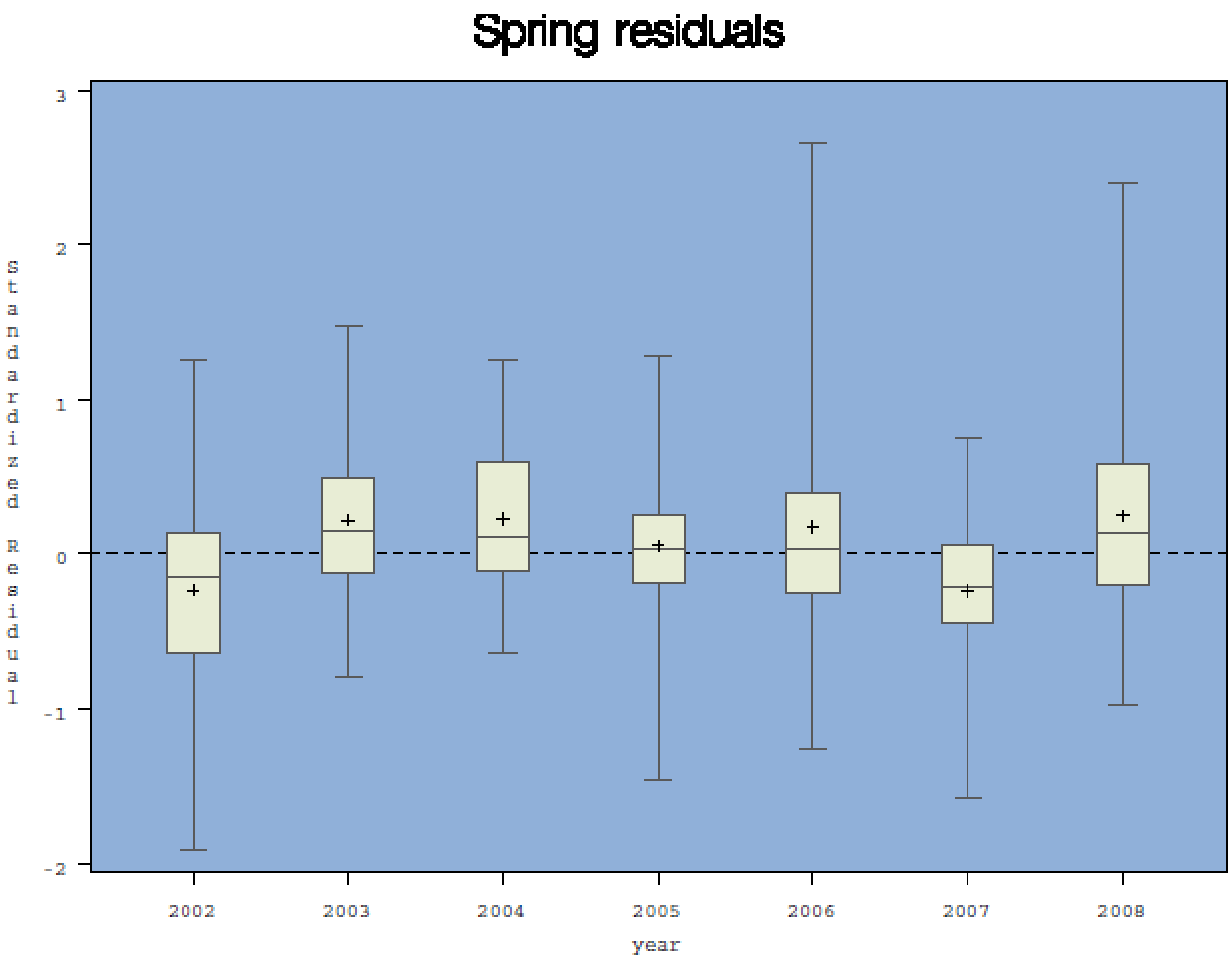
Prediction Errors?

Seasonal Biases?

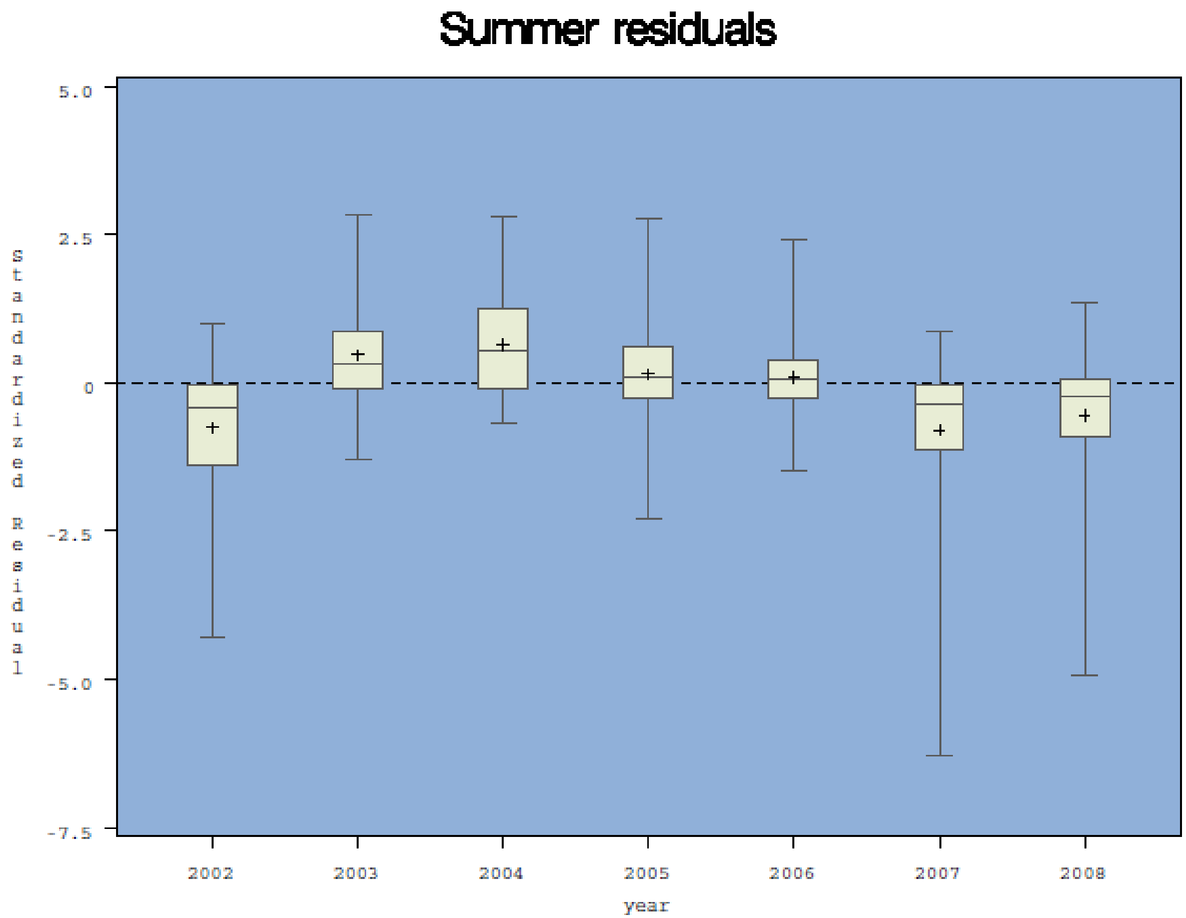
Seasonal Accuracy



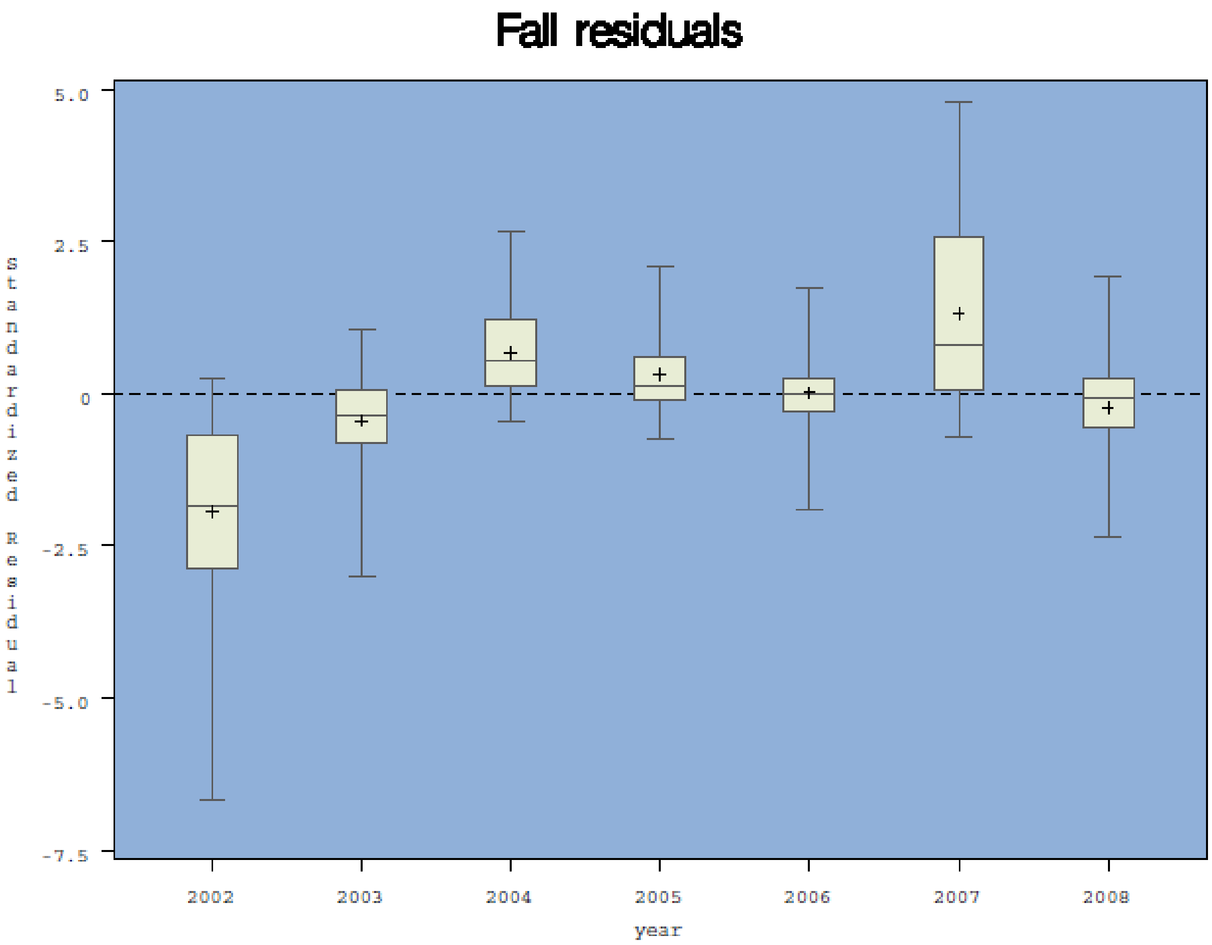
Seasonal Accuracy



Seasonal Accuracy

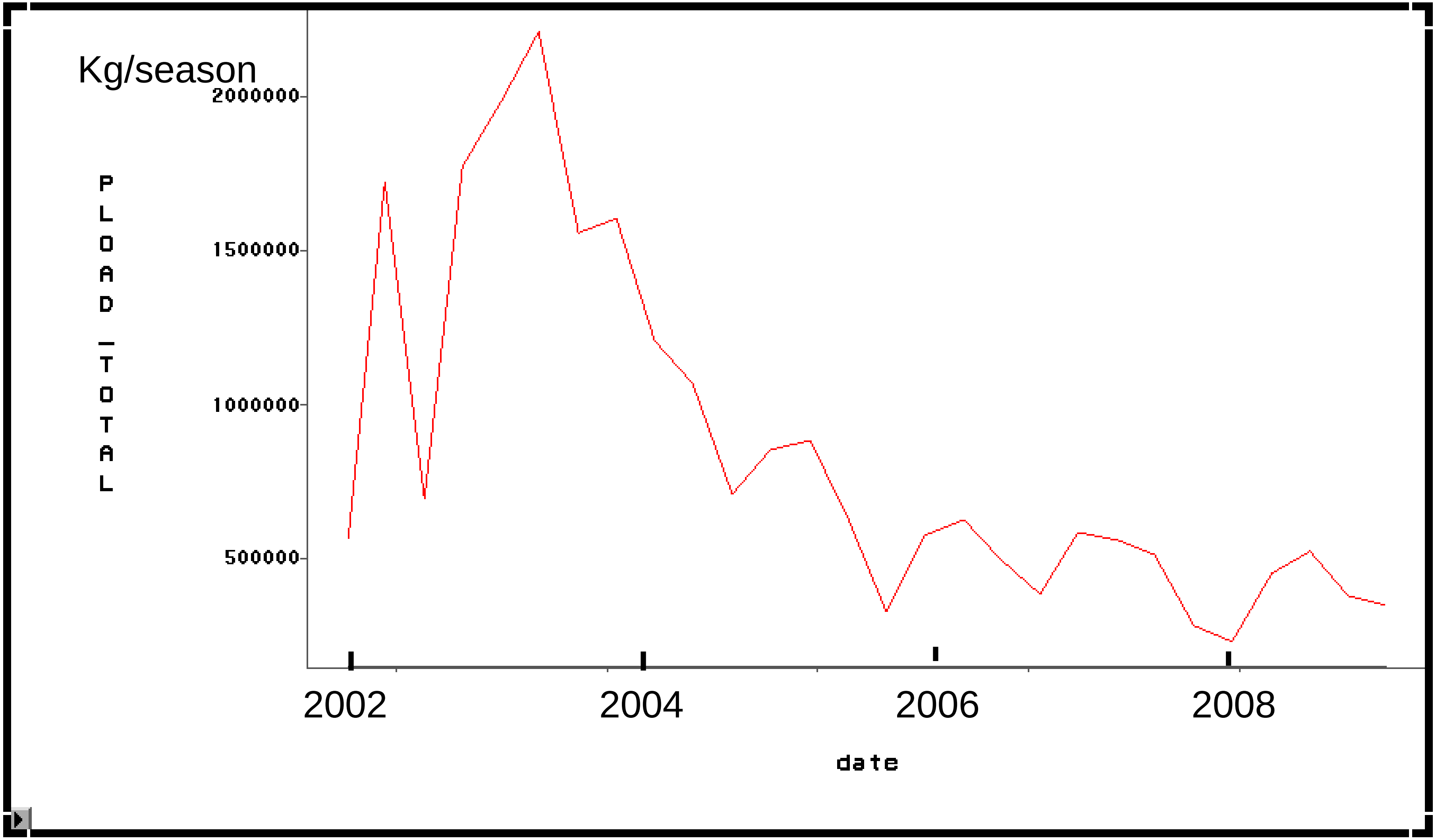


Seasonal Accuracy



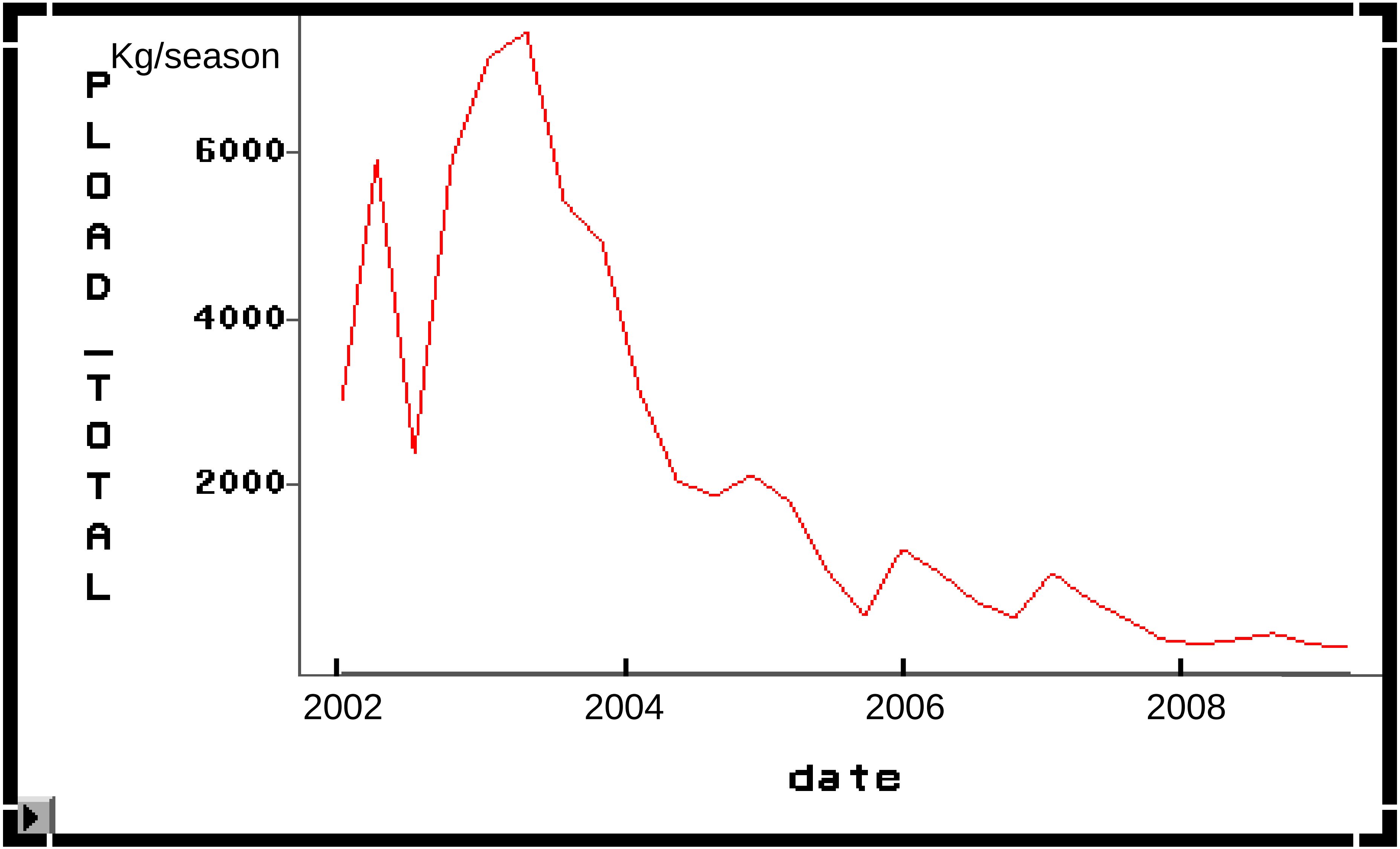
Application: Response Time Following Management Action

Simulation: TN Flux, Potomac River at Chain Bridge
All Nonpoint Sources Set to Zero After First Time Step (Winter 2002)

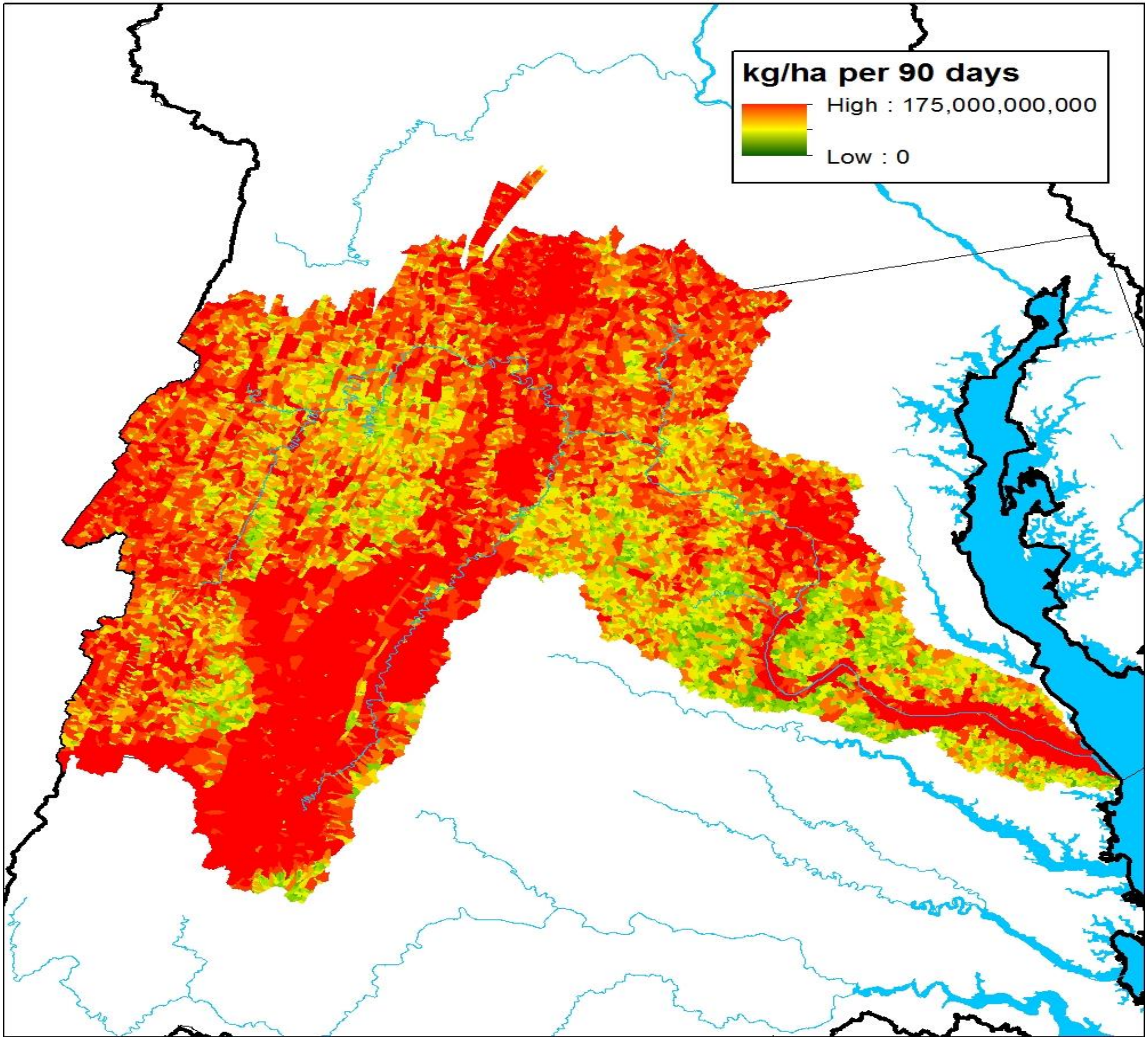


Simulation: TN Flux in Christians Creek, VA

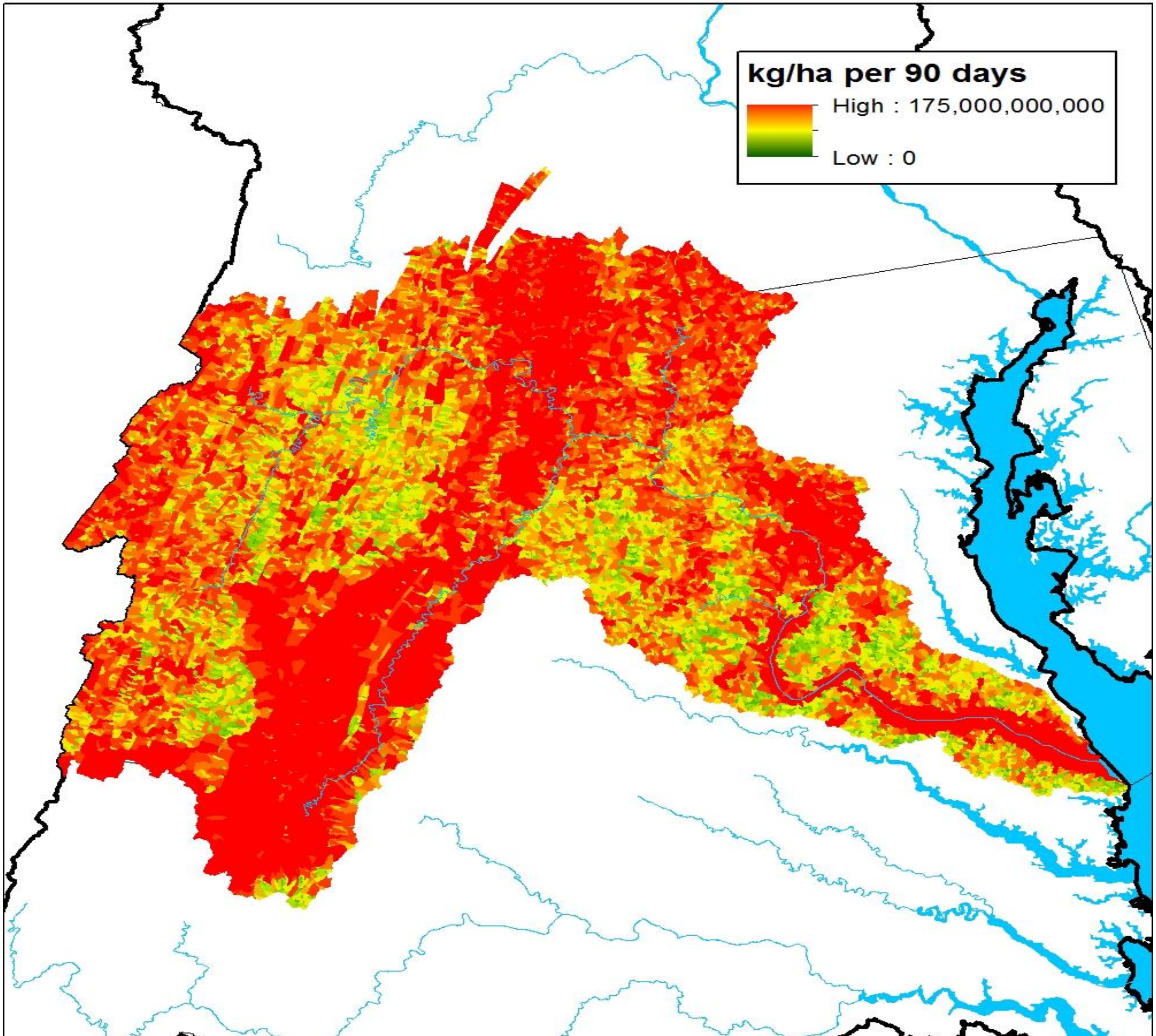
All Nonpoint Sources Set to Zero After First Time Step



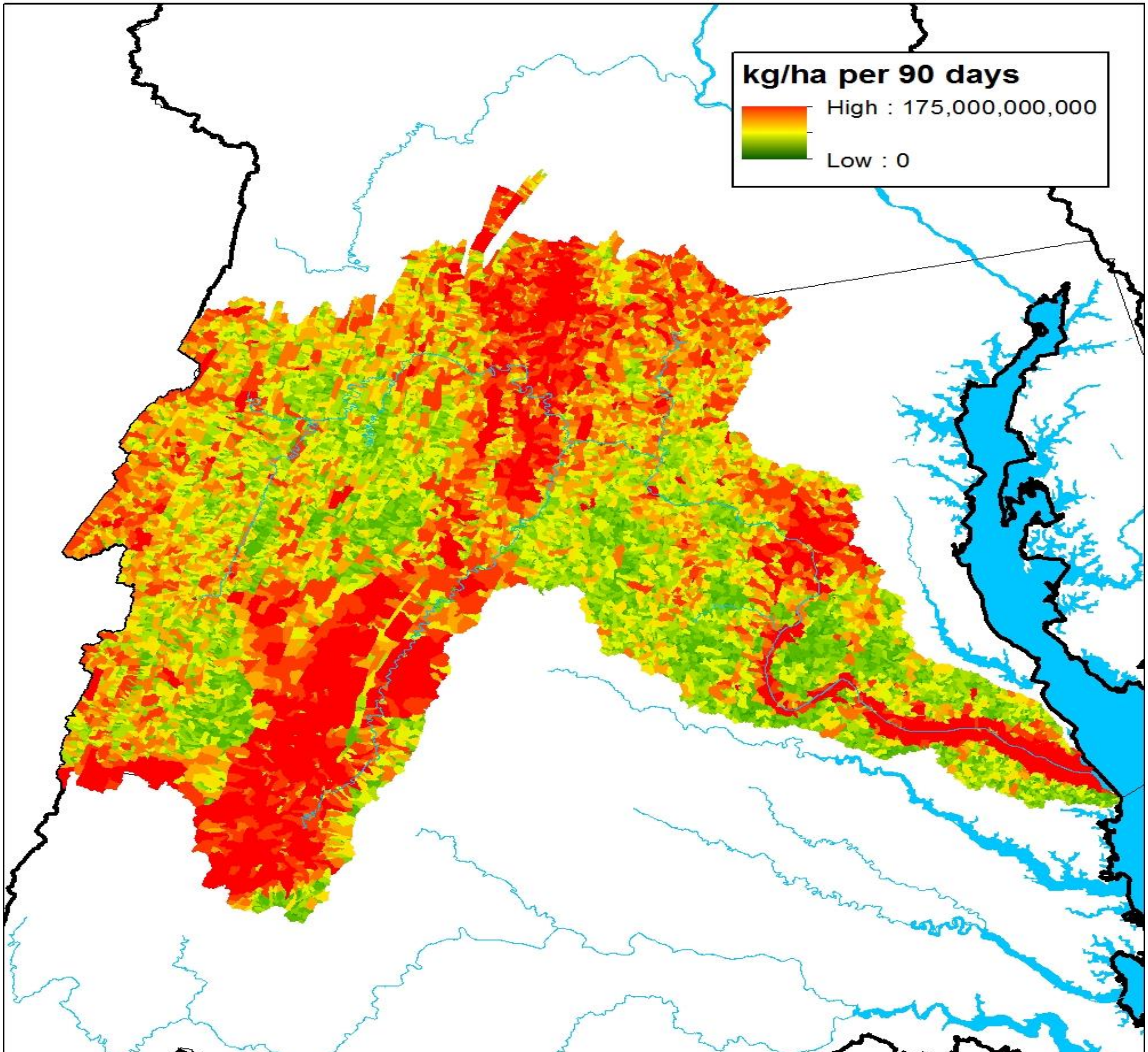
Predicted Incremental TN Load - Spring 2002



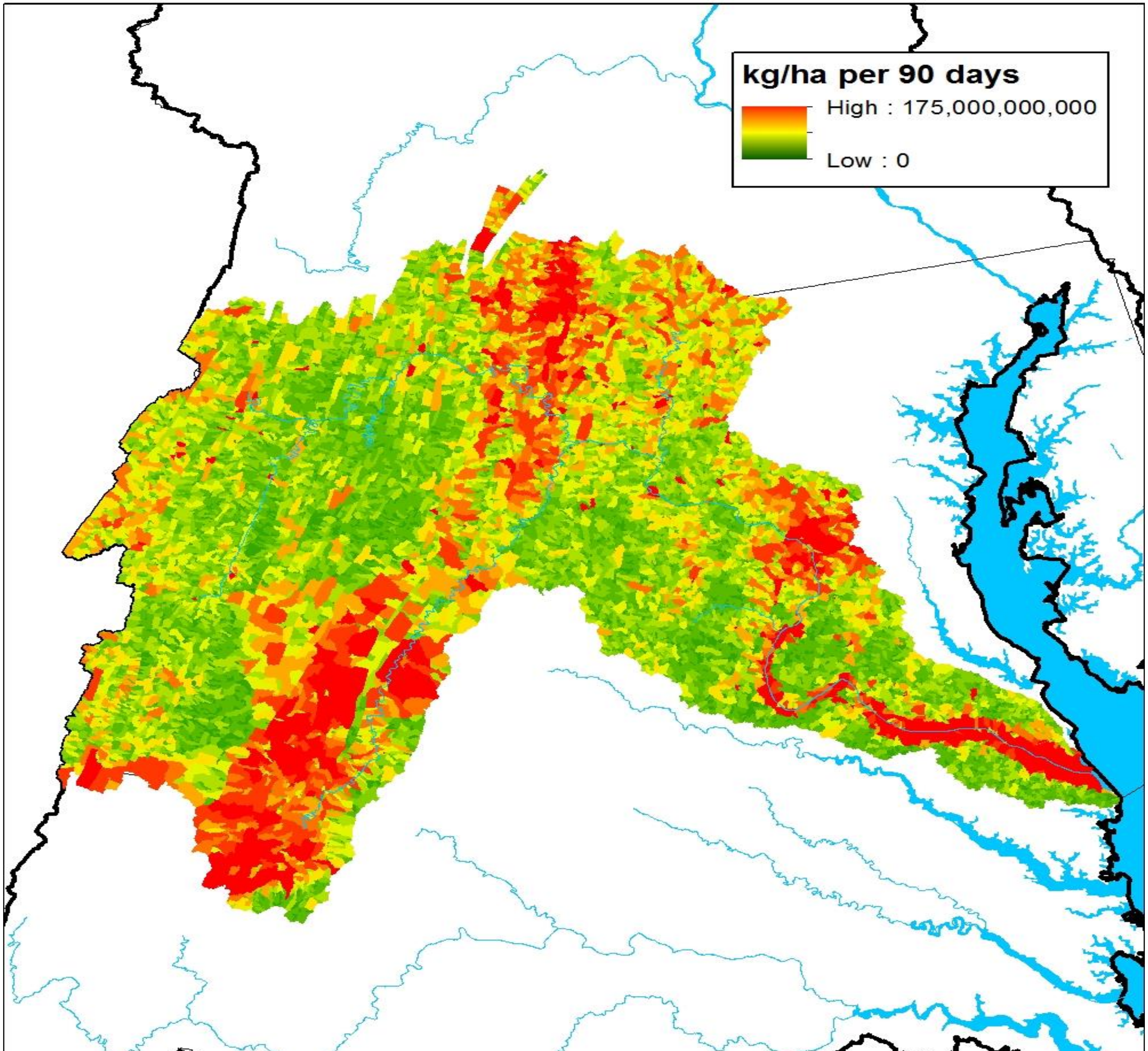
Predicted Incremental TN Load - Spring 2003



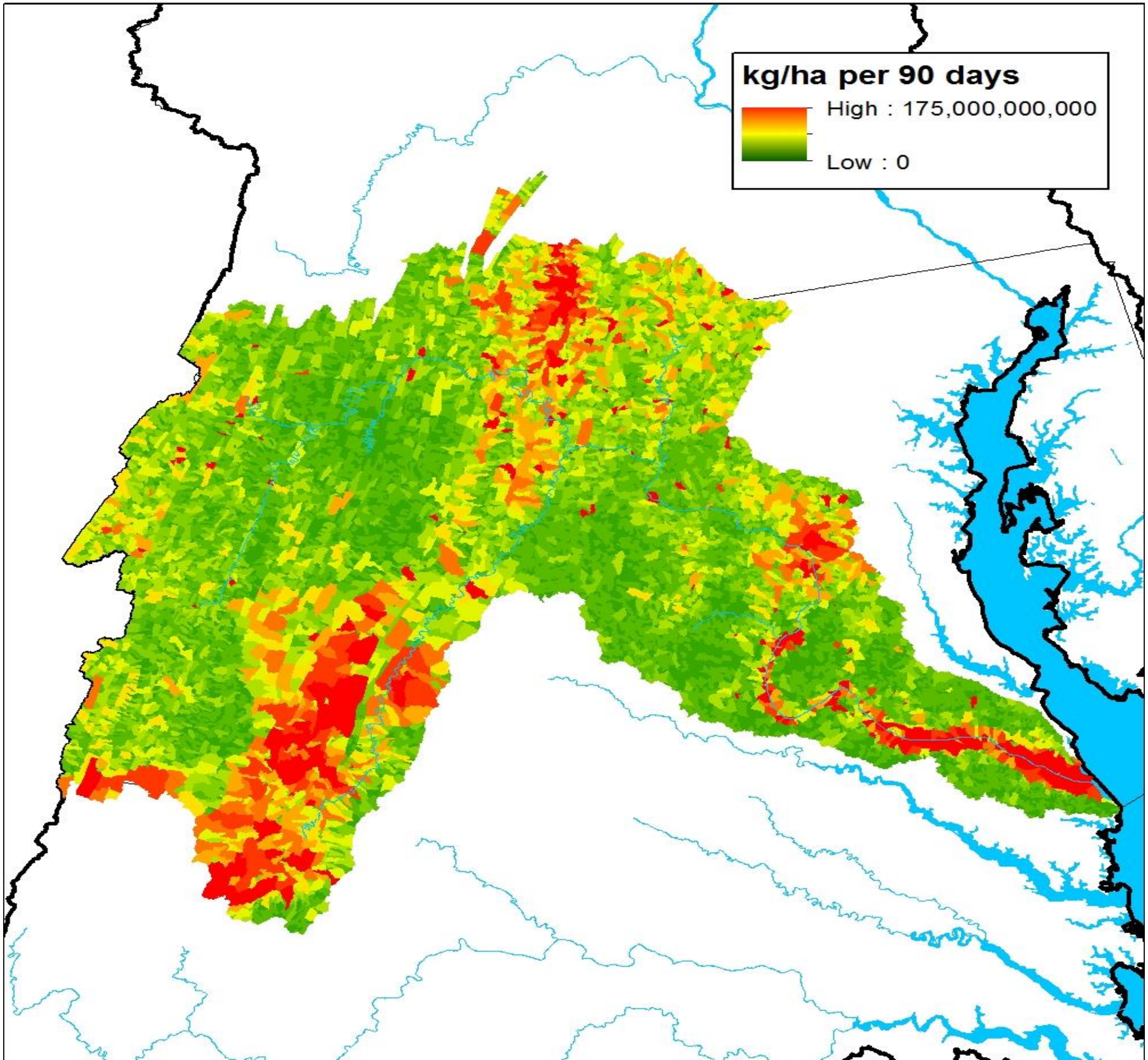
Predicted Incremental TN Load - Spring 2004



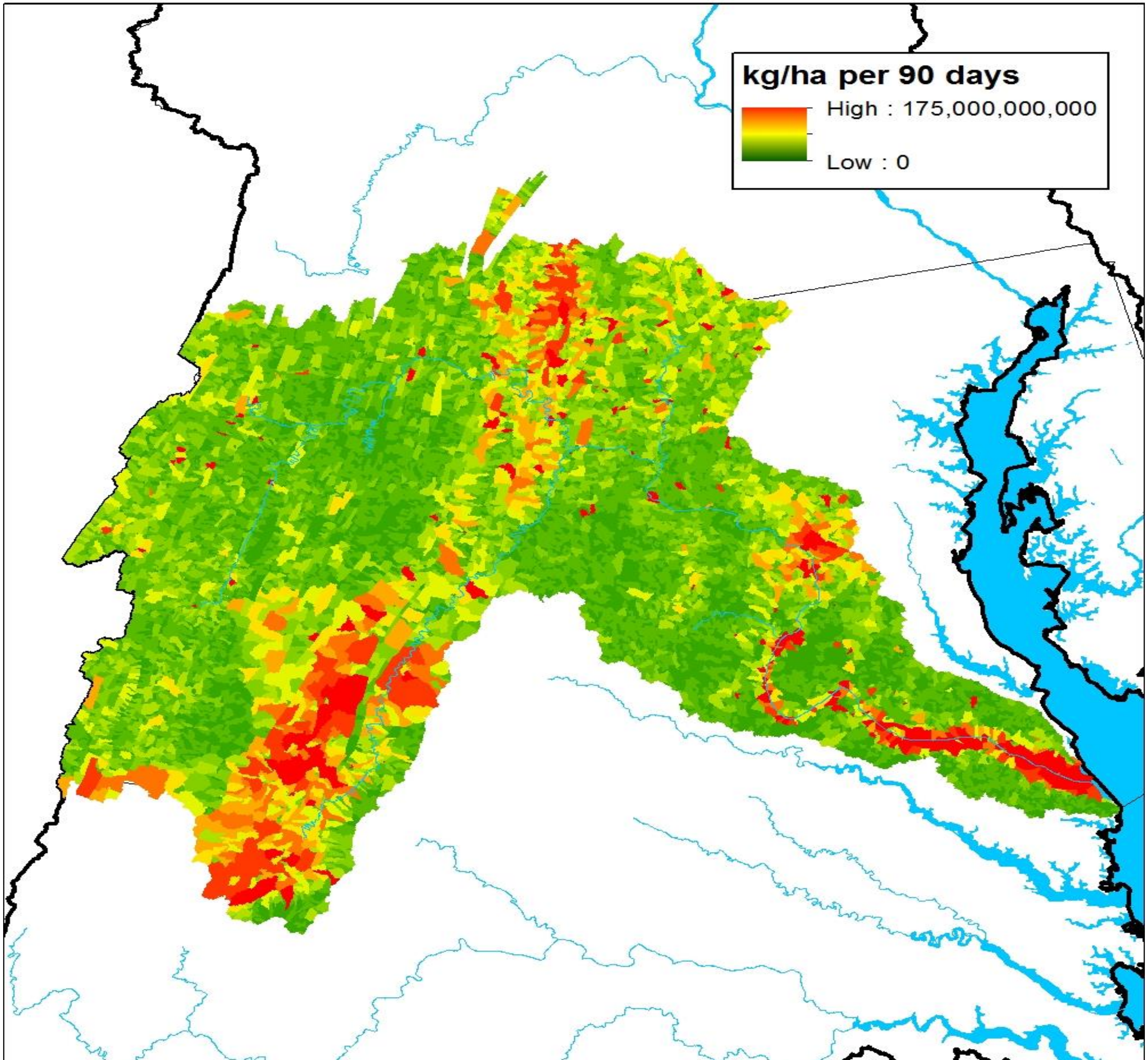
Predicted Incremental TN Load - Spring 2005



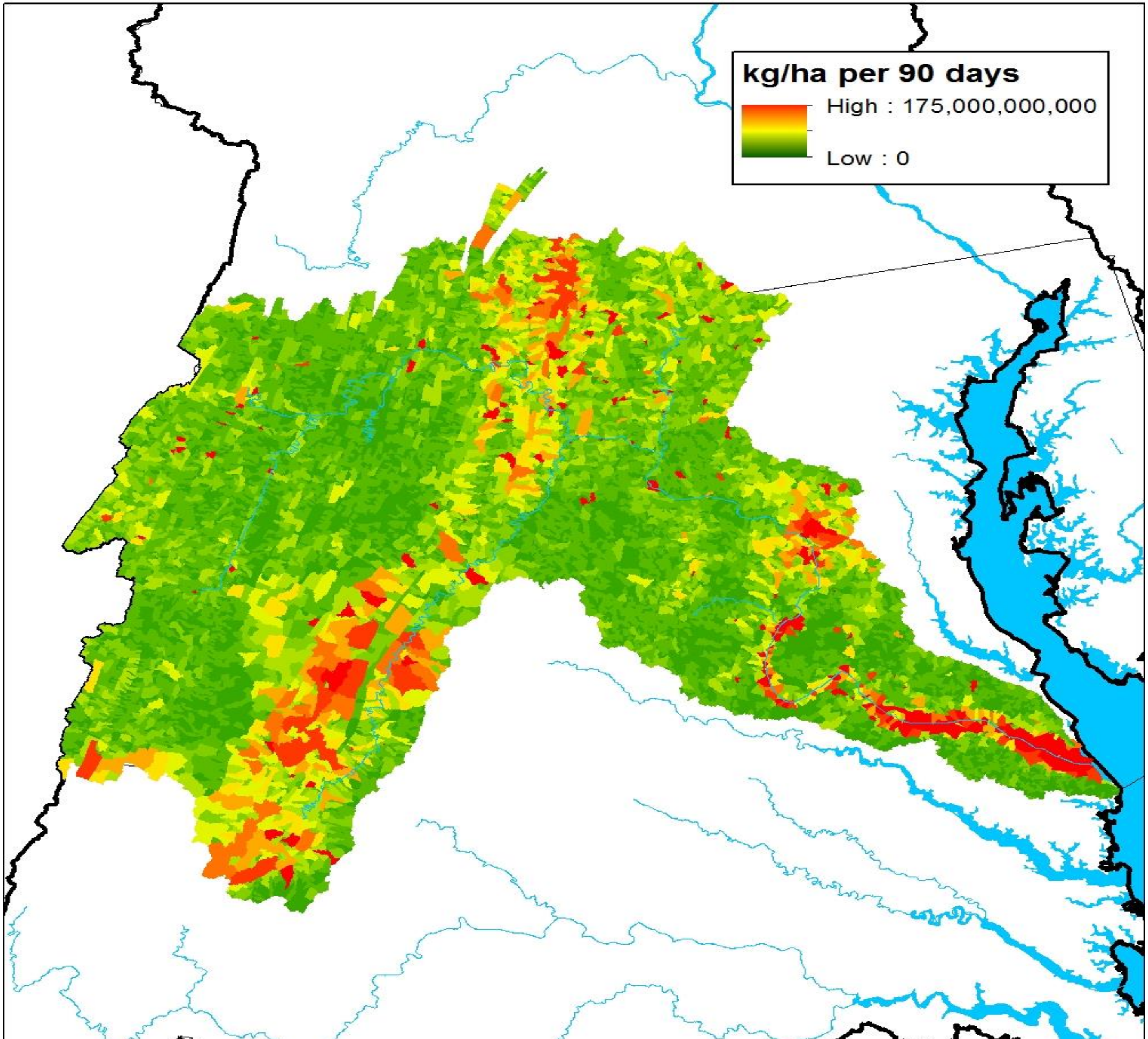
Predicted Incremental TN Load - Spring 2006



Predicted Incremental TN Load - Spring 2007



Predicted Incremental TN Load - Spring 2008



Remaining Questions?

1. Are there ways to verify the model predictions of response times?

 There may be some special opportunities for this.

2. Response times in some parts of the Chesapeake Bay watershed (esp. Coastal Plain) may be very long (e.g. decades) due to long groundwater residence times. Would a dynamic SPARROW model calibration capture such behavior.

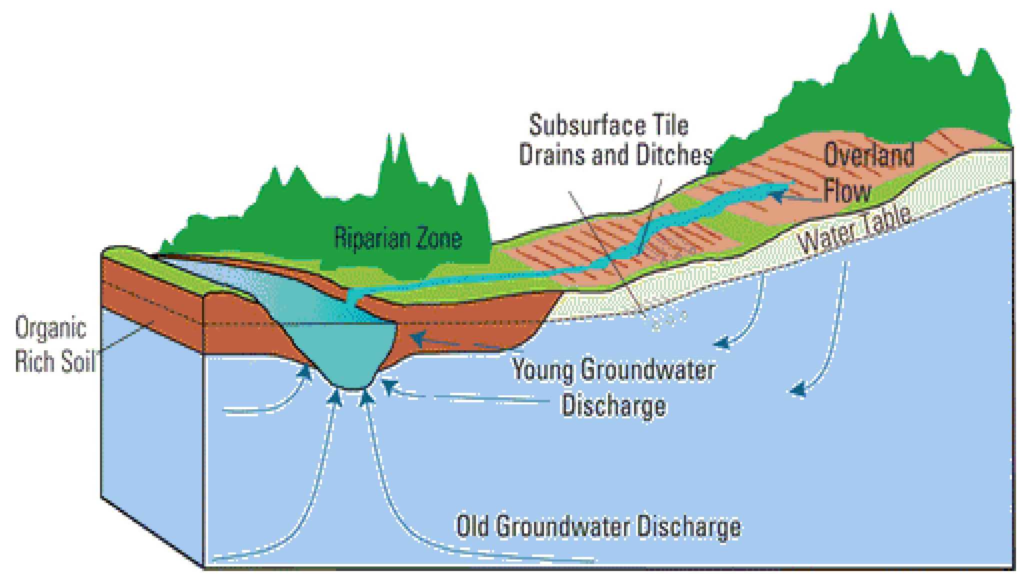
Not as currently constructed. Perhaps with additional, longer lag terms.

3. Could a dynamic SPARROW model be constructed to specifically address long groundwater residence times (and the long-term history of nitrogen sources)?

Yes, hopefully, as suggested below………

USGS Focus on Integrated Modeling of Storage Processes and "Lags" in Effects of Nutrient and Sediment Controls in the Chesapeake Bay Watershed

- **Many participants:**
  - **MD Water Science Center**
  - **National Water Quality Assessment Program**
  - **National Research Program**



- **Combined statistical and deterministic modeling of nutrients and sediment.**

- **Initial emphasis on developing time series of groundwater N inputs to SPARROW models based on historical source data.**

- **Will explore multiple methods for estimating groundwater age distributions, discharge rates, and nitrate concentrations to combine with historical source data.**

Approximate Groundwater and Stream Water Age Distributions for Potomac Basin Based on Preliminary Modflow Modeling (Ward Sanford, personal communication)

Time Interval	% of Groundwater	% of Stream Water (runoff + groundwater)
Past Year (2014)	33	66
2010 - 2013	20	
2000 - 2009	16	
1990 – 1999	7	
1980 - 1989	4.5	
1970 - 1979	3.0	
1960 - 1969	2.3	
Older than 5 yr	48	32
" " 10 yr	37	25
" " 25 yr	24	16
" " 50 yr	15	10
" " 100 yr	8	6

Historical Data Development

- **Atmospheric Deposition estimates 1940-1980:**
  - Husar, R. 1994. Sulphur and nitrogen emission trends for the United States: an application of the materials flow approach. In: Industrial Metabolism: Restructuring for Sustainable Development, United Nations University Press, Tokyo, pp. 1–390.
- **Atmospheric Depostion estimates 1985-2010:**
  - National Atmospheric Deposition Program, 2012, Annual NTN Maps by Analyte, available online at http://nadp.sws.uiuc.edu/ntn/annualmapsbyanalyte.aspx
- **Housing density estimates for 1940-2030:**
  - Hammer, R. B. S. I. Stewart, R. Winkler, V. C. Radeloff, and P. R. Voss. 2004. Characterizing spatial and temporal residential density patterns across the U.S. Midwest, 1940-1990. Landscape and Urban Planning 69: 183 199
- **Fertilizer estimates for 1945-1985:**
  - Alexander, Richard B. and Smith, Richard A., 1990, County-Level Estimates of Nitrogen and Phosphorus Fertilizer Use in the United States, 1945 to 1985. Open-File Report 90-130, U.S. Geological Survey, Reston, available online at http://pubs.usgs.gov/of/1990/ofr90130/report.html
- **Fertilizer estimates for 1982-2001:**
  - Ruddy, Barbara C., Lorenz, David L., and Mueller, David K., 2006, County-Level Estimates of Nutrient Inputs to the Land Surface of the Conterminous United States, 1982-2001. Scientific Investigations Report 2006-5012, U.S. Geological Survey, Reston. available online at http://pubs.usgs.gov/sir/2006/5012
- **Animal numbers for 1950-2002:**
  - Haines, Michael R., and Inter-university Consortium for Political and Social Research. Historical, Demographic, Economic, and Social Data: The United States, 1790-2002. ICPSR02896-v3. Ann Arbor, MI: Inter-university Consortium for Political and Social Research [distributor], 2010-05-21. doi:10.3886/ICPSR02896.v3, available online at http://dx.doi.org/10.3886/ICPSR02896.v3
- **Manure estimates 1950-2002:**
  - United States Department of Agriculture Natural Resources Conservation Service, 1995, Animal Manure Management, available online at http://www.nrcs.usda.gov/wps/portal/nrcs/detail/national/technical/nra/rca/?&cid=nrcs143_014211
- **Recharge, Bedrock Geology, and Surficial Geology**
  - Wieczorek, M.E., and LaMotte, A.E., 2010, Attributes for NHDPlus catchments (version 1.1) for the conterminous United States: U.S. Geological Survey Digital Data Series DS–490–15, available online at http://water.usgs.gov/nawqa/modeling/nhdplusattributes.html.

- Data is averaged in years where gaps exist (for example, between Agricultural Census years and atmospheric deposition data from 1981-1984).
- Atmospheric deposition data from 1940-1980 is only available as a regional multiplier that was applied to 1985 NADP grid data.
- Manure estimated from Agricultural Census animal counts and manure averages per animal from USDA NRCS. High and low ranges estimated.
- Data organized by NHDPlus V1 COMID. Since agriculture census data is only available by county, these data were processed with a simple spatially weighted average.

Specifying a Groundwater Source in SPARROW: Multiple Approaches

1. **Groundwater characteristics (NO3 conc., recharge, BF load, rock type, etc) included in either "source" or "LTW" terms in <u>steady state</u> models.**

2. **Time series of estimated groundwater inputs included as "sources" in <u>dynamic</u> models.**

   - based on historical source data, groundwater age distributions, BF load data.

   - based on historical source data, groundwater age distributions, stream recharge rate, and *groundwater concentration data*.

Summary

- The results of initial calibrations of dynamic SPARROW TN models based on seasonal time series of water quality and basin attribute data were highly encouraging.
- MODIS EVI and Snow/Ice Cover were especially strong predictor, appearing to account for seasonal retention of nitrogen in basin vegetation and snowpack.
- Model predictions for the 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.
- Predicted response times are “reasonable” but difficult to verify.
- Efforts to include specific terms for groundwater residence times (and the long-term history of nitrogen sources) in SPARROW models are underway.

END

Remaining Tasks

1. Refine calibrations (e.g. try a few additional predictors and specifications)

2. Test serial correlation of residuals and develop variance correction method

3. Write up and publish overall method and results

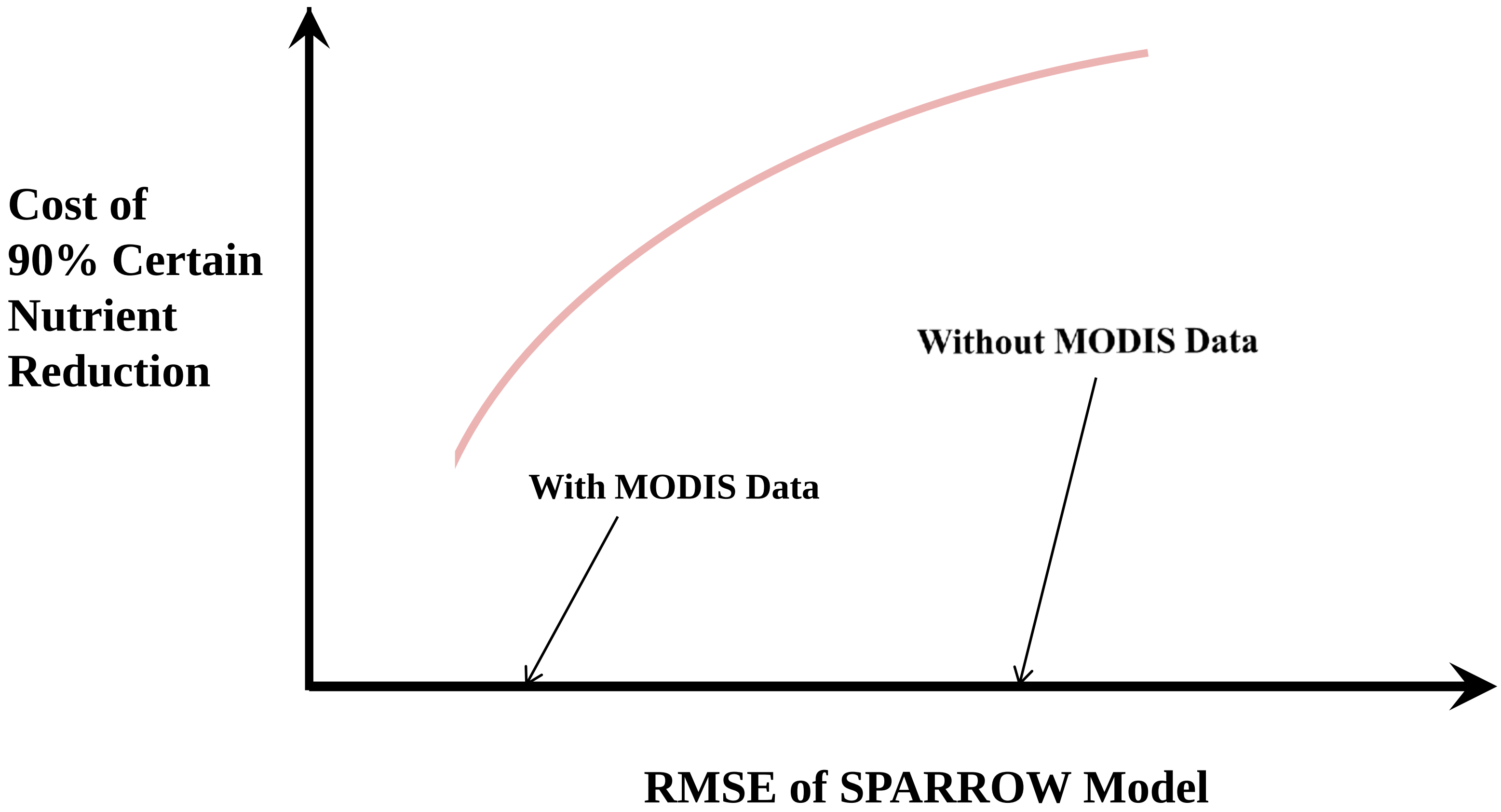
Additional Projects

1. Apply method to additional basins.
    a. Upper Klamath lake (project initiated)
    b. *Entire Chesapeake Bay watershed

2. *Examine/test reasonableness of model predictions and interpretations with independent data.

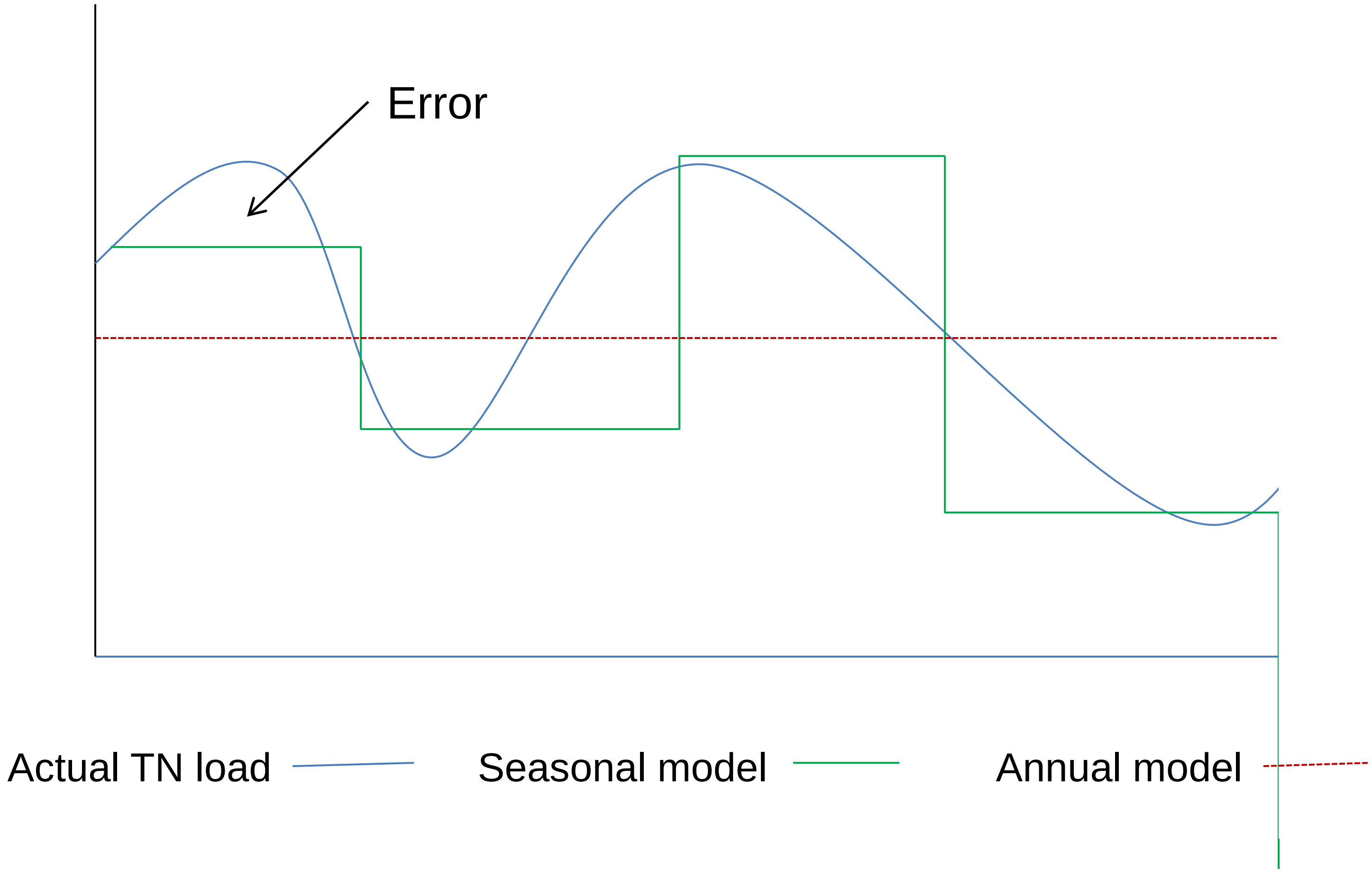
* Possible collaboration with IWS

Economic Value of MODIS Enhancements: Cost of Nutrient Control vs Model Error

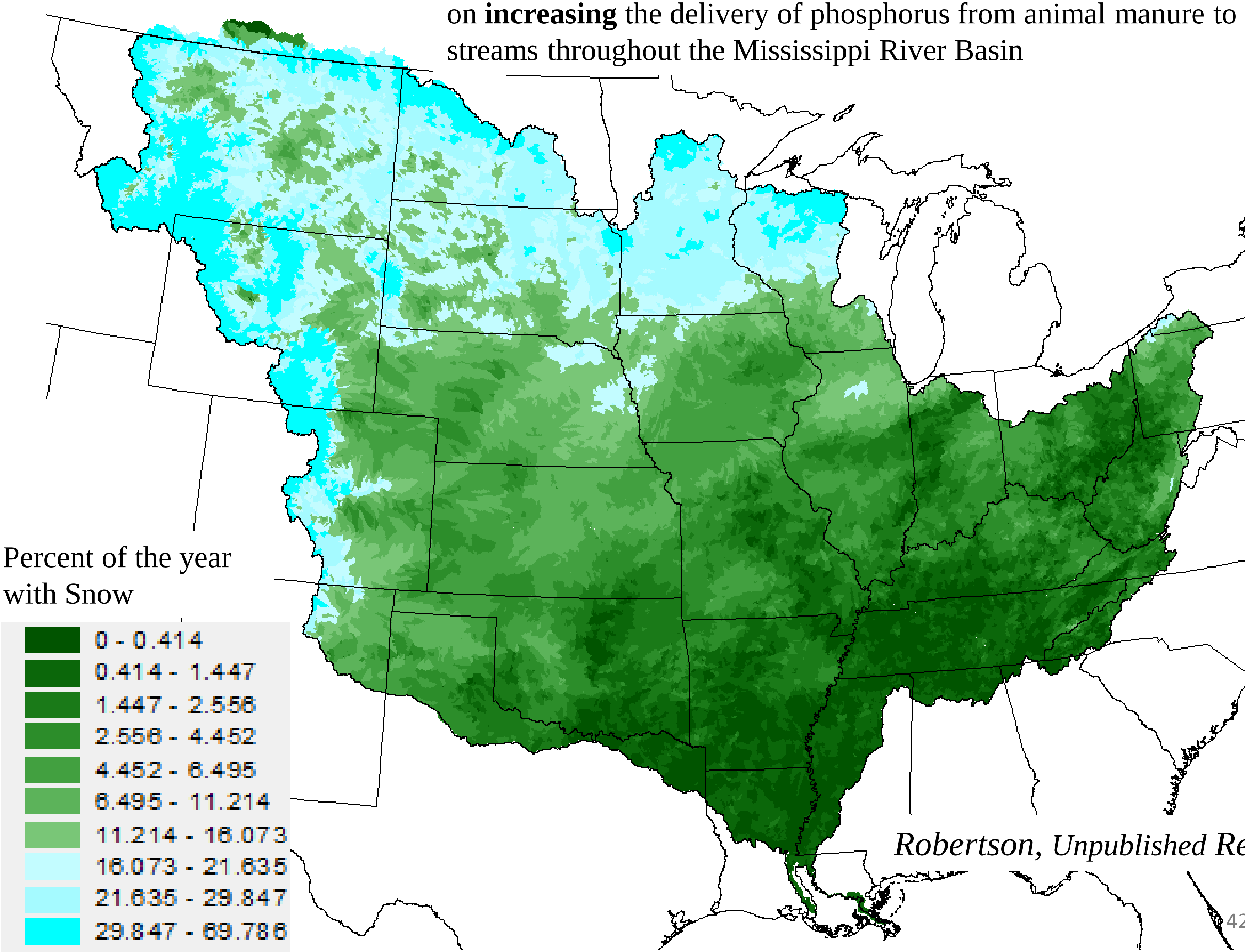


Value of Seasonal (Dynamic) Information

Premise: Cost of management actions could be lowered if spring TN loads were more accurately known.



Percent of the year with frozen ground (snow) has a significant effect on **increasing** the delivery of phosphorus from animal manure to streams throughout the Mississippi River Basin



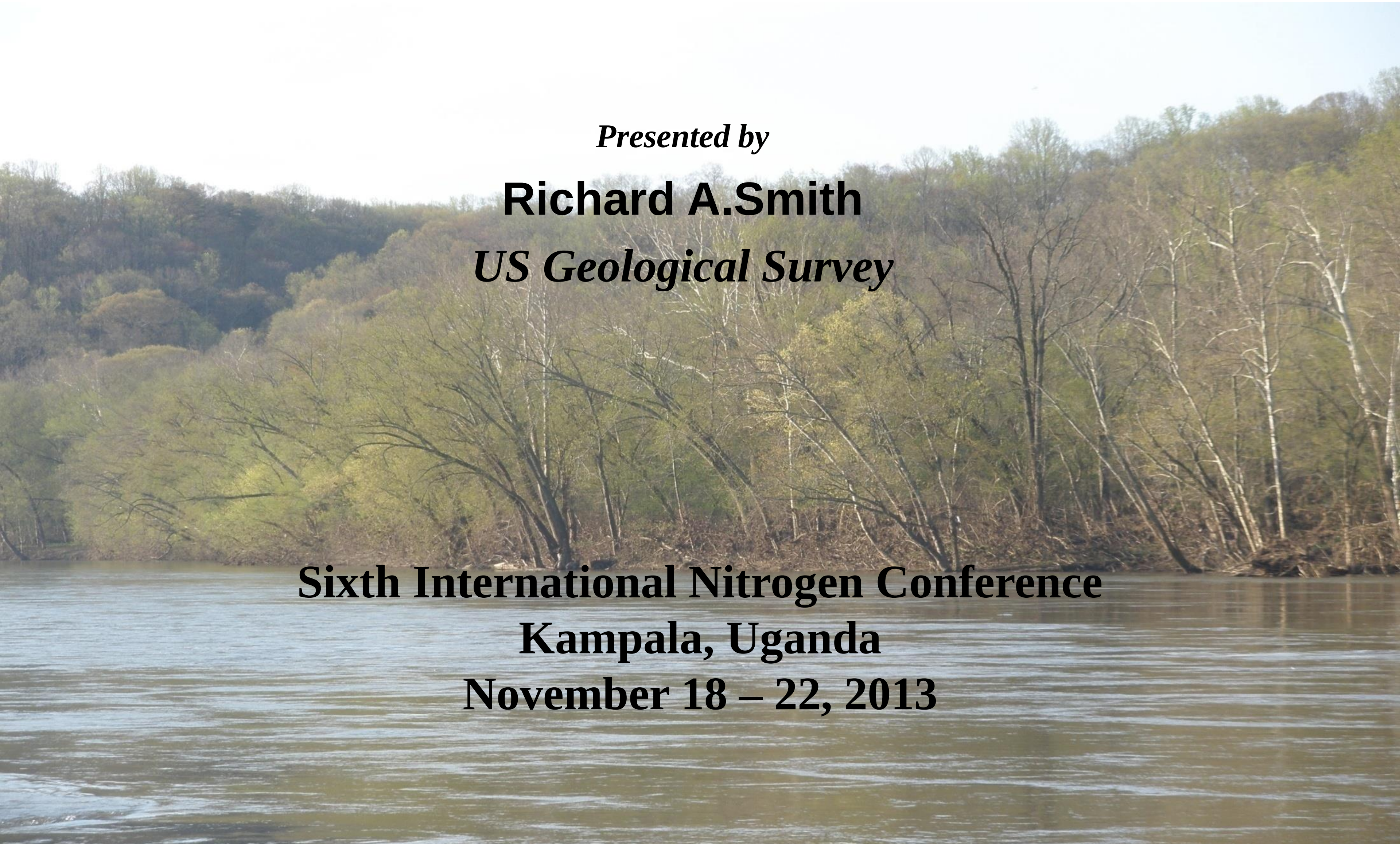
Robertson, Unpublished Results

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

- Chesapeake system: Need for spatially-detailed, seasonal TN loads, and information on response times (i.e. lags) of controls
- 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, lag-1 runoff, MODIS vegetation index
- Seasonal time series of all data for fall 2001 through fall 2008

* New mechanism required for dynamic modeling

Improving Water Quality Management: Use of Earth Observations in SPARROW



Presented by

Richard A.Smith

US Geological Survey

Sixth International Nitrogen Conference
Kampala, Uganda
November 18 – 22, 2013

Improving Water Quality Management: Use of Earth Observations in SPARROW

Research Team

John Brakebill [2], Anne Hoos [2], Molly Macauley [1], Richard Moore [2], Anne Nolin [3], Dale Robertson [2], Gregory Schwarz [2], Jhih-Shyang Shih [1], and Richard Smith [2]

1 Resources for the Future

2 USGS science for a changing world

3 OSU Oregon State University

Thank you: NASA

SPARROW Water Quality Model:

(**SPA**tially **R**eferenced **R**egression **o**n **W**atershed **A**ttributes)

- ***Mechanistic Features***
  - contaminant sources and landscape attributes linked to stream/river network
  - nonlinear contaminant processes
  - non-conservative transport
  - Steady-state mass balance form
  - dynamic version (with MODIS input) under development

- ***Statistical Features***
  - "data-driven" (from large, long-term, monitoring network (1000+ sites)
  - statistical calibration (nonlinear regression)
  - coefficients estimated from the data, not litterature
  - promotes hypothesis testing of mechanistic interpretation
  - provides error quantification

Water quality parameters modeled with SPARROW to date

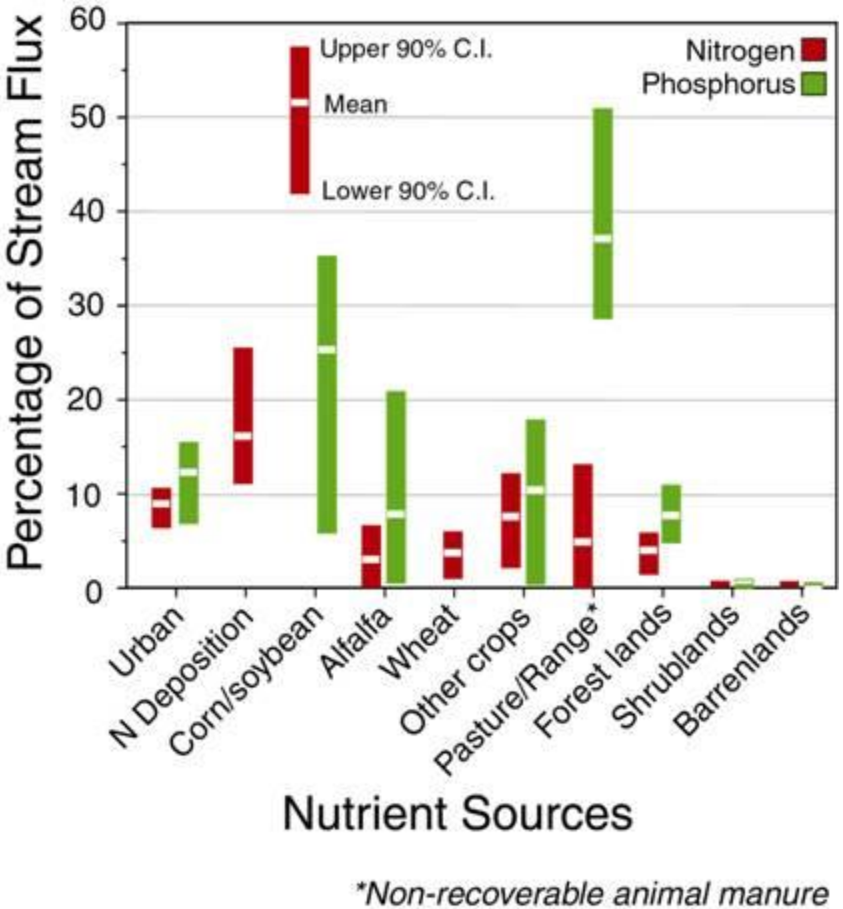
1. Reactive Nitrogen*
2. Total Phosphorus
3. Total Organic Carbon
4. Total Dissolved Solids
5. Suspended Sediment
6. Ammonium
7. Fecal Coliform Bacteria
8. Cryptosporidium
9. Atrazine

* This study

RFF

Example Application: Quantifying the Sources of Nutrients Delivered to the Gulf of Mexico

Mississippi/Atchafalaya River Basin



Alexander et al., 2008, Environ. Sci. Technol., v 42

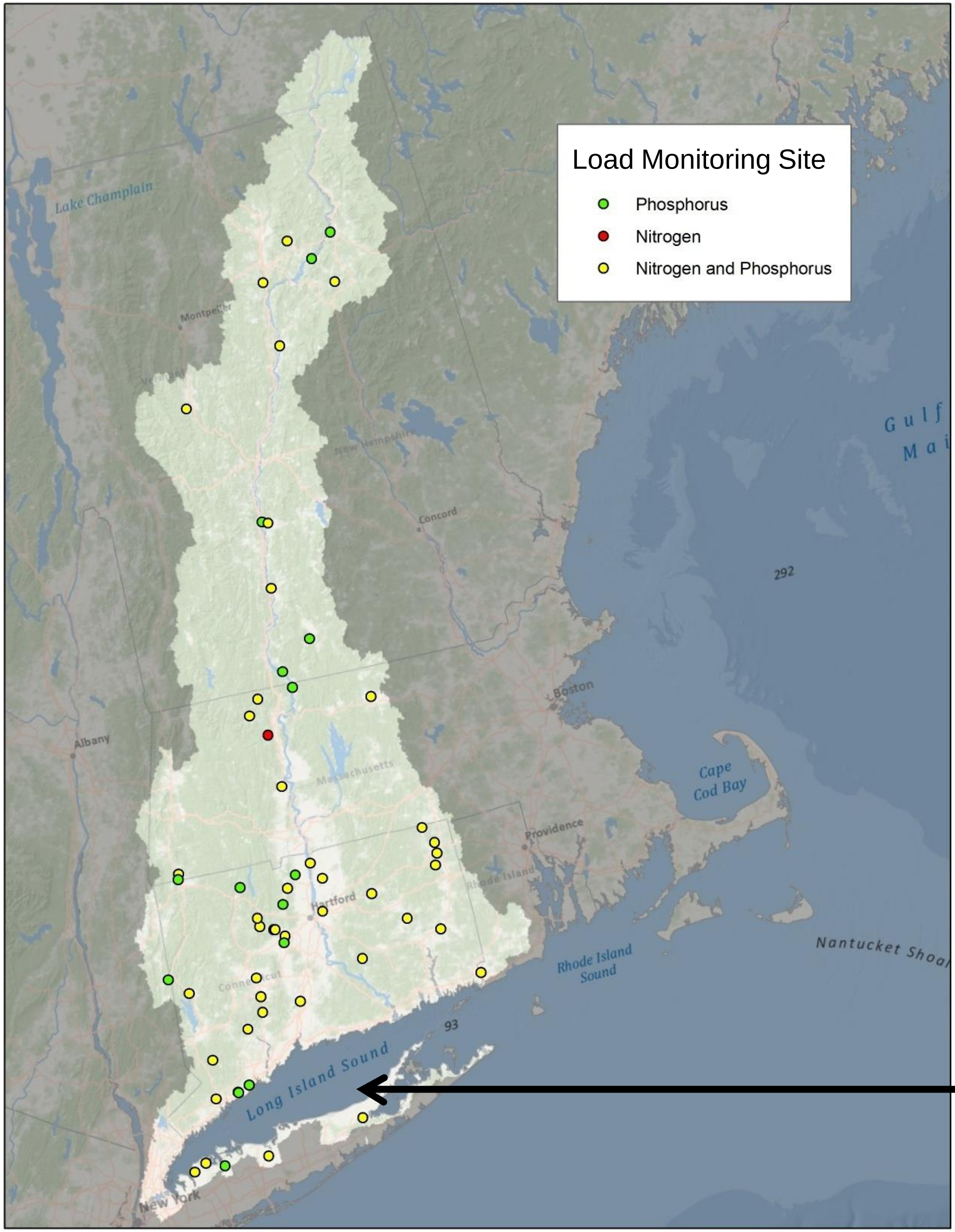
Calibration Results

No. of observations	2268
R^2	0.90
Yield R^2	0.68
RMSE	0.69

N Source	Units	Coeff.	Significance (p)
Point sources	kg/yr	0.66	$< 10^{-4}$
Urban	sq km	427	$< 10^{-4}$
Atmos.	kg/yr	0.11	$< 10^{-4}$
Fertilizer	kg/yr	0.034	$< 10^{-4}$
Animal waste	kg/yr	0.060	$< 10^{-4}$
“Storage	kg/yr	0.85	$< 10^{-4}$
ln EVI	-	-0.90	$< 10^{-4}$

Partners and User Community

- USGS (4 science Centers + Reston)
- USEPA
  - Chesapeake Bay Program
  - Narragansett Laboratory
  - Gulf of Mexico Program
- State of South Carolina
- NEIWPCC
- Four NE State DEPs

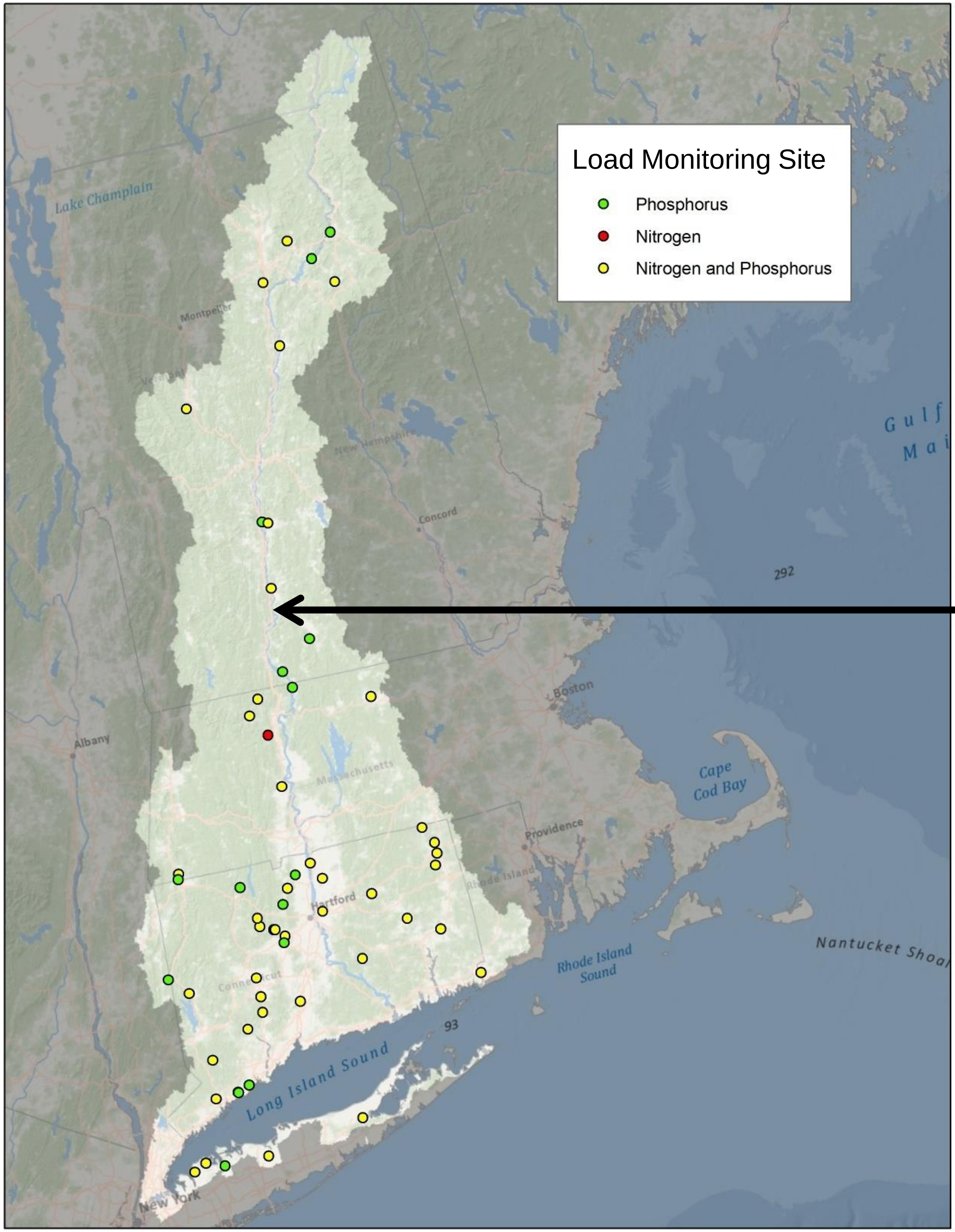


Application to Long Island Sound (LIS)

Low concentrations of dissolved oxygen (hypoxia), as a result of nitrogen enrichment, often occur during the summer in the western part of LIS.

Partners / User Community

- New England Interstate Water Pollution Control Commission (NEIWPCC)
- Four New England States especially Connecticut Dept. Env. Protection
- New York Dept. Env. Conservation
- U.S. Environmental Protection Agency (USEPA)



Long Island Sound (LIS)

Nitrogen transport from the watershed to LIS varies seasonally. Much of the nitrogen transport occurs during the spring freshet.

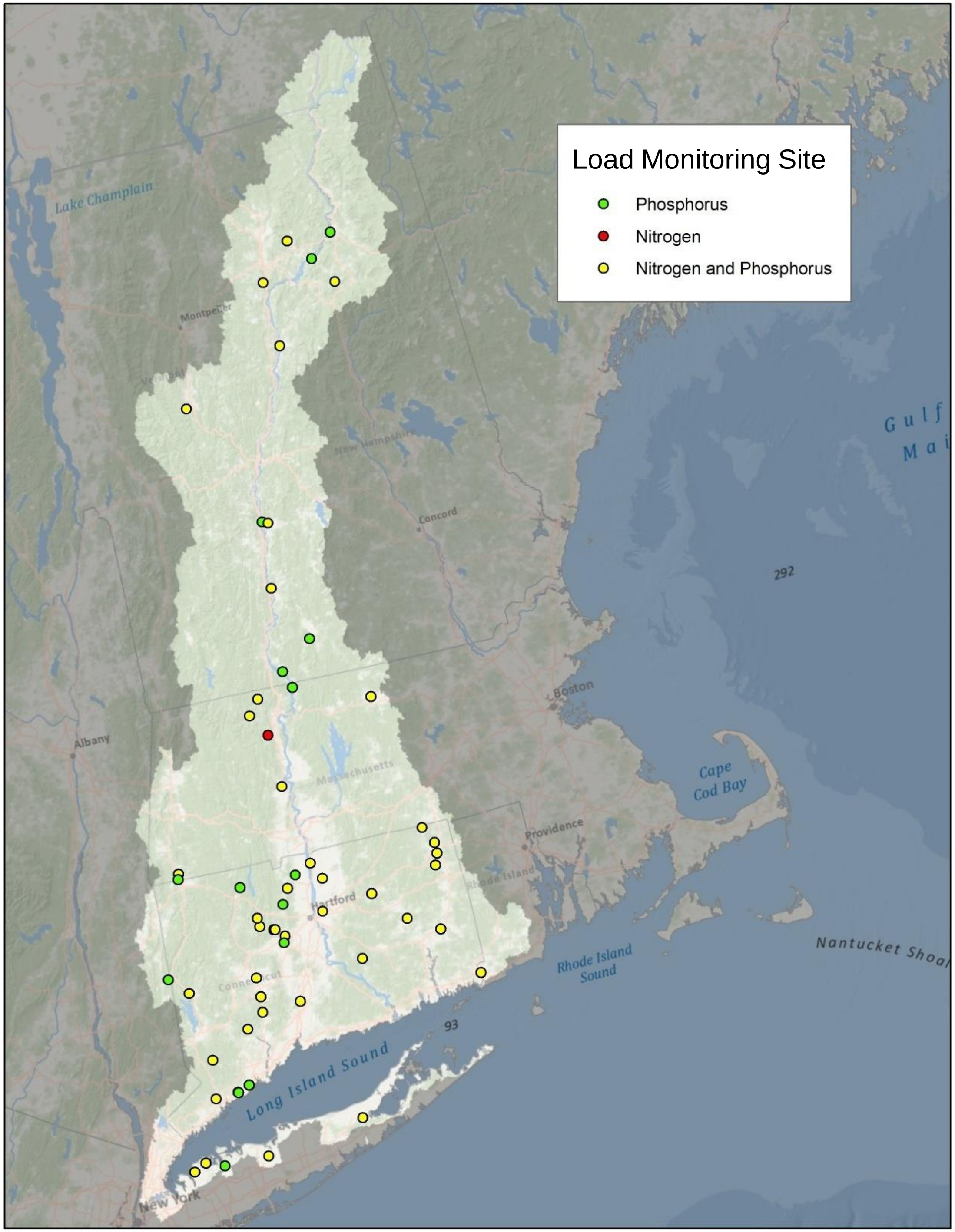
Modeling Approach

Dynamic – Seasonal SPARROW Winter 2001 - Summer 2009

Seasonal loads at monitoring sites are the dependent variable

Standard suite of SPARROW predictors plus NASA predictors compiled seasonally:

- The Enhanced Vegetation Index (EVI)
- Percent snow cover



Long Island Sound (LIS)

Anticipated outcome

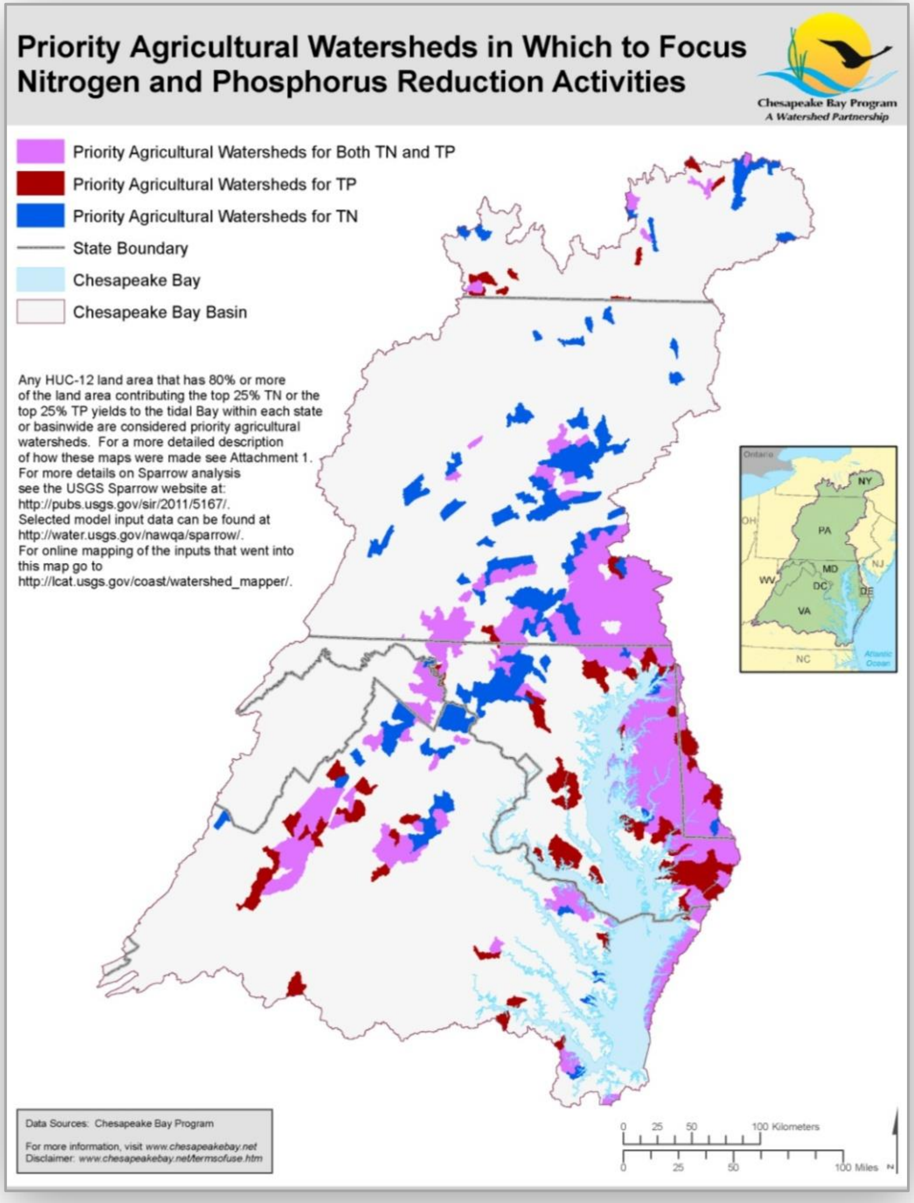
Improved understanding of the source and transport of nitrogen to LIS and how it varies seasonally.

Intended to aid in targeting nutrient controls.

Modeling "in progress".

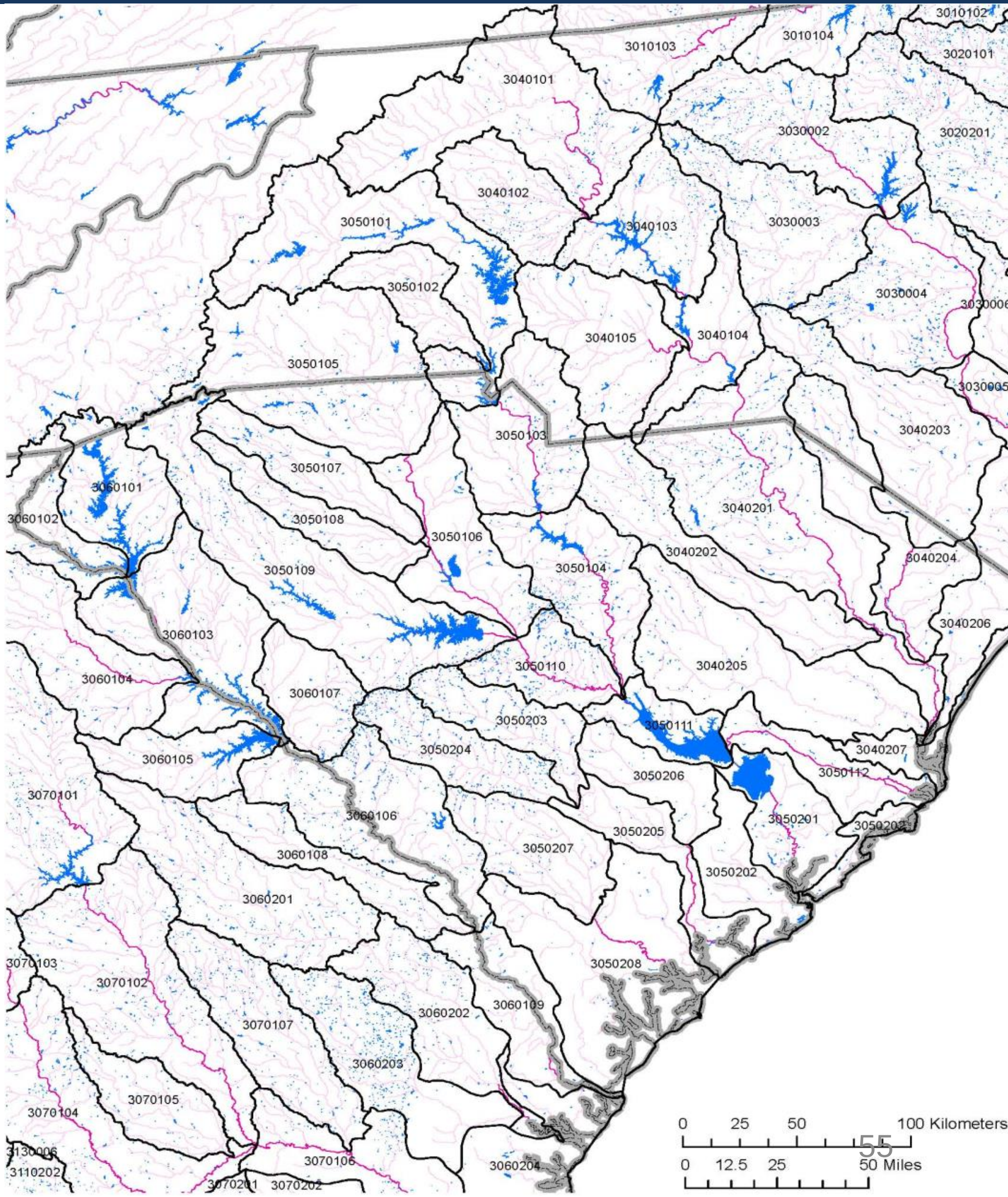
SPARROW Model Applications

Targeting of Management Actions in Chesapeake Bay Watershed



Assisting South Carolina HEC with Development of Nutrient Criteria for South Carolina Estuaries

- Algae and Cyanobacteria blooms are significant problem.
- Existing SPARROW models are used to predict mean annual N and P conditions
- State HEC officials would prefer seasonally- specific (spring/summer) predictions
- Preliminary Seasonal SPARROW TN model with MODIS EVI input has been (highly) successfully calibrated.
- Especially close communication with (and high anticipation from!) state and local officials.



Study Basins and Model Details

Drainage Basin	Area (km^2)	Stream Segments	In-Stream Monitoring Stations	No. Time Steps	Nitrogen Sources	Storage Processes (MODIS DATA)	Total Est. Coeff
South Carolina Coastal	134,300	76,742	34	15	Point, Urban, Atmosphere, Fert., Manure	Plant/Soil Uptake	14
Potomac River (Ches. Bay)	30,100	16,500	81	28	Point, Urban, Atmosphere, Fert., Manure	Plant/Soil Uptake	13
Long Island Sound	41,600	22,059	38	35	Point, Urban, Atmosphere, Fert. Rotation, Fert. Other, Manure	Plant/Soil Uptake, Snow/Ice Cover	15

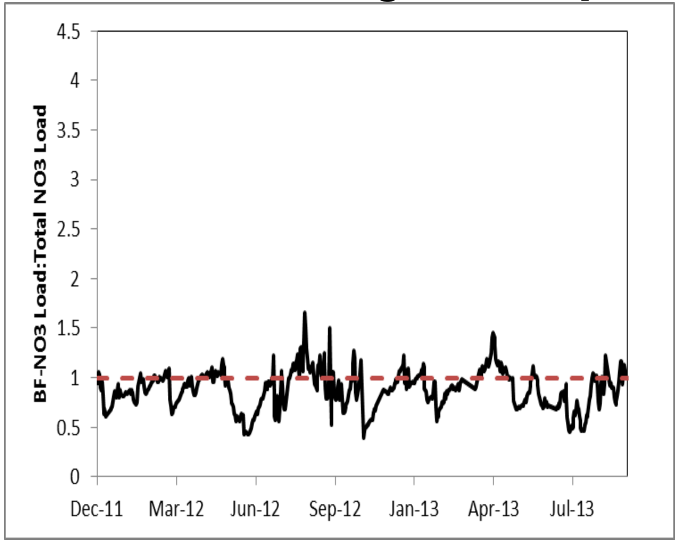
Results

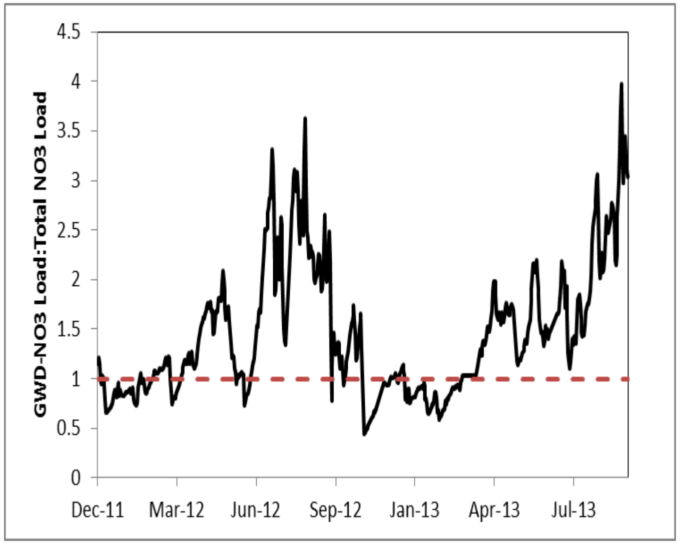
Drainage Basin	Area (km^2)	Storage Processes	Model r^2 (RMSE)	Est. Mean Residence Time (yr)	Δ N Flux / Δ GPP …… Δ Flux/ Δ Spring Snow Cover (% / %)
South Carolina	134,300	Plant/Soil Uptake	0.90 (0.64)	1.1	-4.2
Potomac River	30,100	Plant/Soil Uptake	0.90 (0.69)	1.5	-2.2
Long Island Sound	22,059	Plant/Soil Uptake …… Snow/Ice Cover	0.94 (0.44)	0.27	-4.3 …… 0.5 - 1.0

Approach: estimate time-variable baseflow nitrate (BF-NO_3) and groundwater discharged nitrate (GWD-NO_3) loads at selected stream sites within the Chesapeake Bay watershed that have continuous [NO_3], [SC], and discharge data

Objectives:

1. Demonstrate the difference between BF-NO_3 loads and GWD-NO_3 loads. Specifically, by investigation of the ratio of BF-NO_3 and GWD-NO_3 loads to STR-NO_3 loads, we will be able to assess the relative importance of in-stream processing over time and space.
2. Provide "gold standard" estimates of BF-NO_3 and GWD-NO_3 loads using continuous nitrate data against which similar estimates obtained using discrete [NO3] data will be compared.

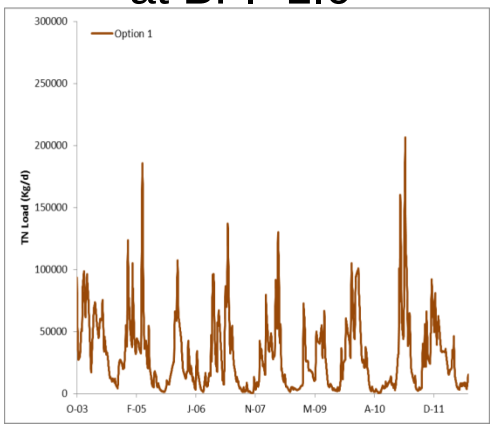


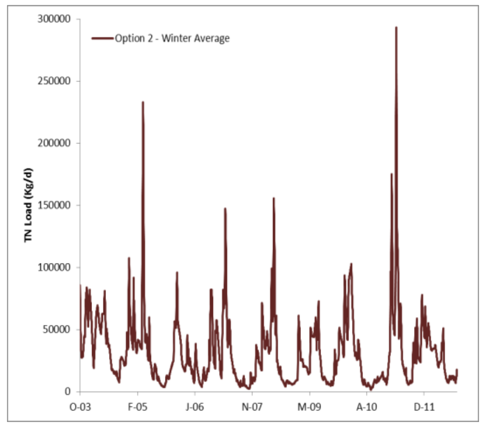


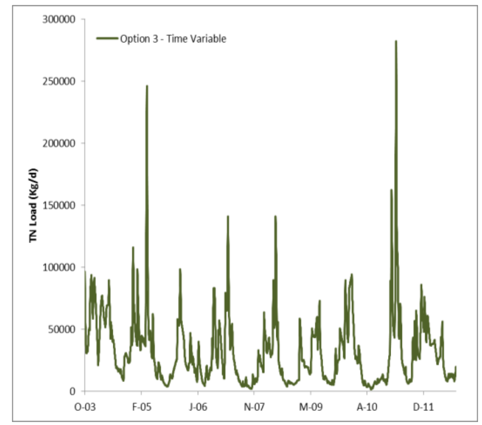
Groundwater TN Loads: Potomac River at Chain Bridge

Options…

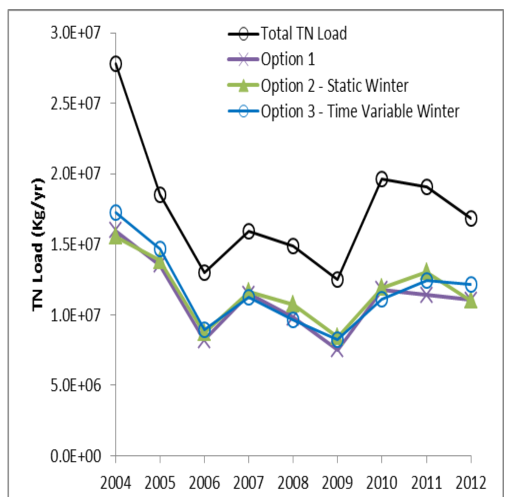
1. Baseflow discharge x LOADEST Predicted [TN]
2. Baseflow discharge x Average Winter [TN] at BFI=1.0
3. Baseflow discharge x Time Variable Winter [TN] at BFI=1.0







From "big picture" perspective there is little difference in loads among groundwater [TN] options



SPARROW and Groundwater

Traditional SPARROW models do n include GW sources of N to the stre

$$\mathrm{Load}_i = \left\{ \sum_{j \in J(i)} \left[\sum_{n=1}^{N} S_{n,j} \underbrace{\beta_n \exp(-\alpha' Z_j)}_{} \right] \underbrace{\exp(-\delta' T_{i,j})}_{} \right\} \underbrace{\exp(\epsilon_i)}_{}$$

ASSUMPTION: GW, as a <u>source of N</u> to the stream, can be added to SPARROW

1) by the addition of "<u>land-to-water variables</u>" for subsurface characteristics, N loads, …that the model could choose

→ No changes in equations

→ Multiple descriptors of the subsurface could be useful

2) by adding a N in GW as a "<u>source term</u>"

Sources of N to the stream: <u>N processed "recently" through landscape</u>