SPARROW Surface Water Quality Workshop
October 29-31, 2002
Reston, Virginia

Section 7. SPARROW Model Applications

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Section 7. SPARROW Model Applications

Topics for Consideration

- Prediction statistics
- Management applications
- Uncertainty analysis
- Web access to SPARROW applications

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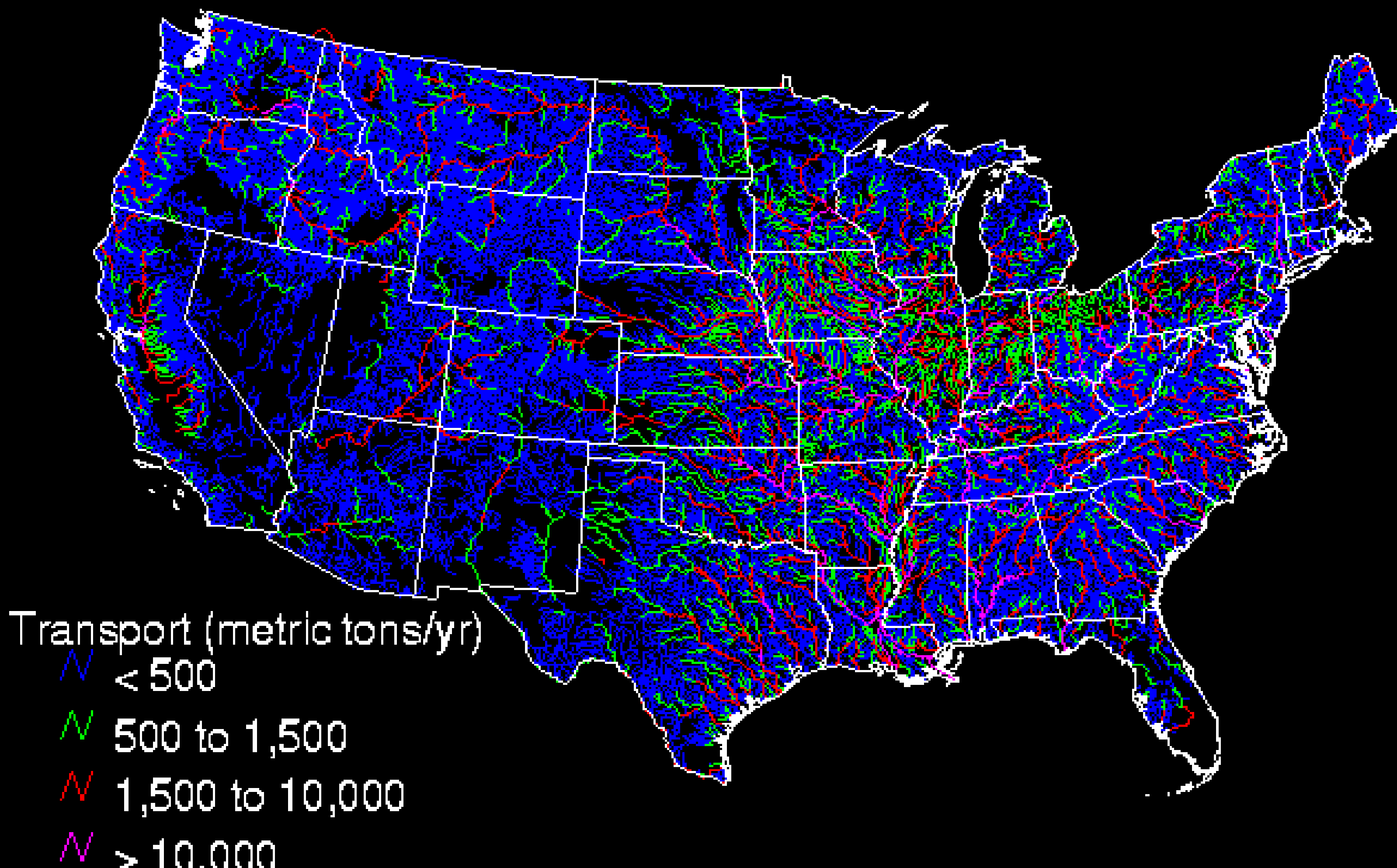
SPARROW Prediction Statistics
(Mean & Percentiles)

- Loads/yields exported from watersheds
- Contaminant losses in streams and reservoirs
- Loads/yields delivered to downstream sites (e.g., estuaries, reservoirs)
- Contaminant sources and budgets
- Concentration
- Probability of exceeding environmentally relevant load/concentration thresholds

SPARROW Predictions of Total Nitrogen Transport in Rivers of the Conterminous United States



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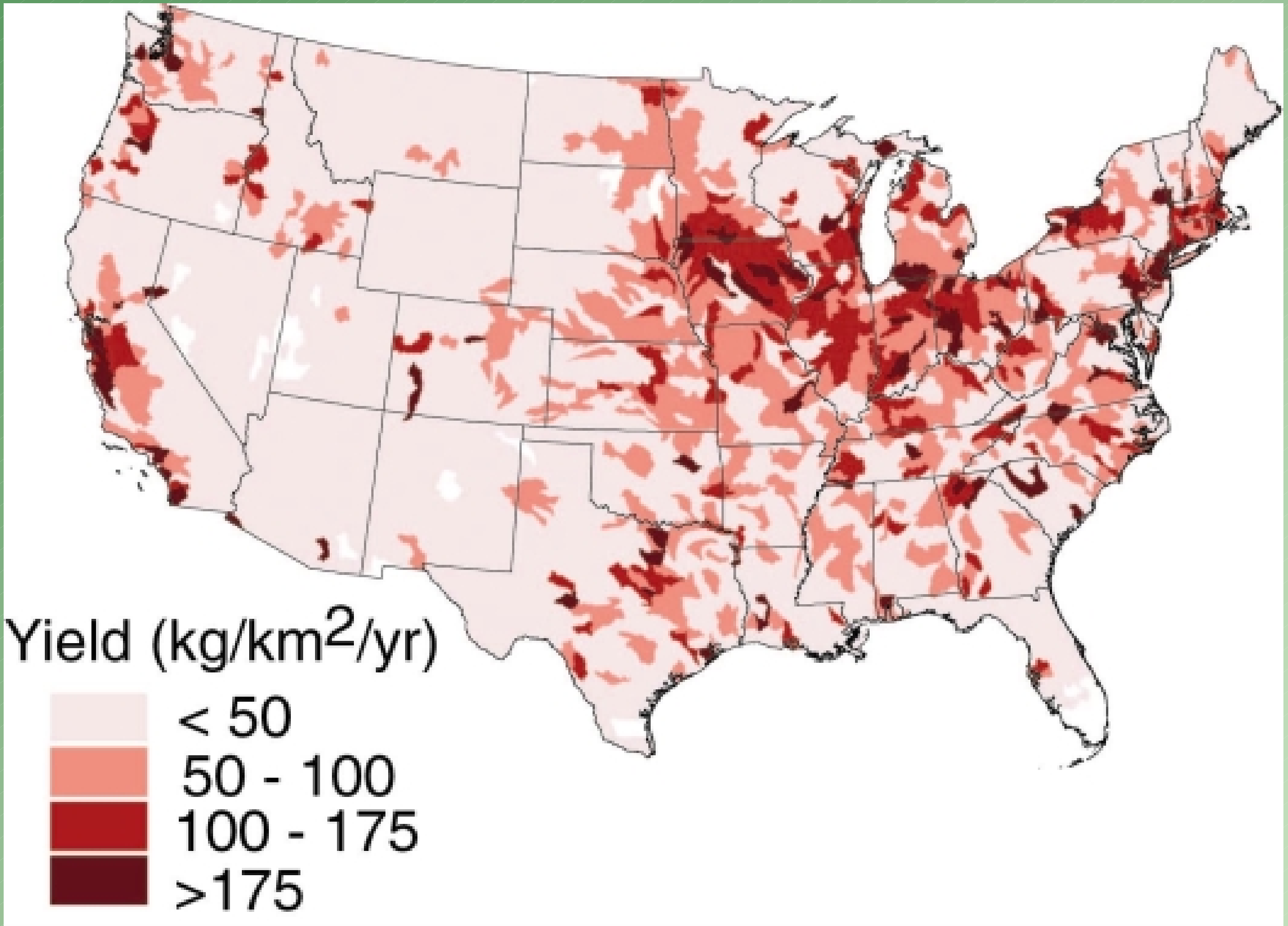
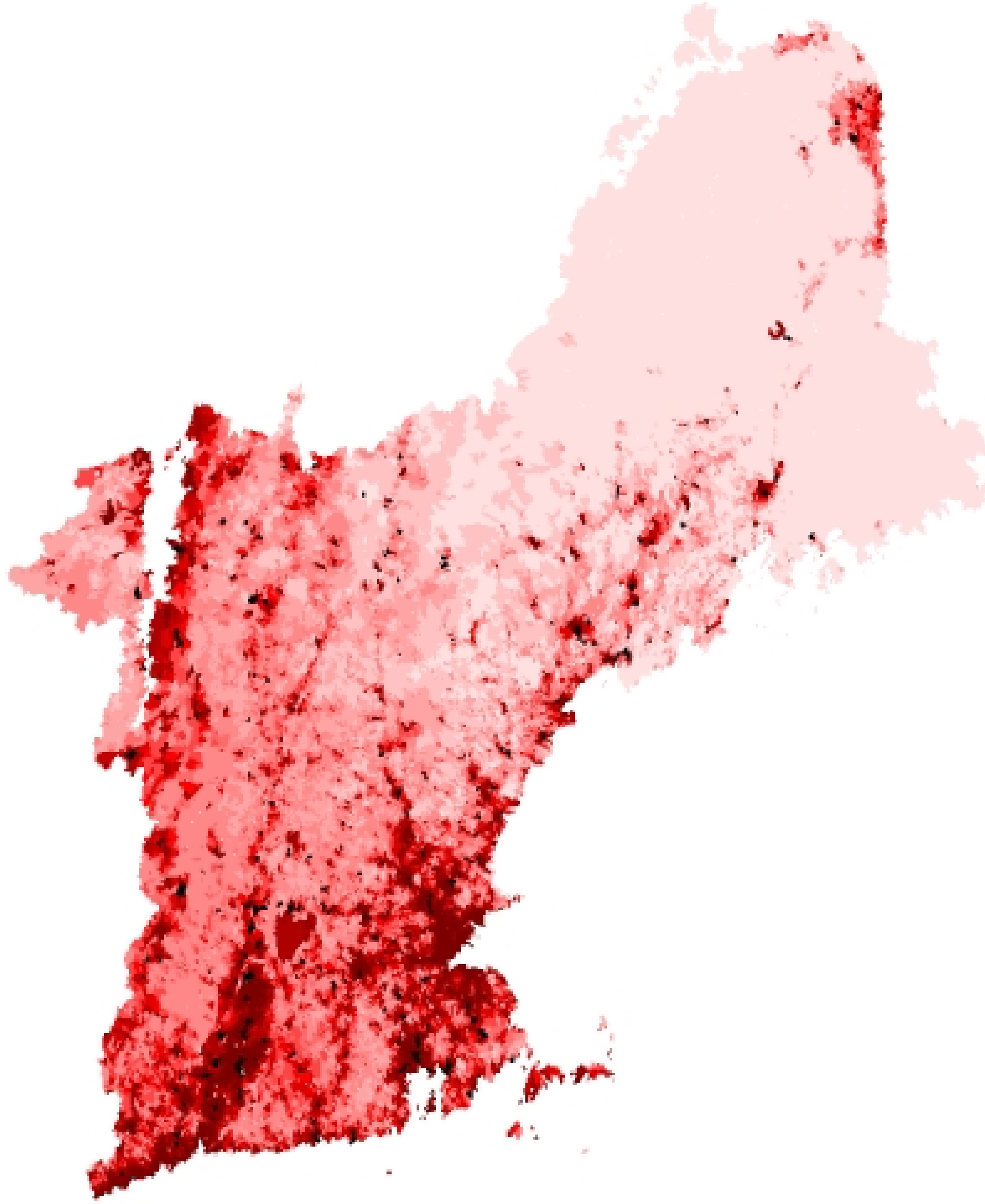
TOTAL PHOSPHORUS
Predictions in Hydrologic Units



SPARROW Predicted Nitrogen Yield

Catchment Yield (kg / sq km)

- 100
- 200
- 250
- 300
- 400
- 500
- 600
- 800
- 1,000
- 1,500
- 2,300
- 2,700 - 4,800
- 4,800 - 10,000
- 10,000 - 32,000
- > 32,000



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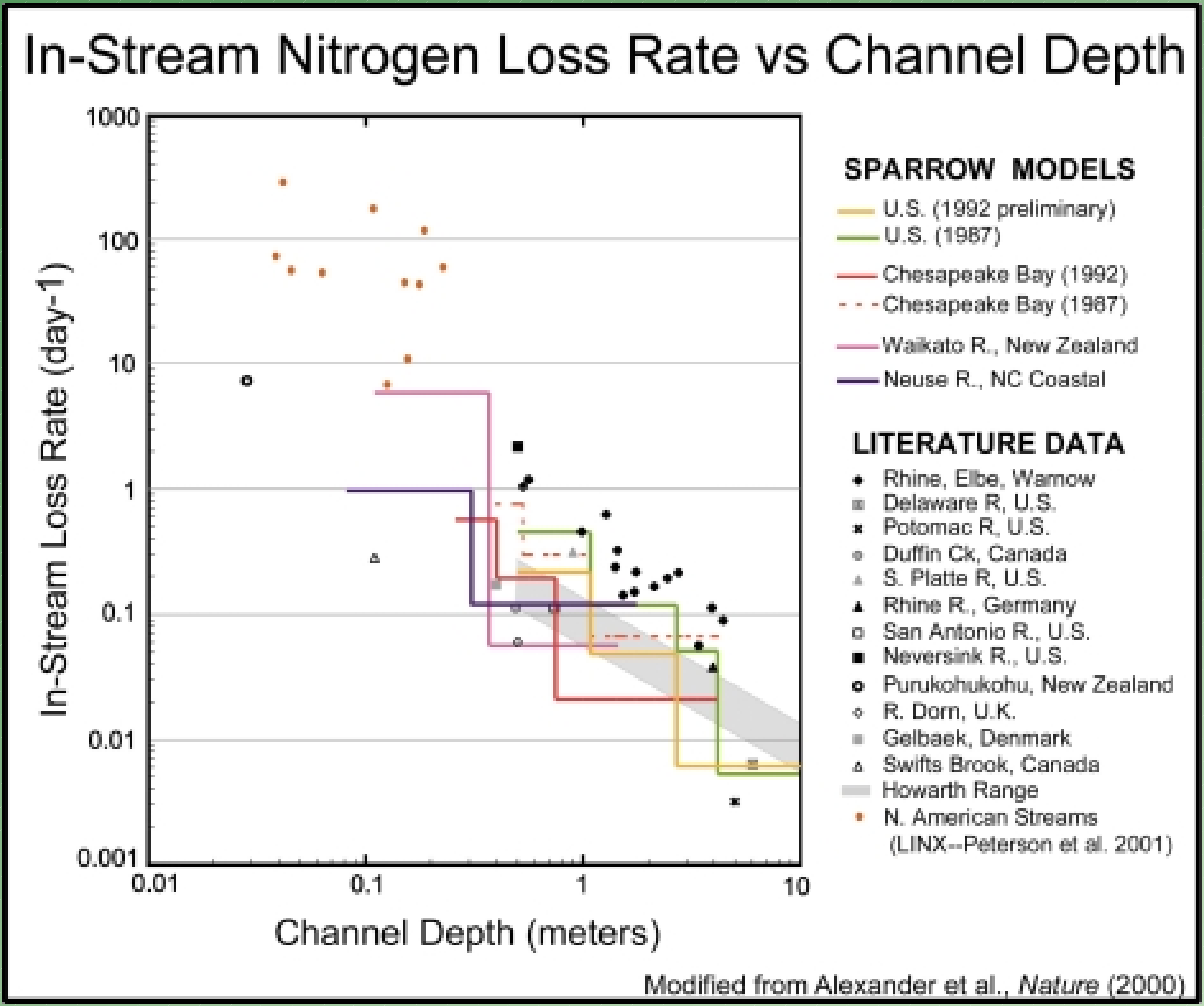
National and Regional SPARROW Models

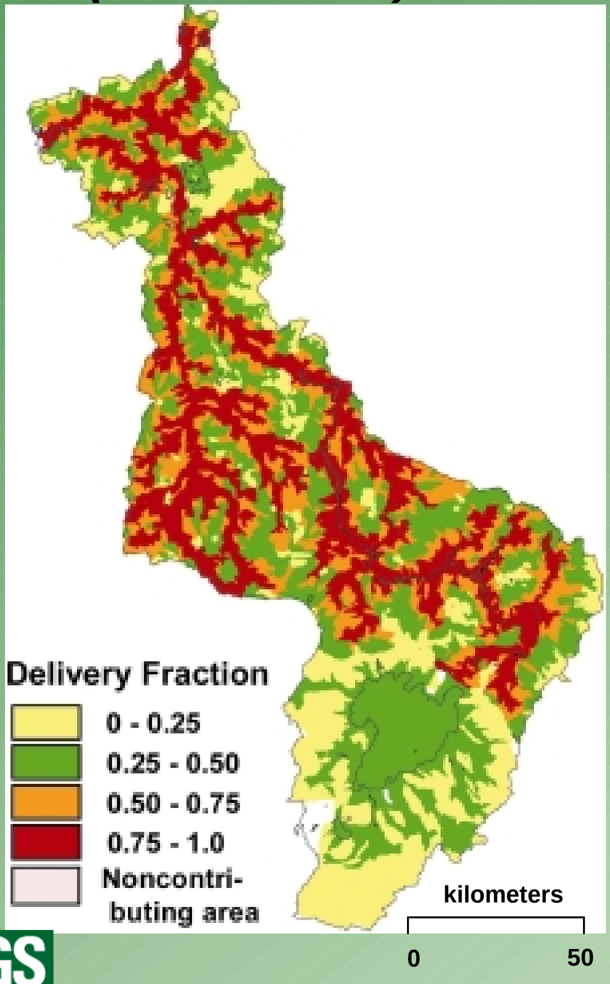


In-stream routing of contaminants performed as a function of 1st-order decay (e^{-kt}) and water time of travel or channel length estimated for a range of stream sizes

Fraction of In-Stream Nitrogen Delivered to Watershed Outlet

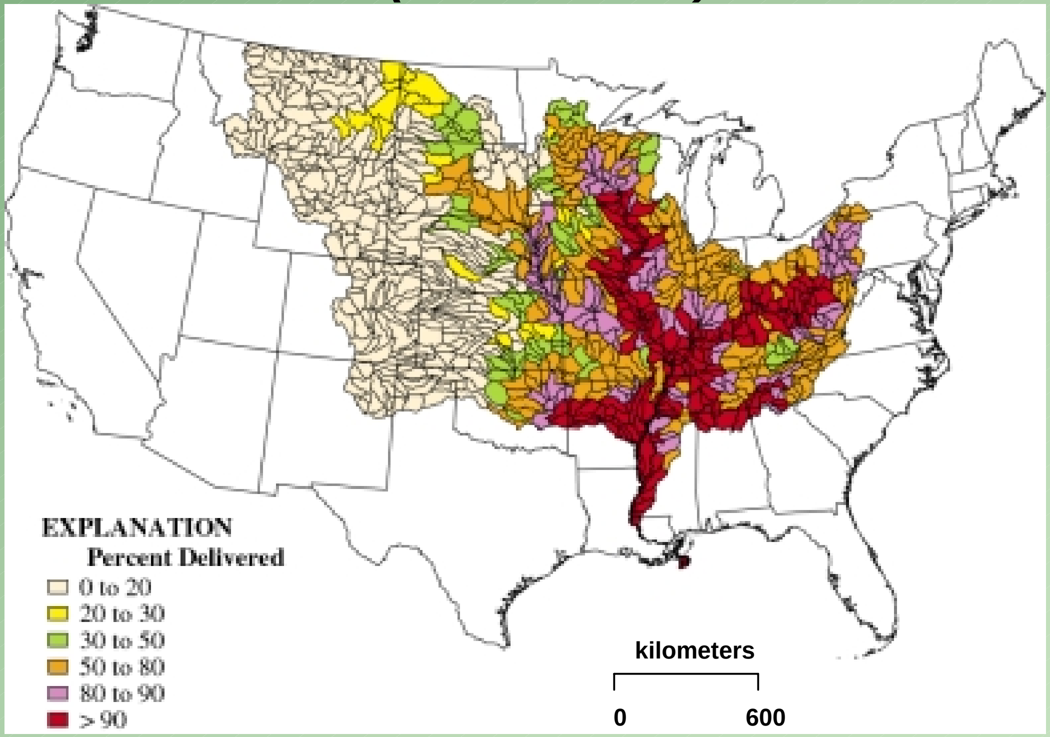
Waikato R. Basin, N.Z.

(1.4 x 10^4 km^2)



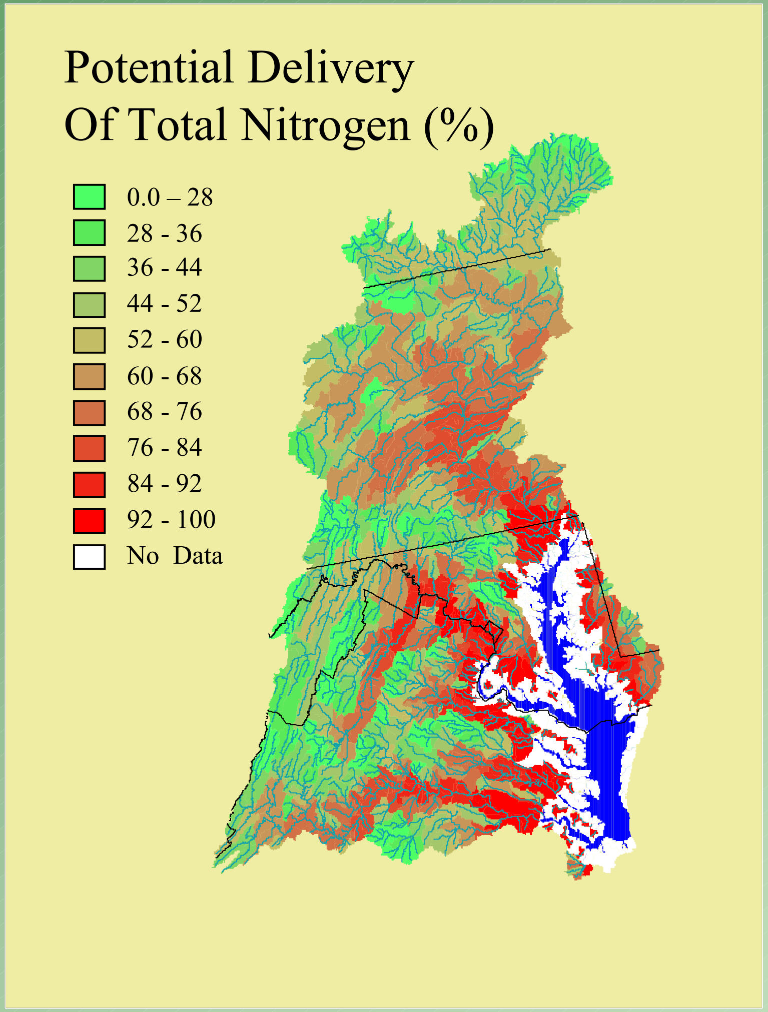
Mississippi R. Basin

(2.9 x 10^6 km^2)



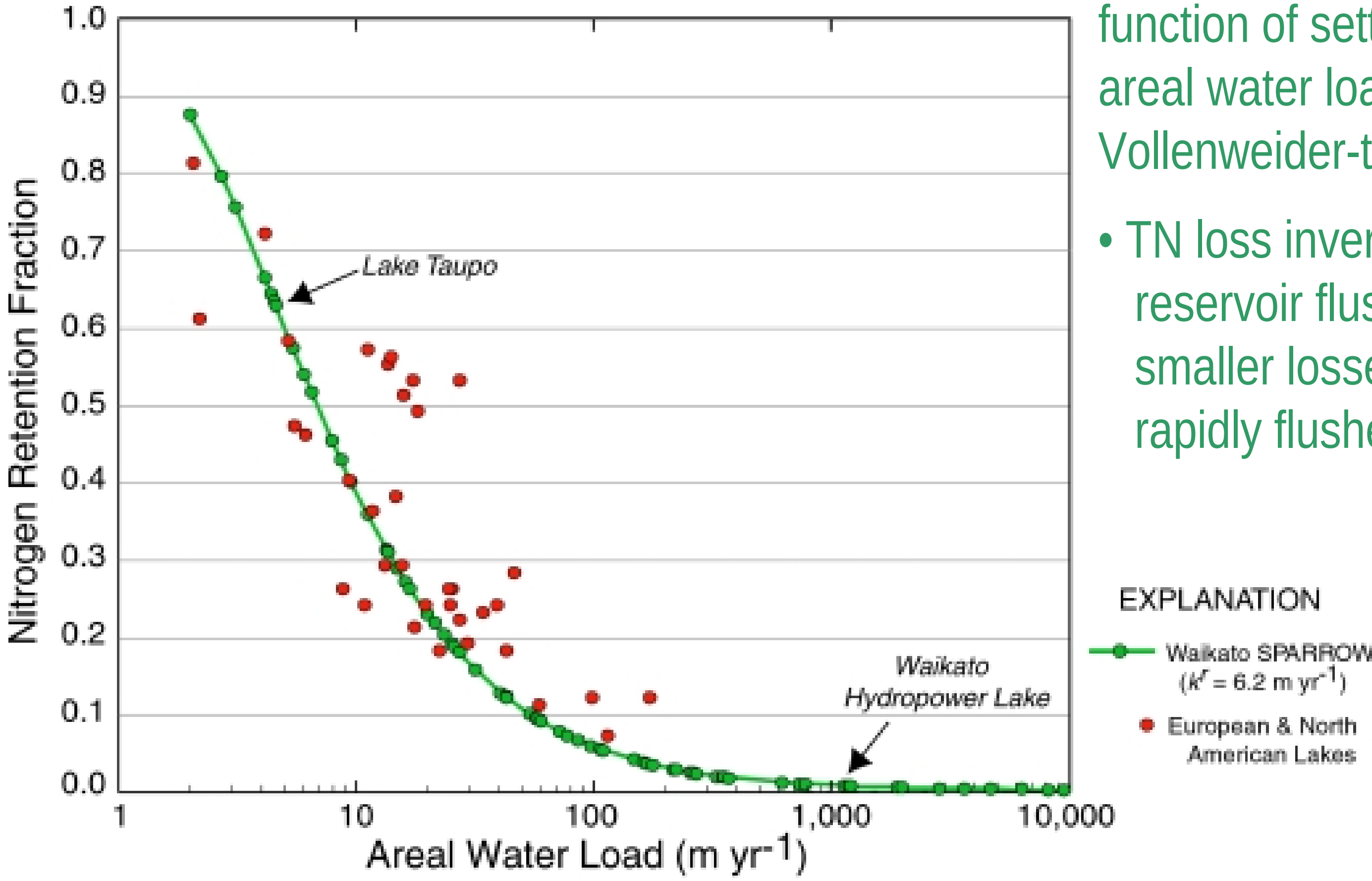
from Alexander et al. (2000; *in press*)

Chesapeake Bay Watershed



Reservoir Routing of Total N

Reservoirs of the Waikato River Basin, New Zealand



- Empirically estimated transport function of settling velocity and areal water load (based on Vollenweider-type models)
- TN loss inversely related to reservoir flushing rate—i.e., smaller losses occur in more rapidly flushed reservoirs

Alexander et al., *Water Resour. Res., in press*

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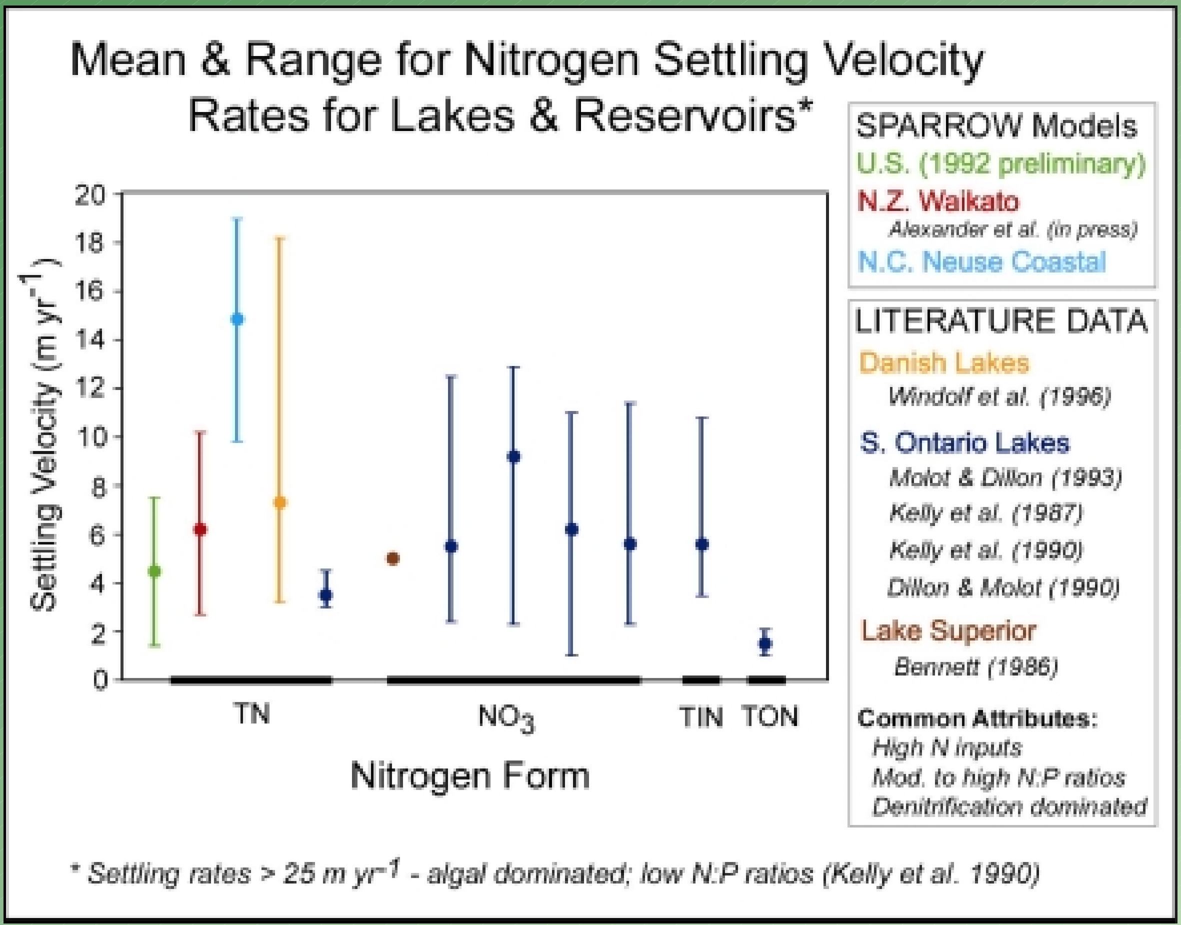
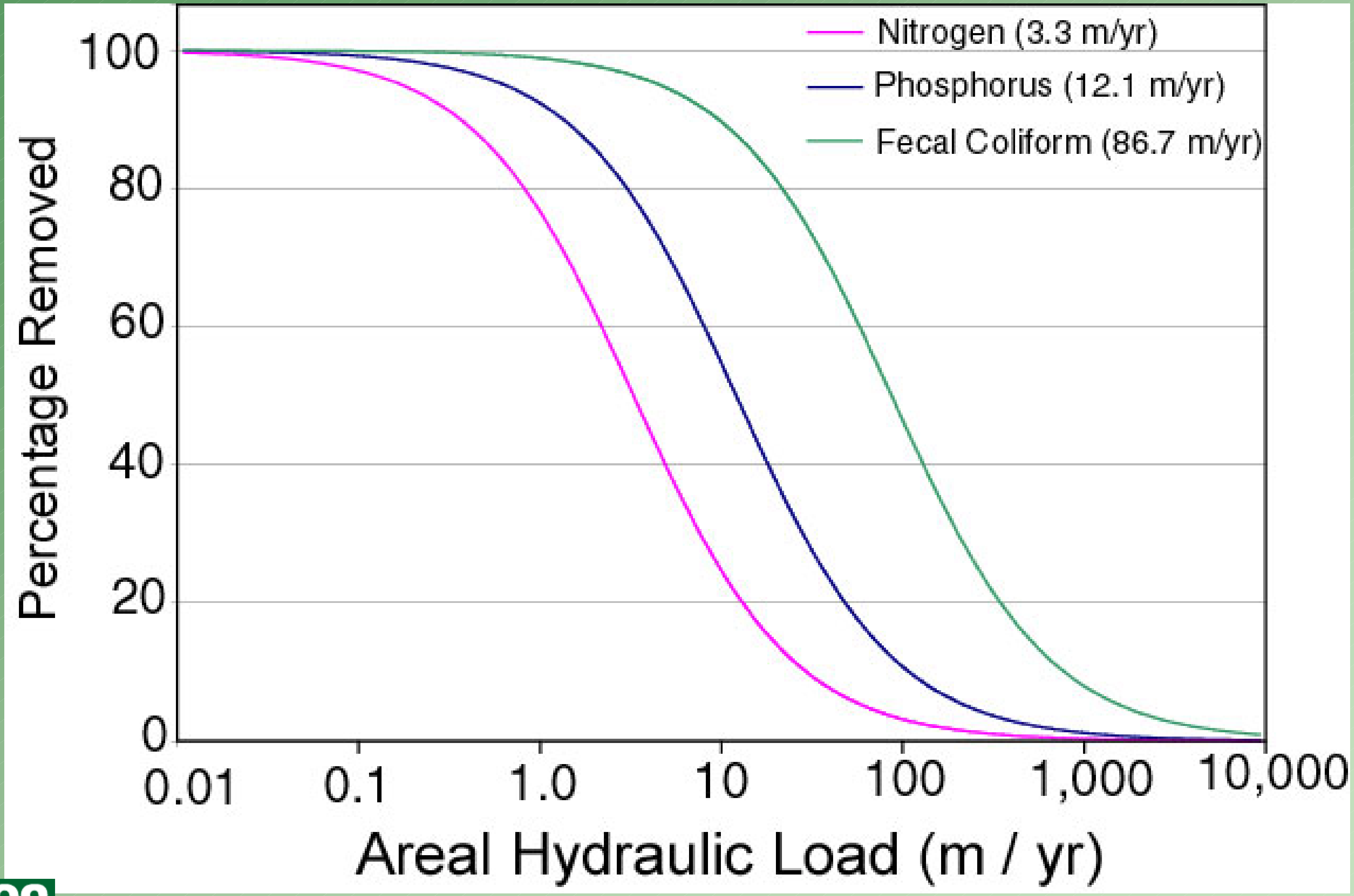
SPARROW Estimates of Nitrogen Loss in Reservoirs



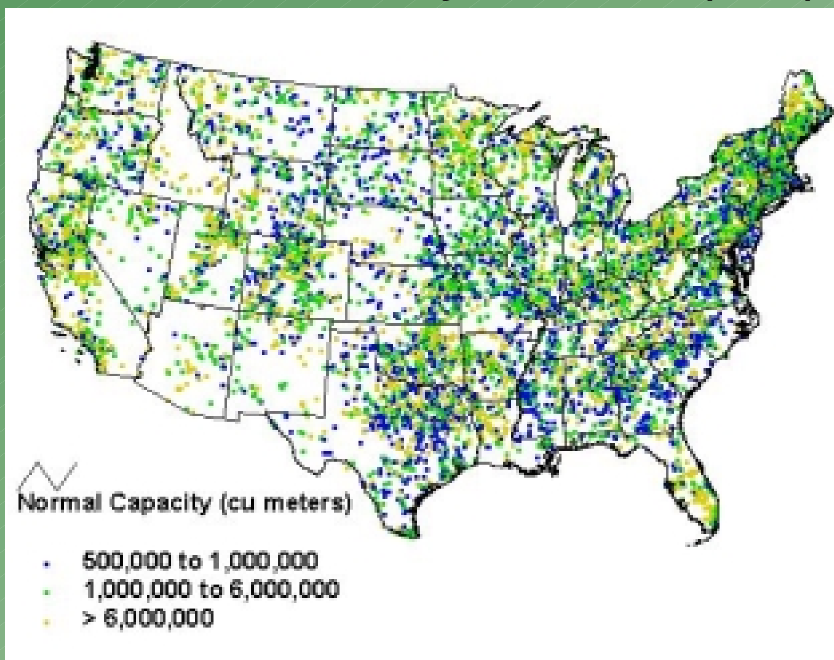
- SPARROW settling rates compare favorably with literature
- Magnitude of SPARROW rates suggest denitrification (rather than algal uptake and particulate burial) may be a dominant long-term loss process in reservoirs

SPARROW Predictions of Nutrient and Fecal Bacteria Loss in Lakes and Reservoirs

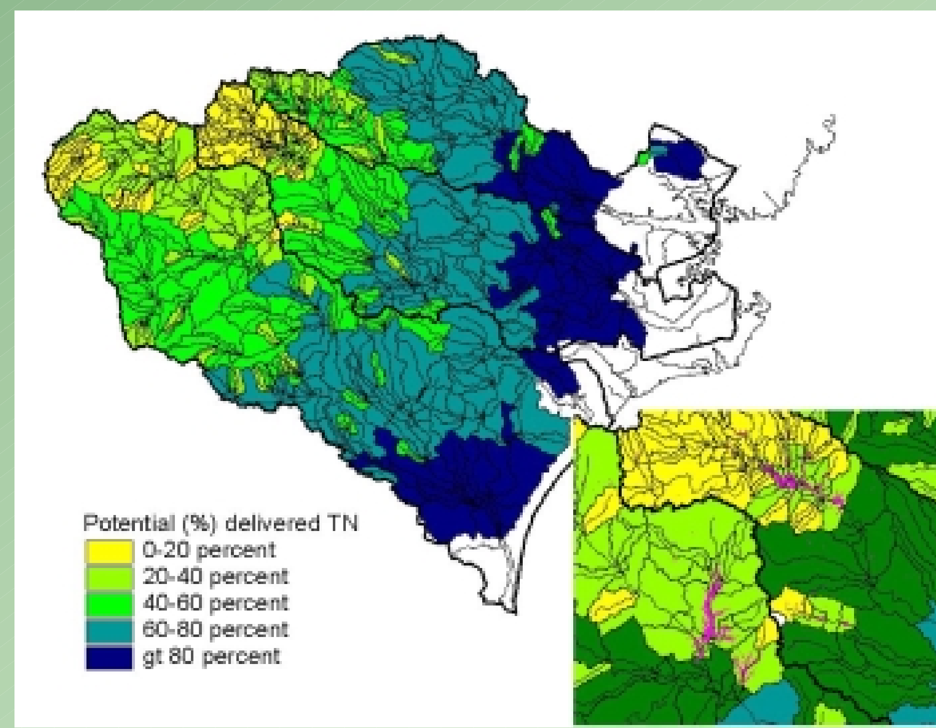


Impoundments are prominent features of U.S. landscape (> 70,000)—their location and size may be important to understanding contaminant fate in watersheds

Reservoirs, Lakes, Ponds
National Inventory of Dams (NID)



North Carolina Coastal SPARROW



SPARROW Prediction Statistics
(Mean & Percentiles)

- Loads/yields exported from watersheds
- Contaminant losses in streams and reservoirs
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- Contaminant sources and budgets
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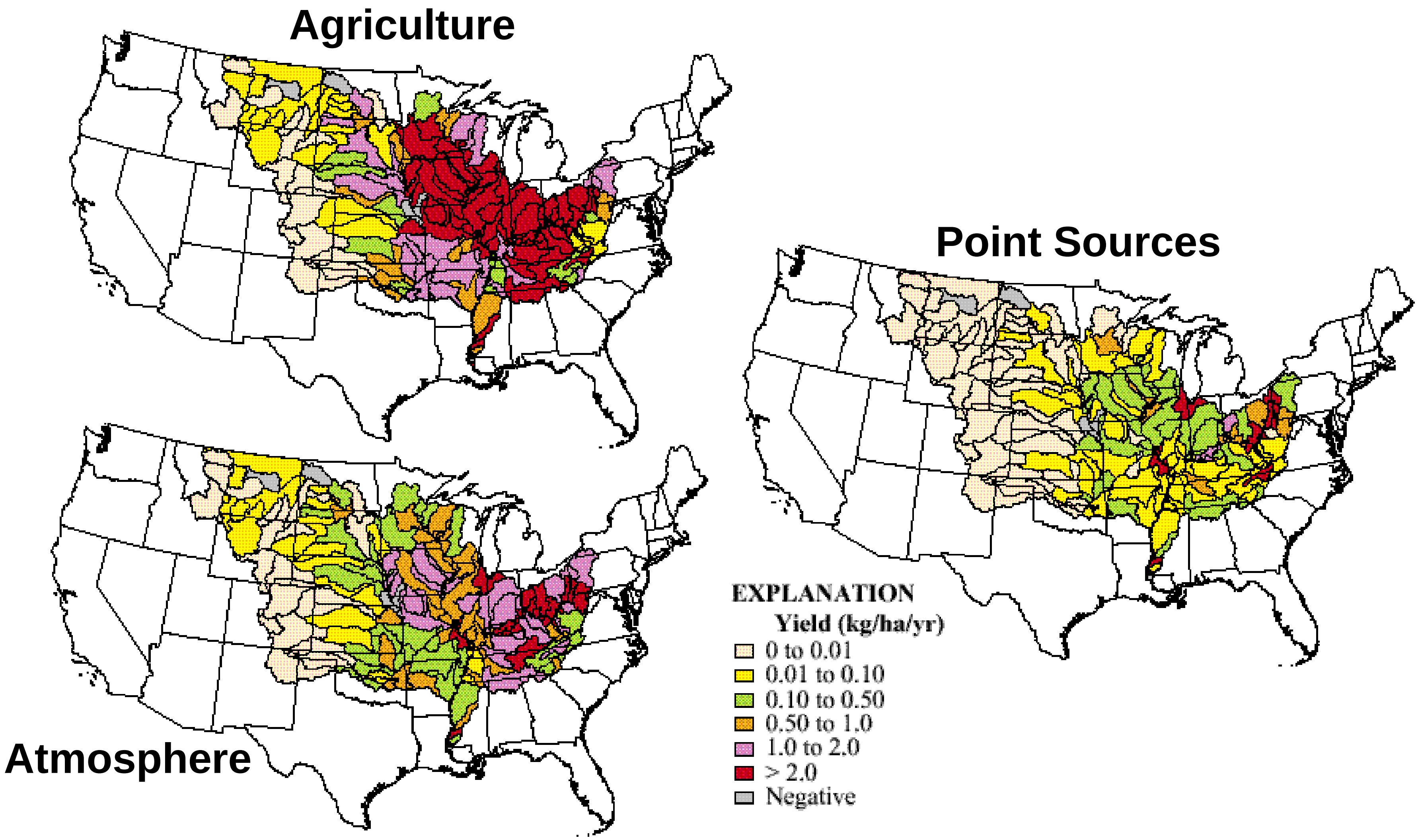
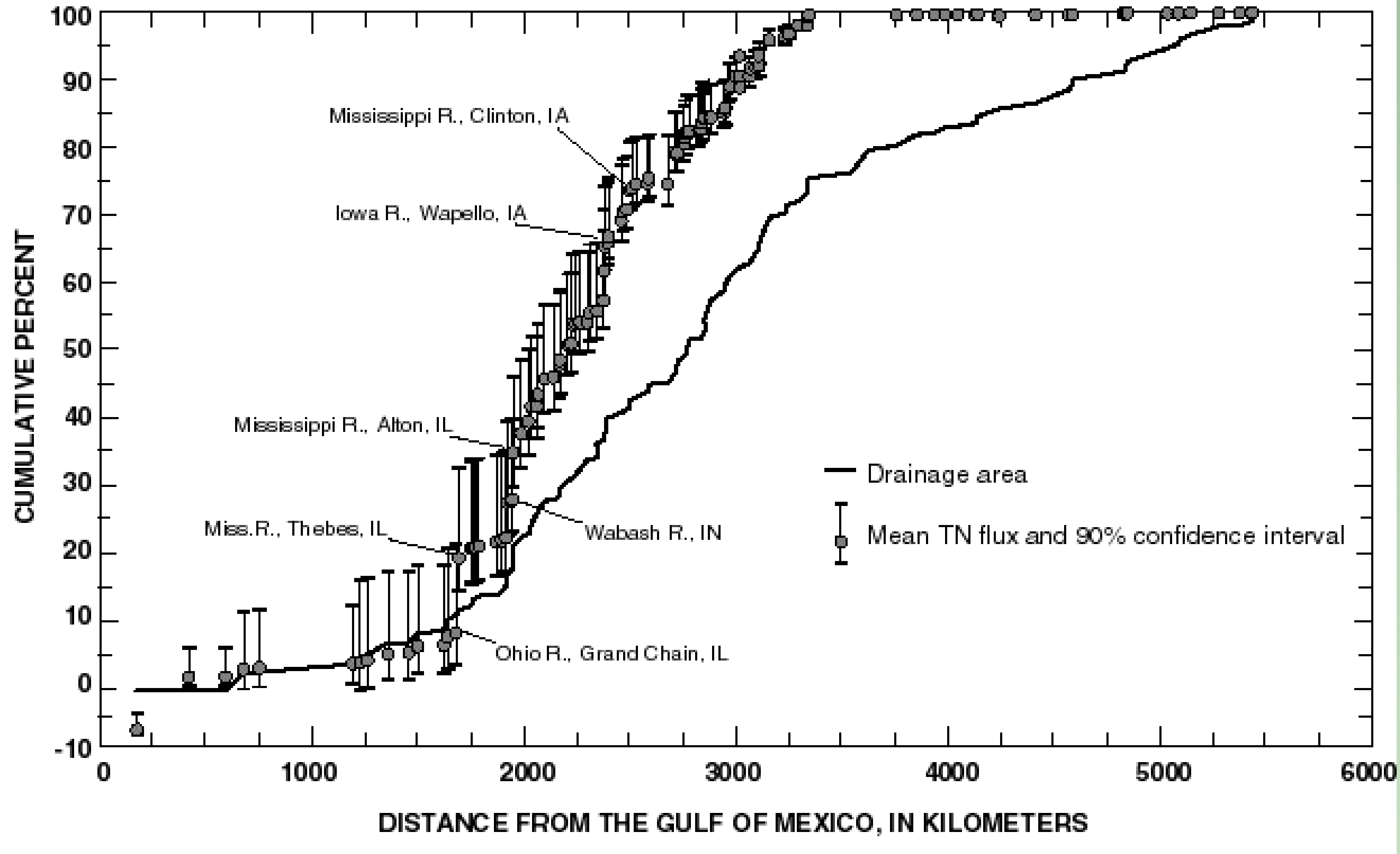
Nitrogen Delivery to the Gulf of Mexico

SPARROW Estimates of Delivered TN Yield



Cumulative Percentage of TN Flux Delivered to Gulf from Intervening Watersheds of Monitoring Stations



(based on model data from Alexander et al. 2000)

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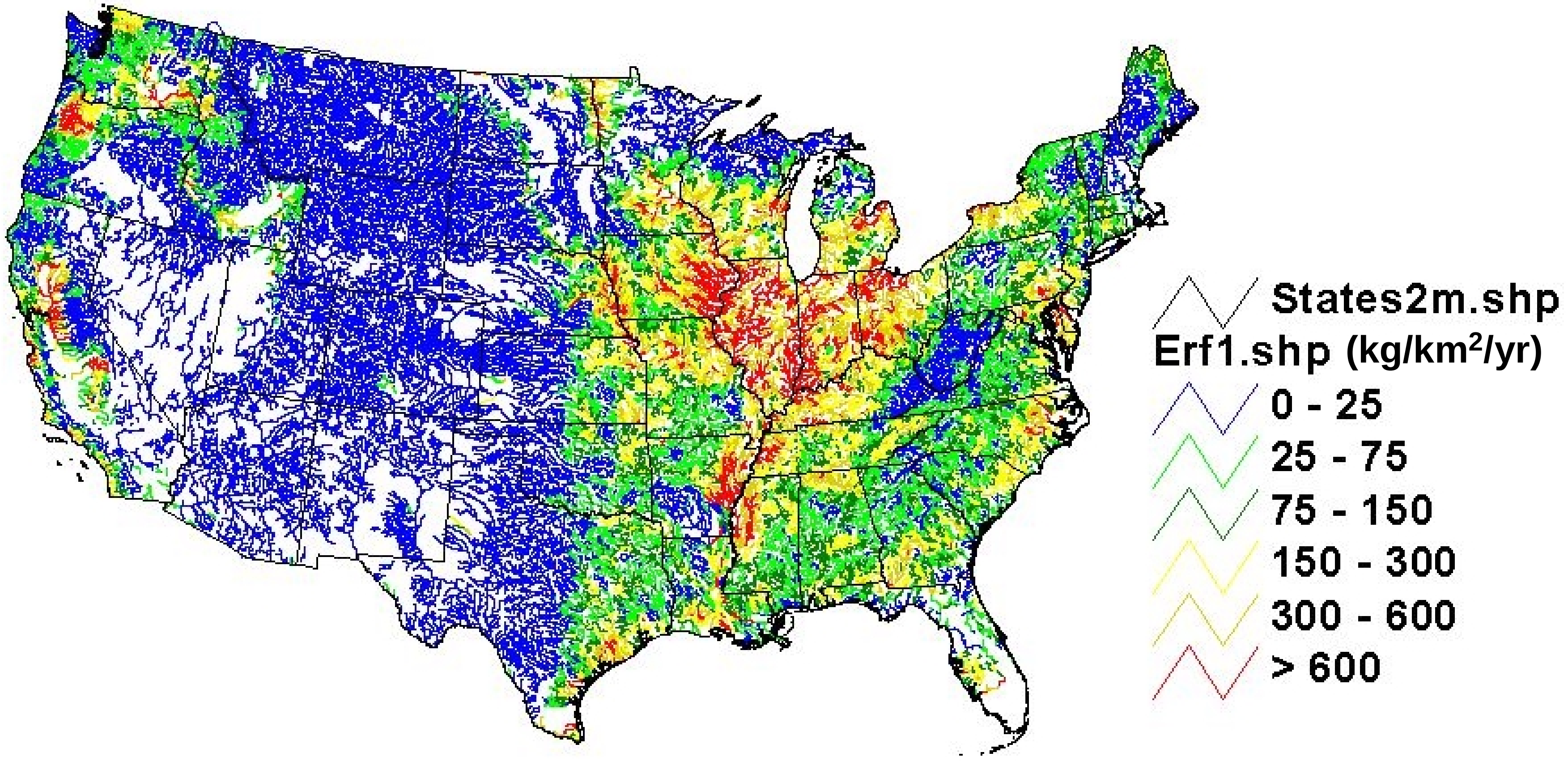
Nitrogen Delivery to the U.S. Coastal areas

Fertilizer Nitrogen Delivered Yield



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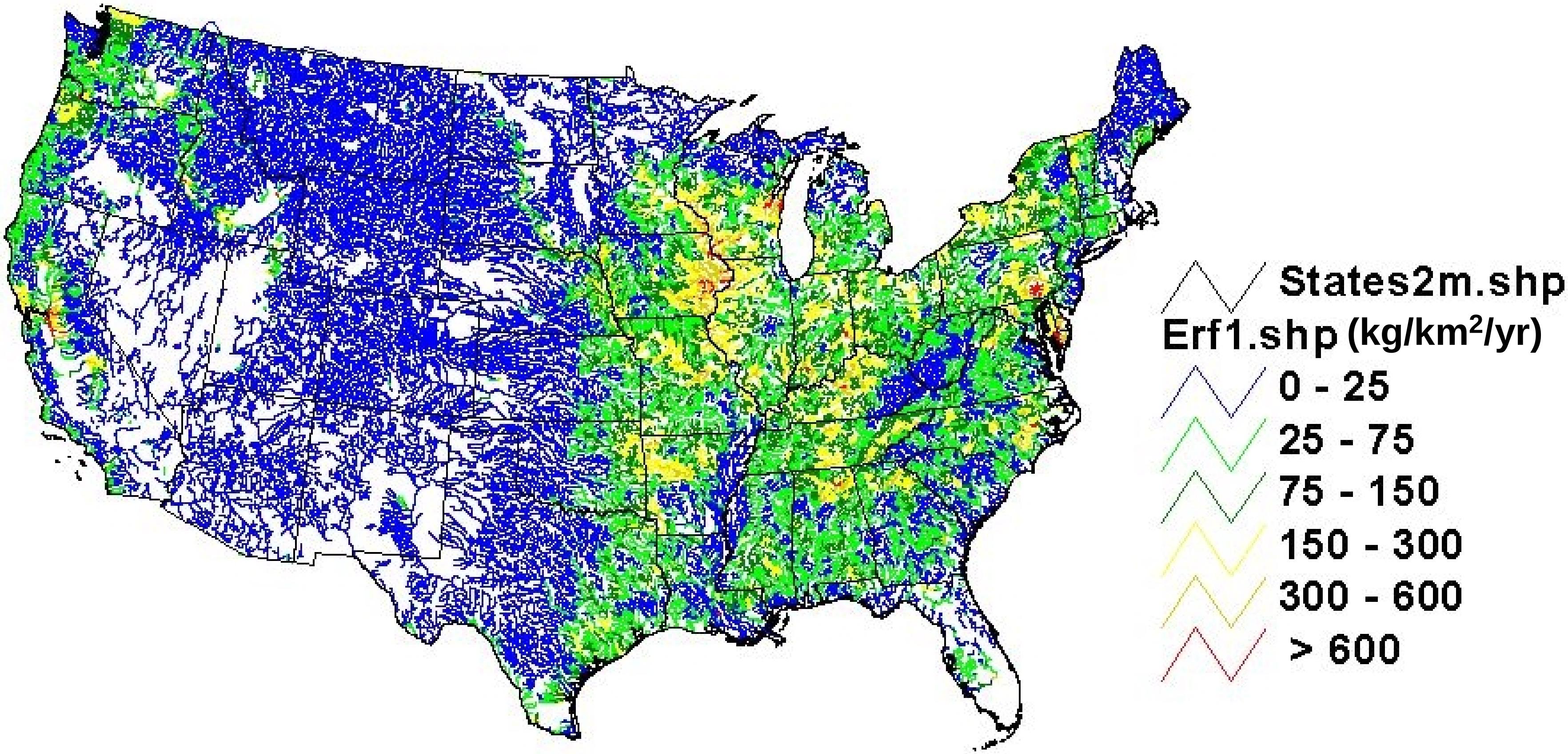
Livestock Waste Nitrogen Delivered Yield



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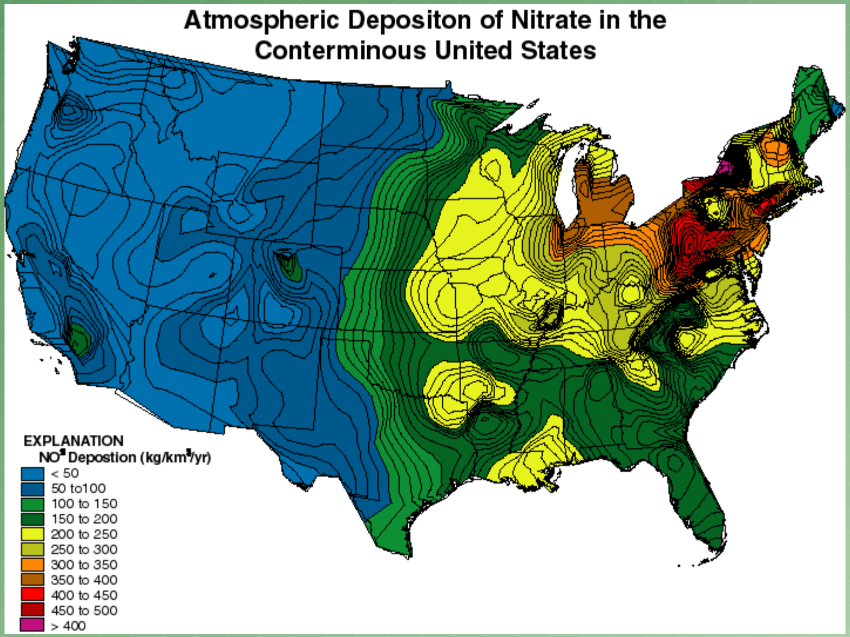
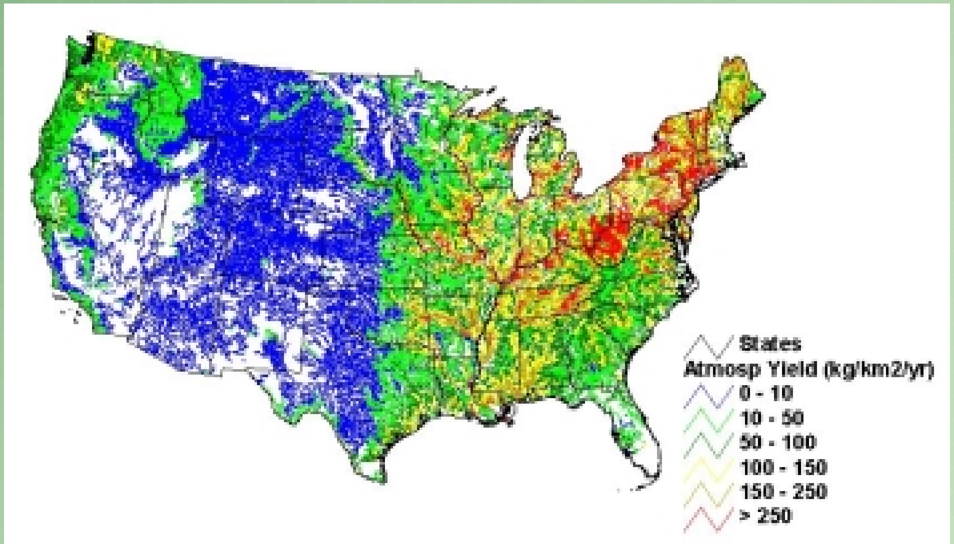
SPARROW Predictions
Atmospheric Nitrogen Delivered to Estuaries
in comparison to Deposition Inputs



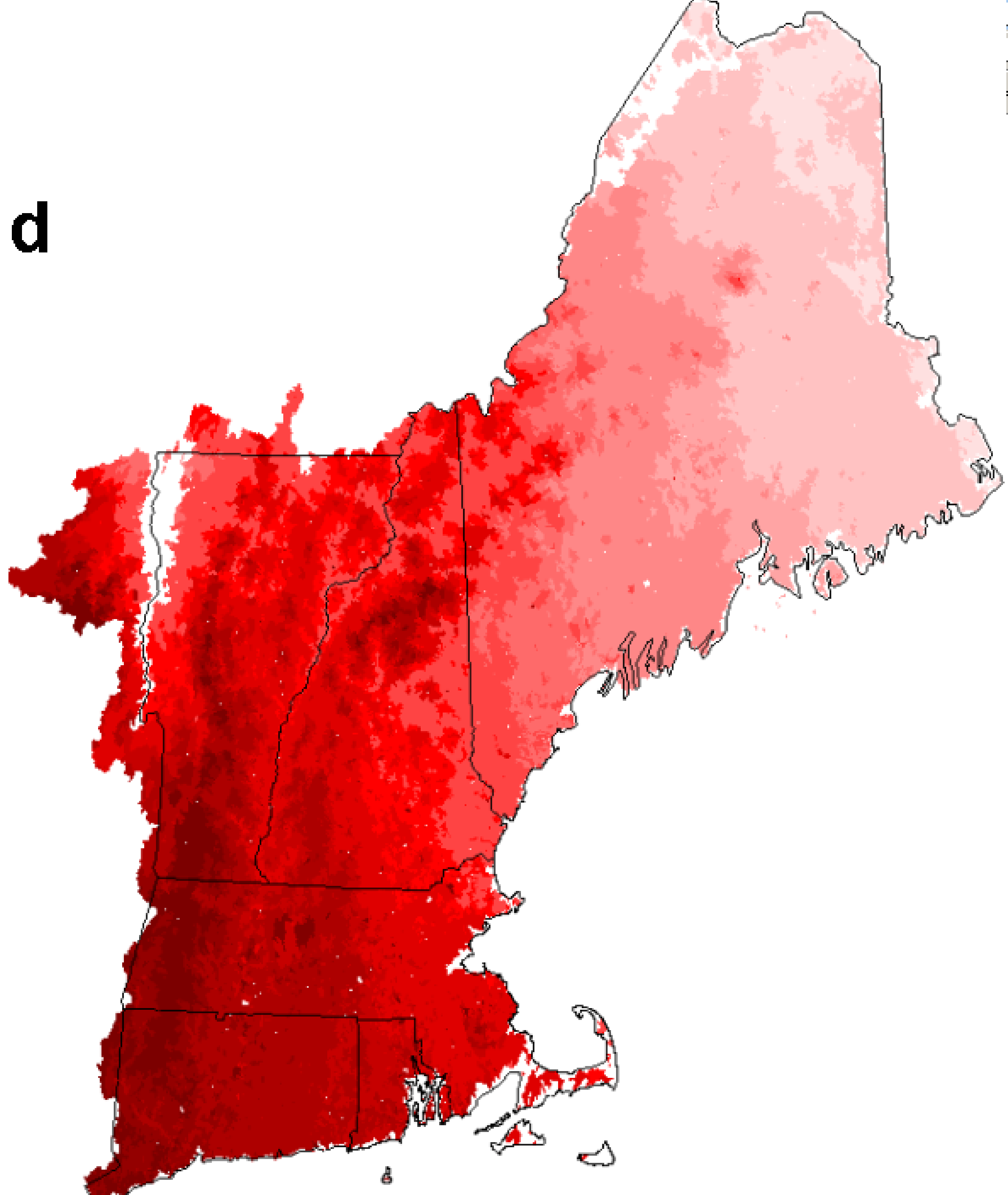


Nitrogen Delivery to the New England Coastal areas

SPARROW Predicted Nitrogen Yield Atmospheric Deposition

Catchment Yield
(kg / sq km)

- 0 - 142
- 142 - 165
- 165 - 187
- 187 - 209
- 209 - 228
- 228 - 248
- 248 - 267
- 267 - 290
- 290 - 411
- 411 - 616



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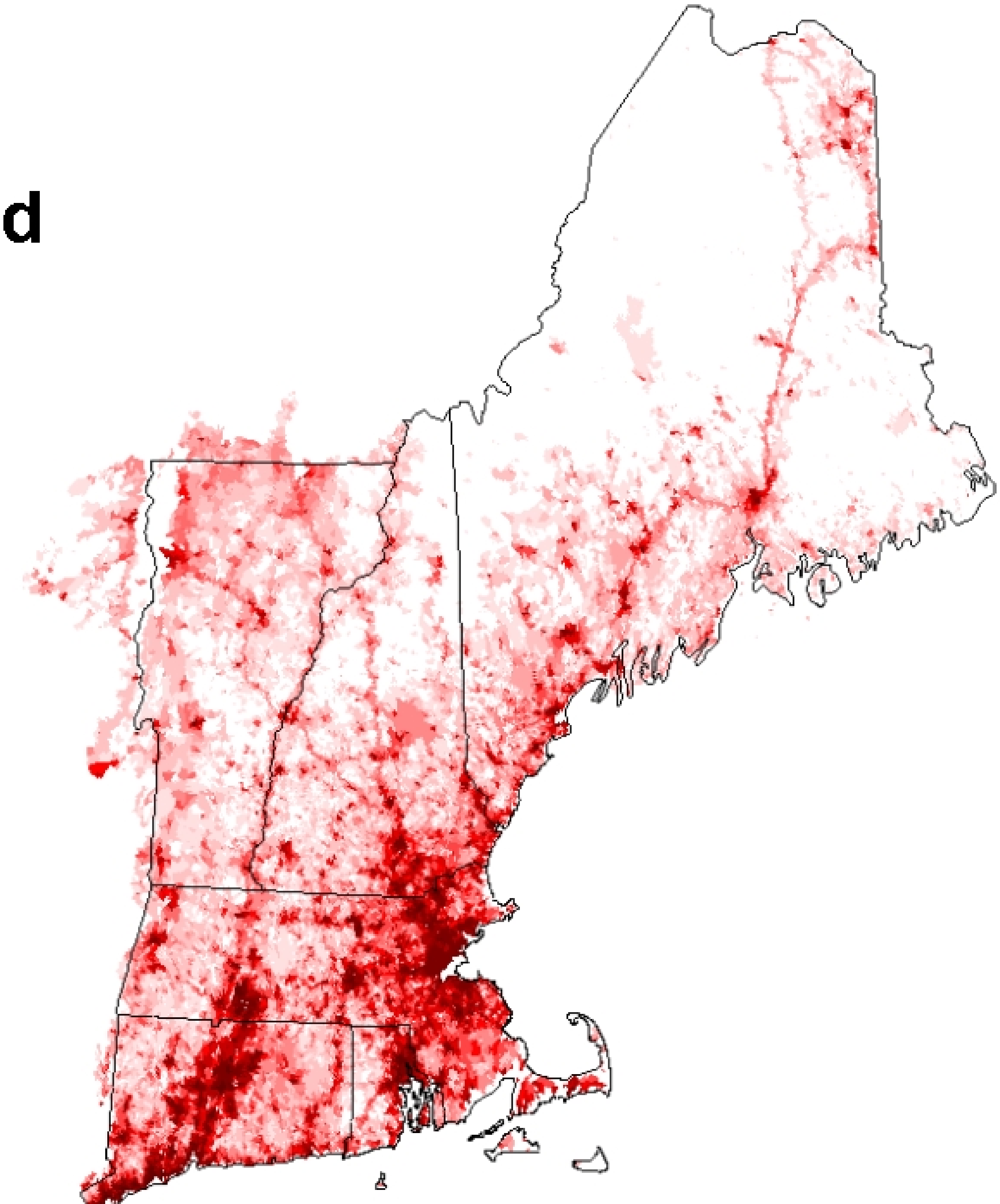
SPARROW Predicted Nitrogen Yield URBAN Sources



Catchment Yield
(kg / sq km)

- 0
- 2 - 15
- 15 - 35
- 35 - 67
- 67 - 114
- 114 - 183
- 183 - 277
- 277 - 400
- 400 - 552
- 552 - 776
- 776 - 1271

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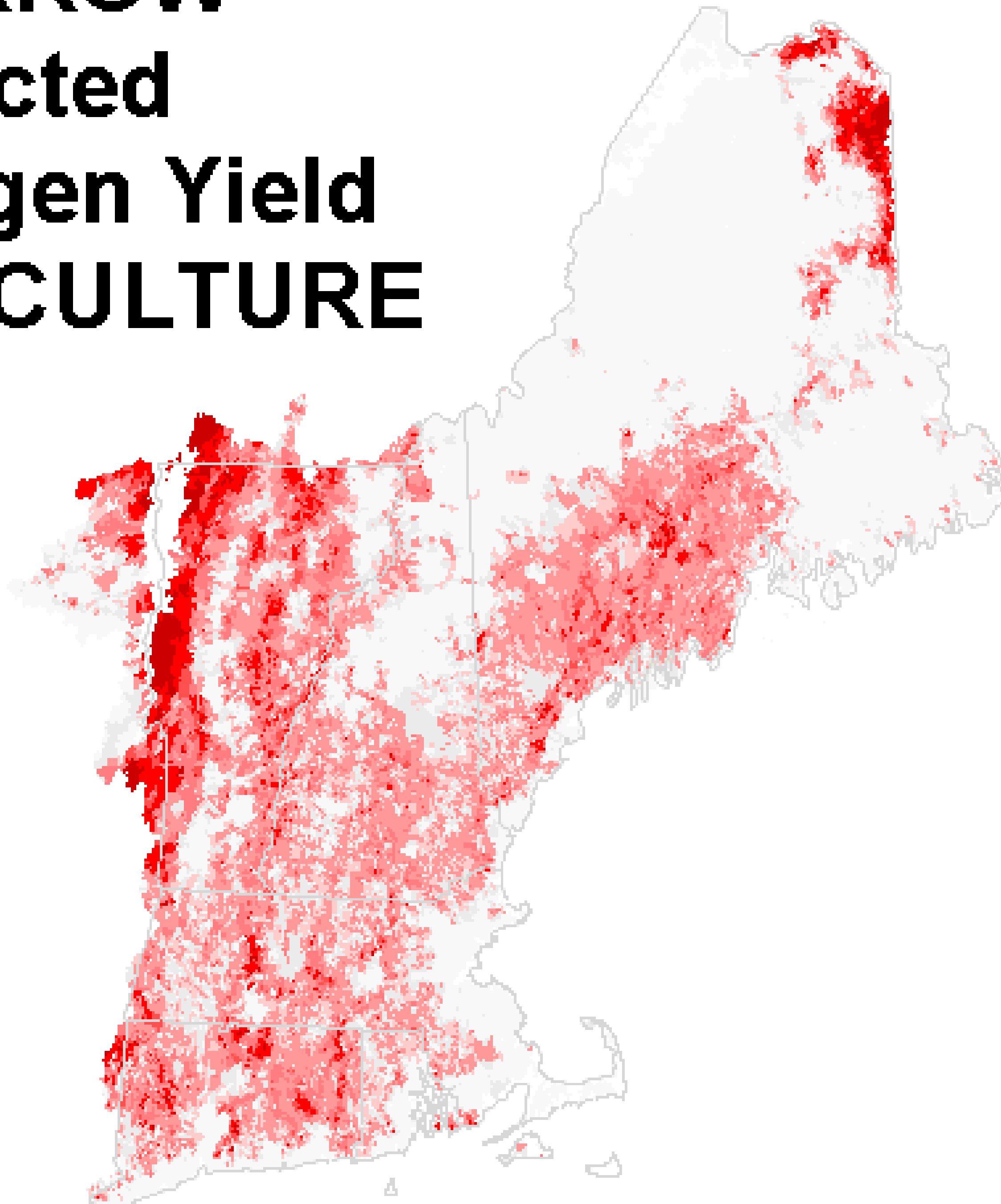
SPARROW Predicted Nitrogen Yield AGRICULTURE



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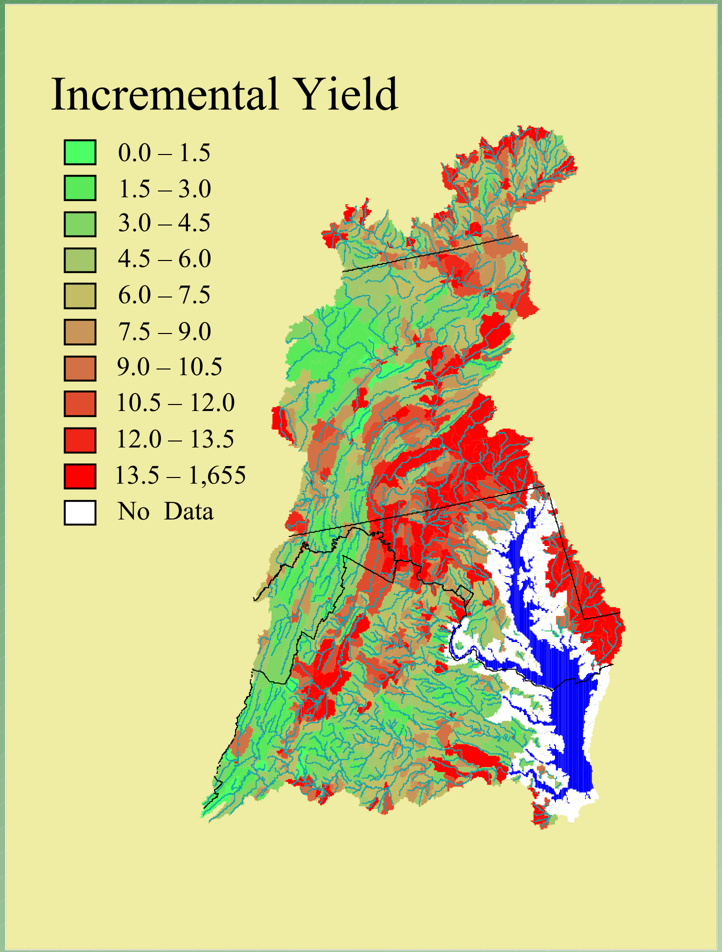
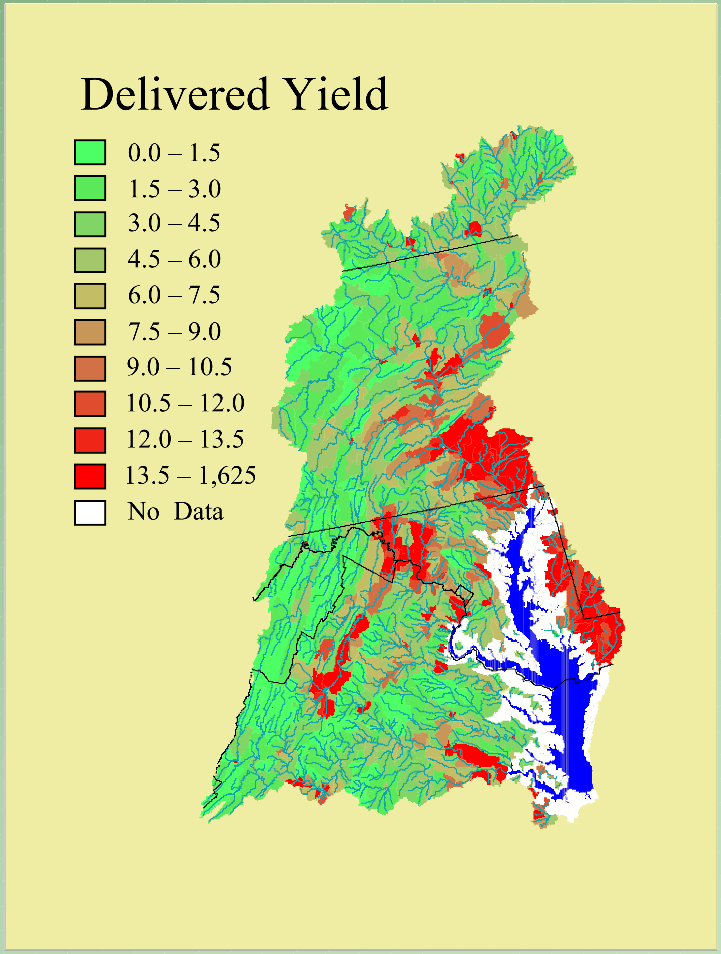
Nitrogen Delivery to the Chesapeake Bay

Chesapeake Bay Watershed

Nitrogen Yield (kg/ha-yr)





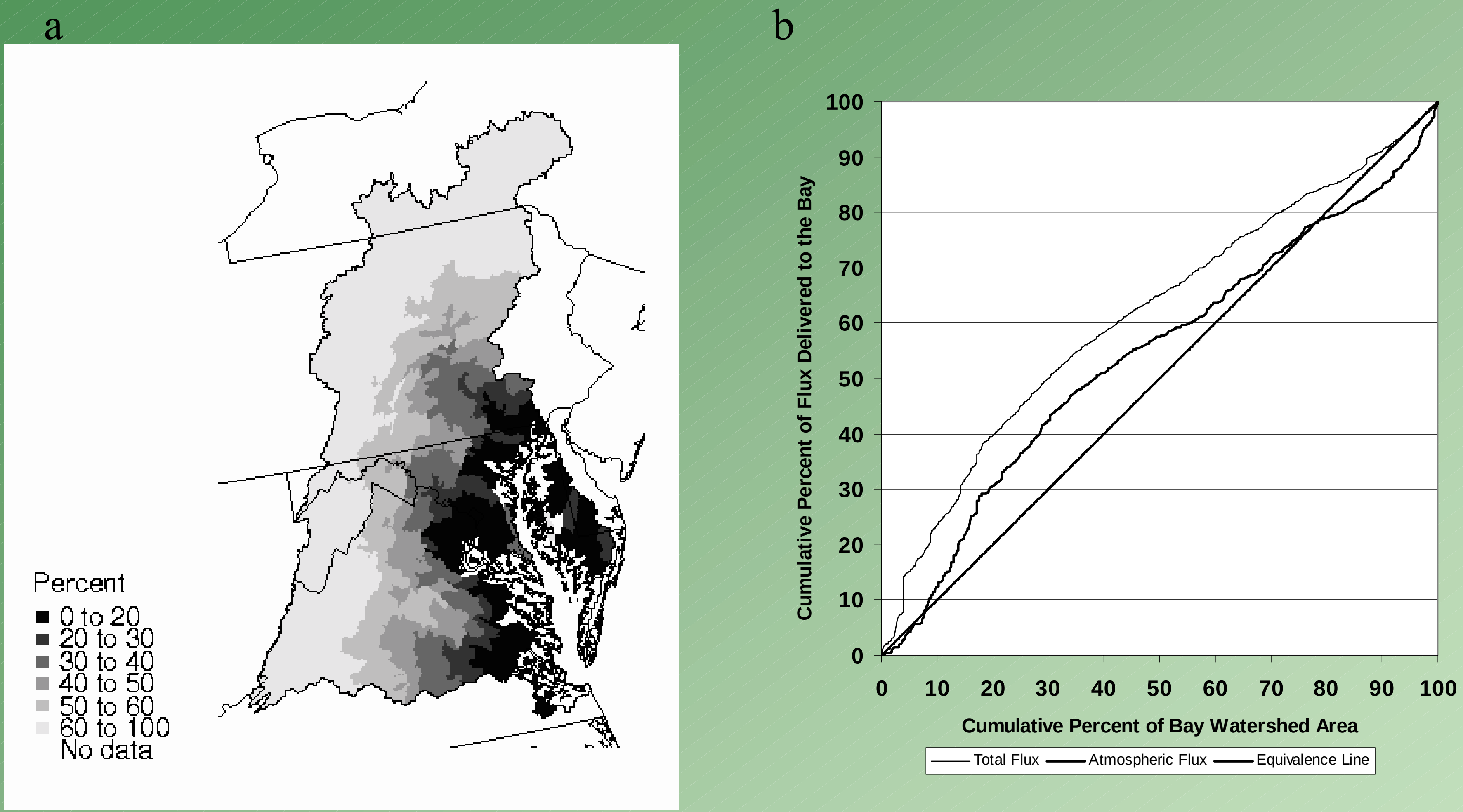
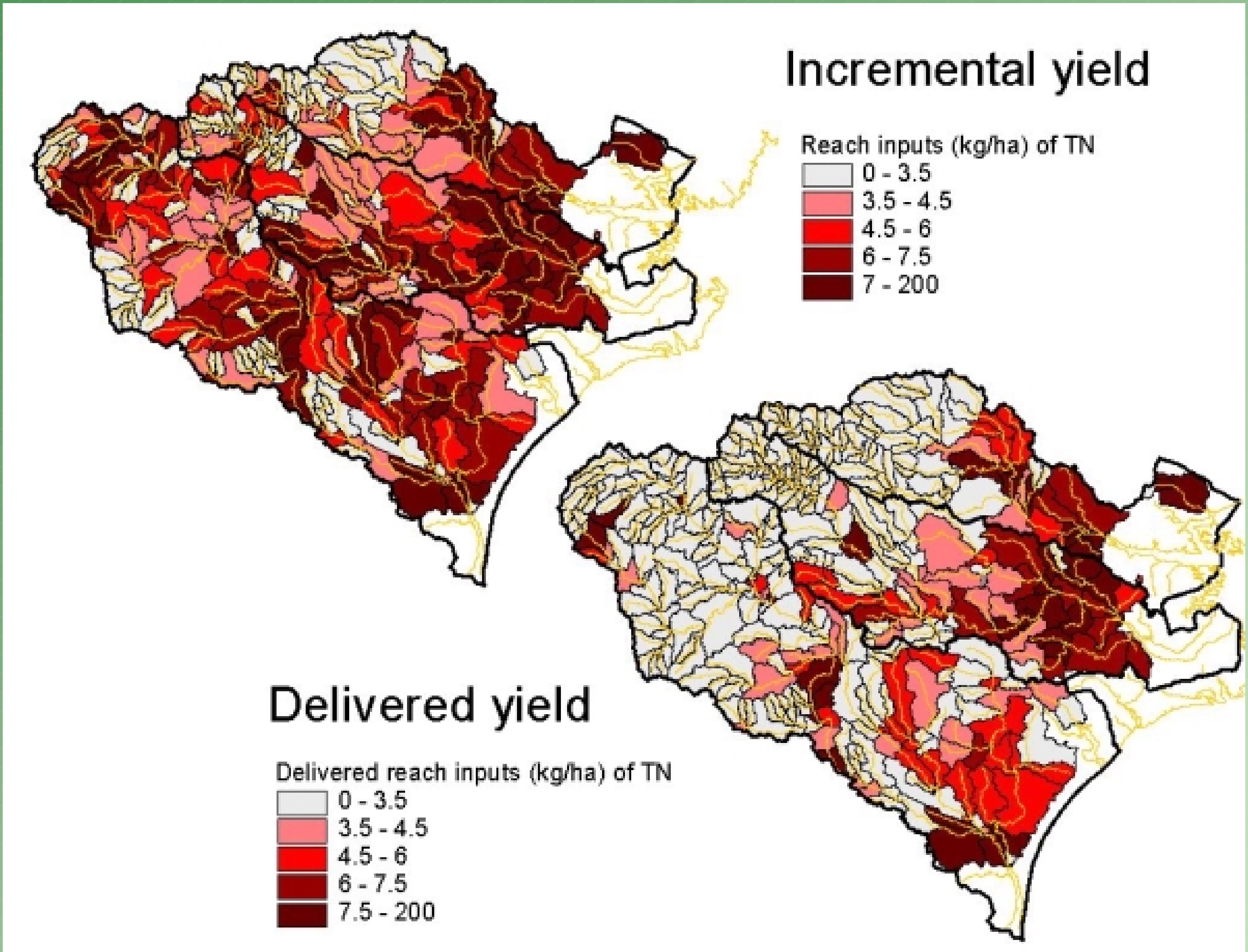
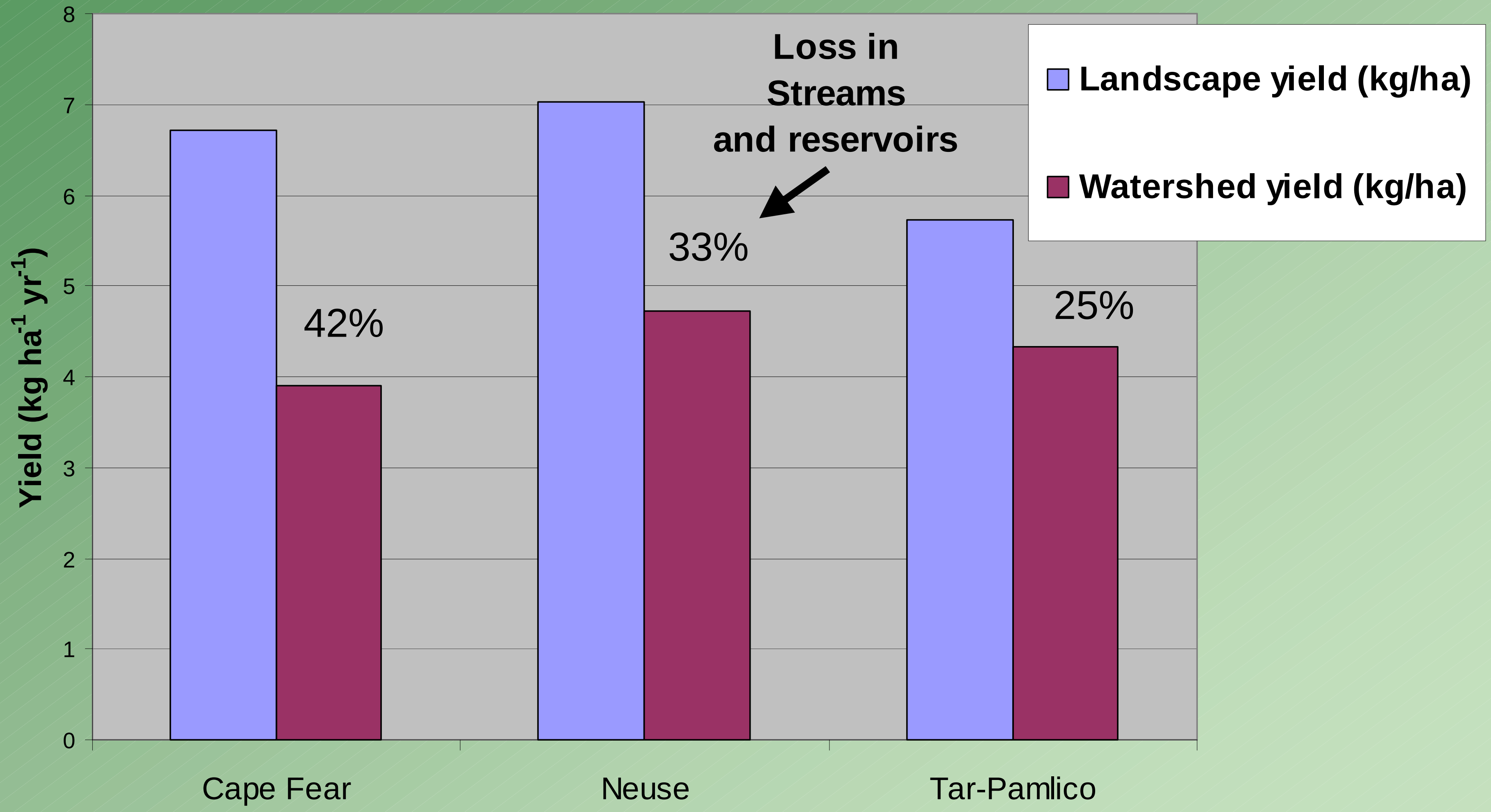


Figure 10. Cumulative percentage of the stream nitrogen delivered to the Chesapeake Bay from interior watersheds as a function of river channel distance from the Bay: (a) map of atmospheric nitrogen by watershed; (b) total and atmospheric flux in relation to watershed area.

Nitrogen Delivery to Coastal North Carolina


Incremental yield
Reach inputs (kg/ha) of TN
0 - 3.5
3.5 - 4.5
4.5 - 6
6 - 7.5
7 - 200
Delivered yield
Delivered reach inputs (kg/ha) of TN
0 - 3.5
3.5 - 4.5
4.5 - 6
6 - 7.5
7.5 - 200

NC SPARROW TN yield (kg/ha) at edge of stream and at watershed outlet



SPARROW Prediction Statistics
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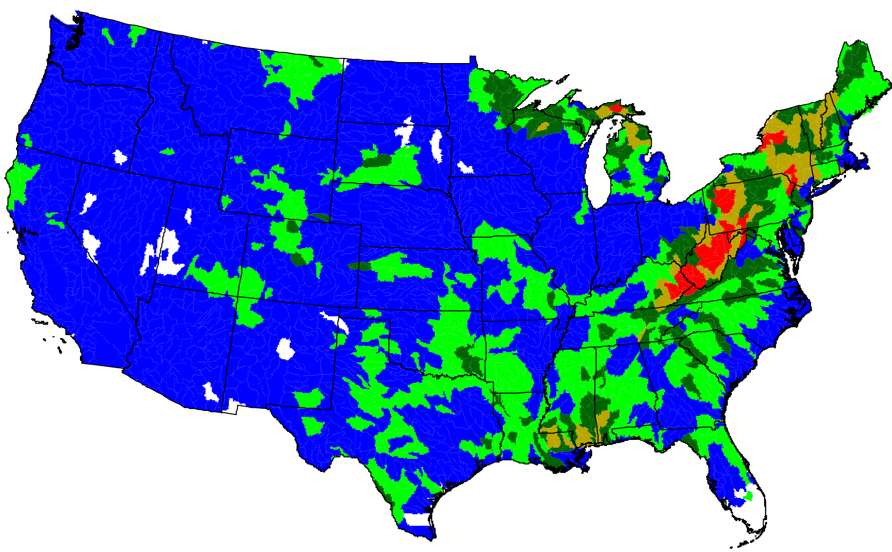
Contaminant sources and budgets contiguous U.S.

Nutrient Sources in U.S. Watersheds*

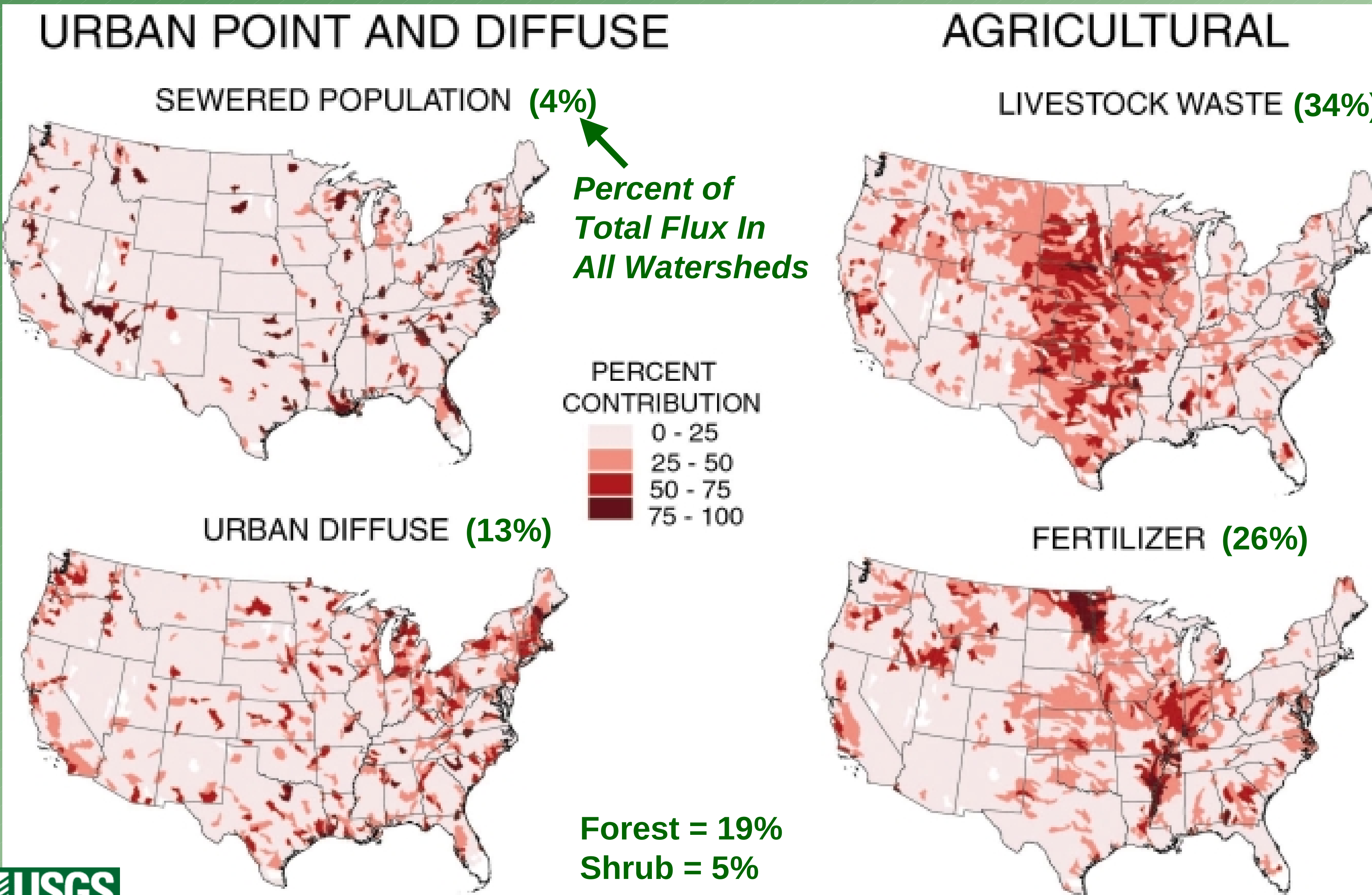
Atmospheric Contributions to Total Nitrogen Export



- Nutrient management conference
- Useful general summary of sources
- Results for TN and TP
- Tabulated by cataloging unit
- Gives budgets at outlets of units
- Differ from budgets based on inputs
- Accounts for variations in delivery among sources and watersheds

* Smith and Alexander, 2000

SPARROW TP Intensive-Source Model



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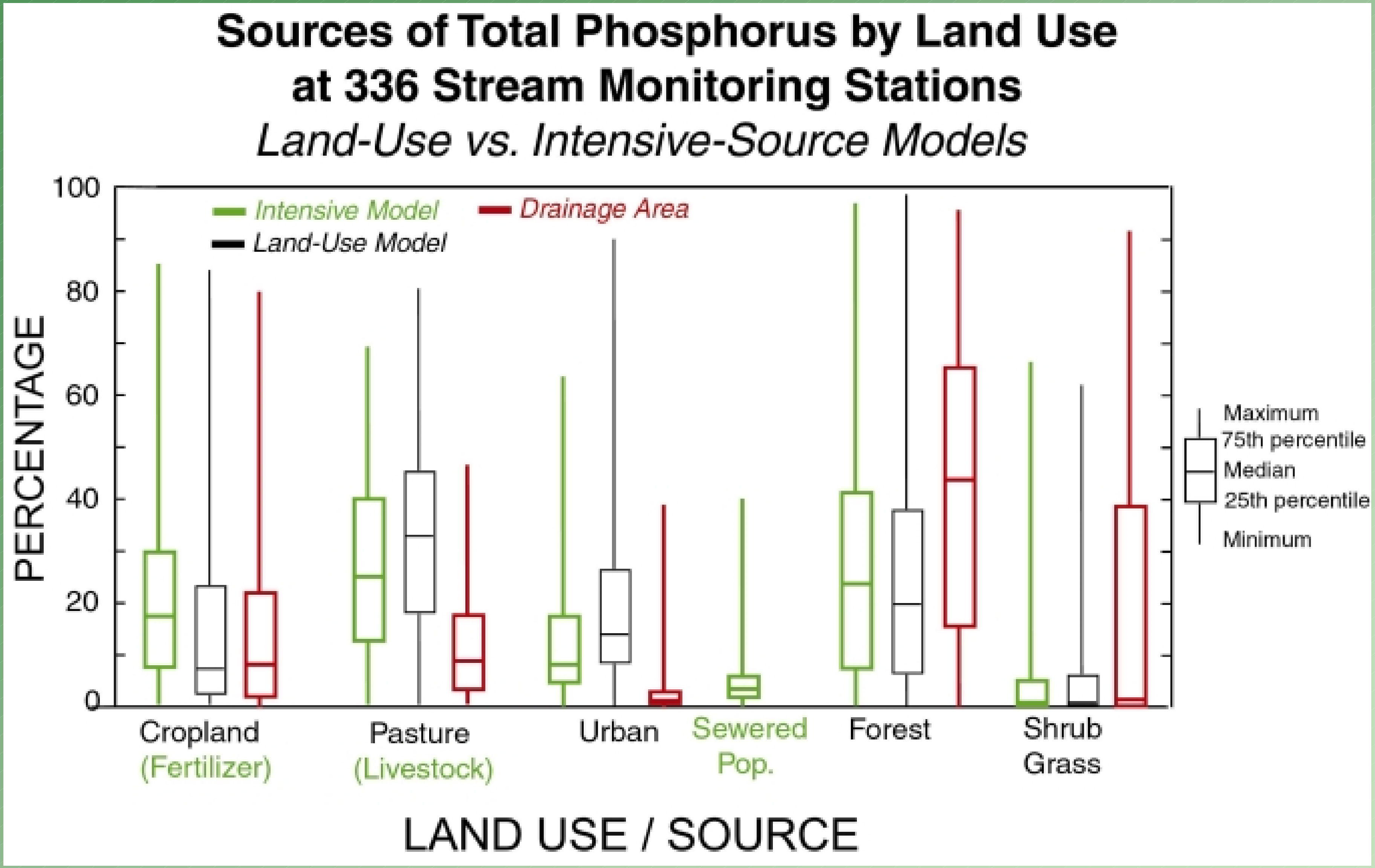
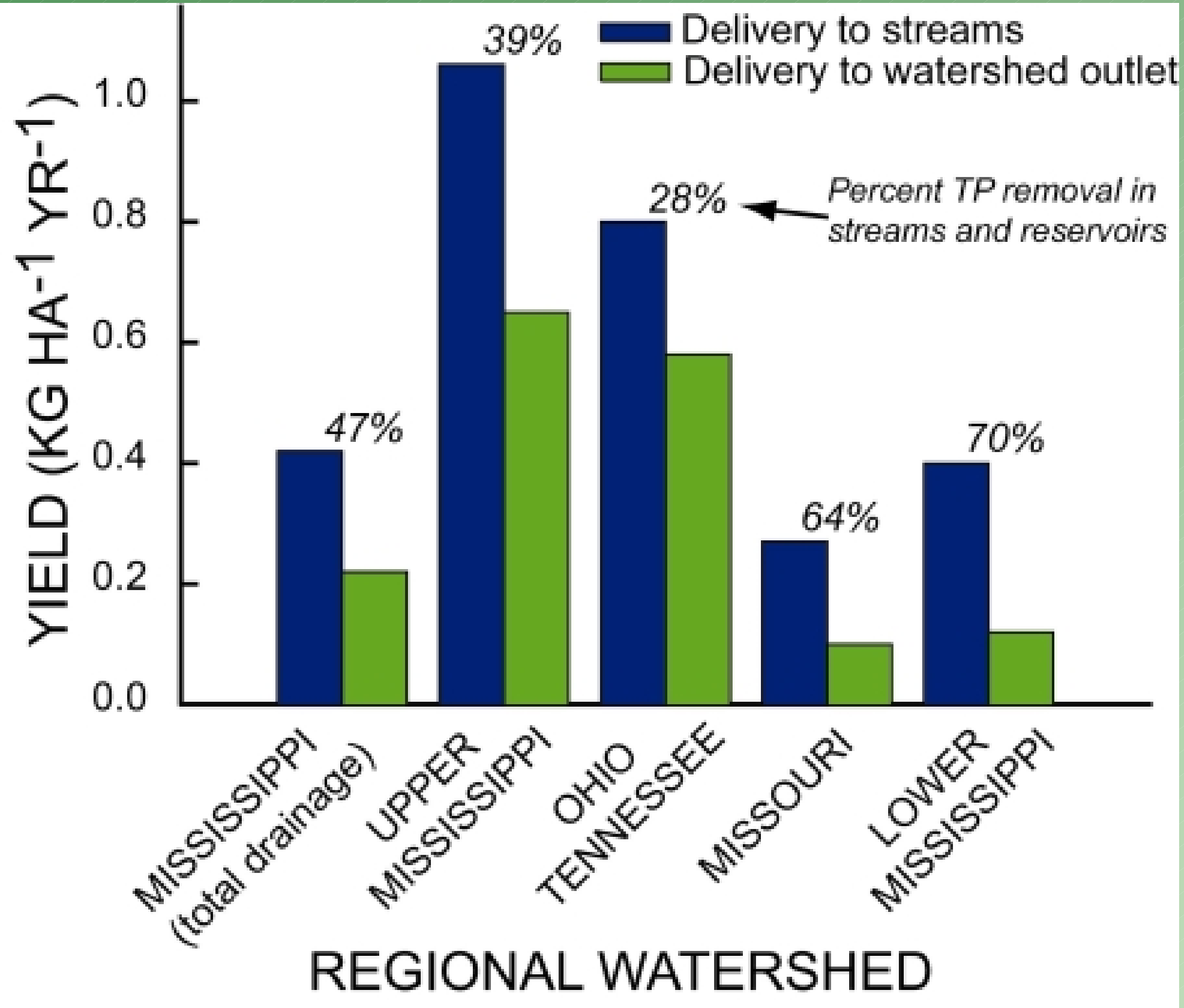
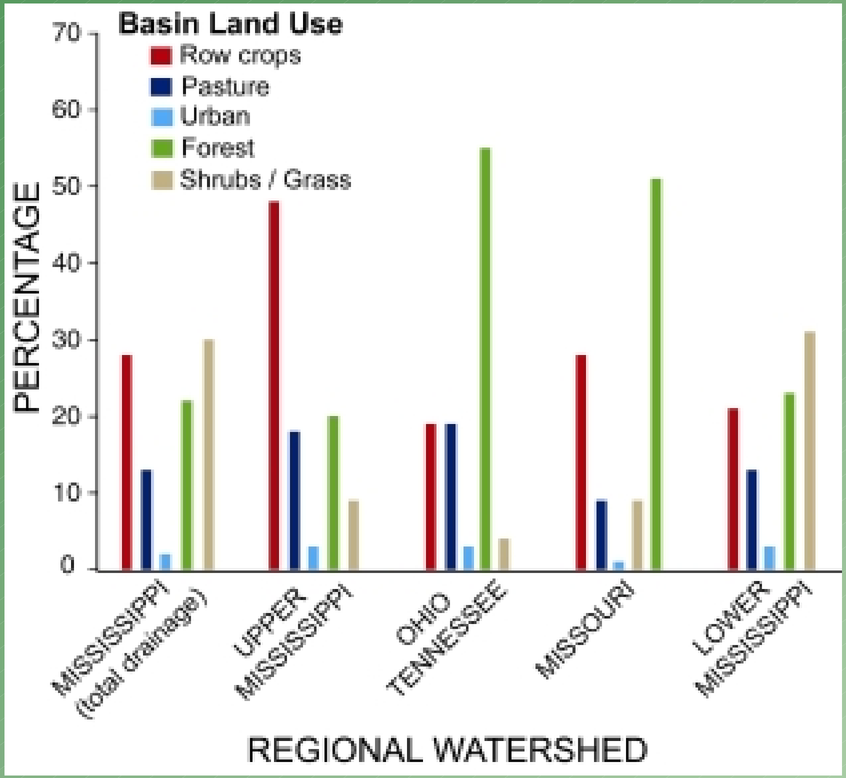

Sources of Total Phosphorus by Land Use
at 336 Stream Monitoring Stations
Land-Use vs. Intensive-Source Models
Intensive Model
Drainage Area
Land-Use Model
100
80
60
40
20
0
PERCENTAGE
Maximum
75th percentile
Median
25th percentile
Minimum
Cropland
(Fertilizer)
Pasture
(Livestock)
Urban
Sewered
Pop.
Forest
Shrub
Grass
LAND USE / SOURCE

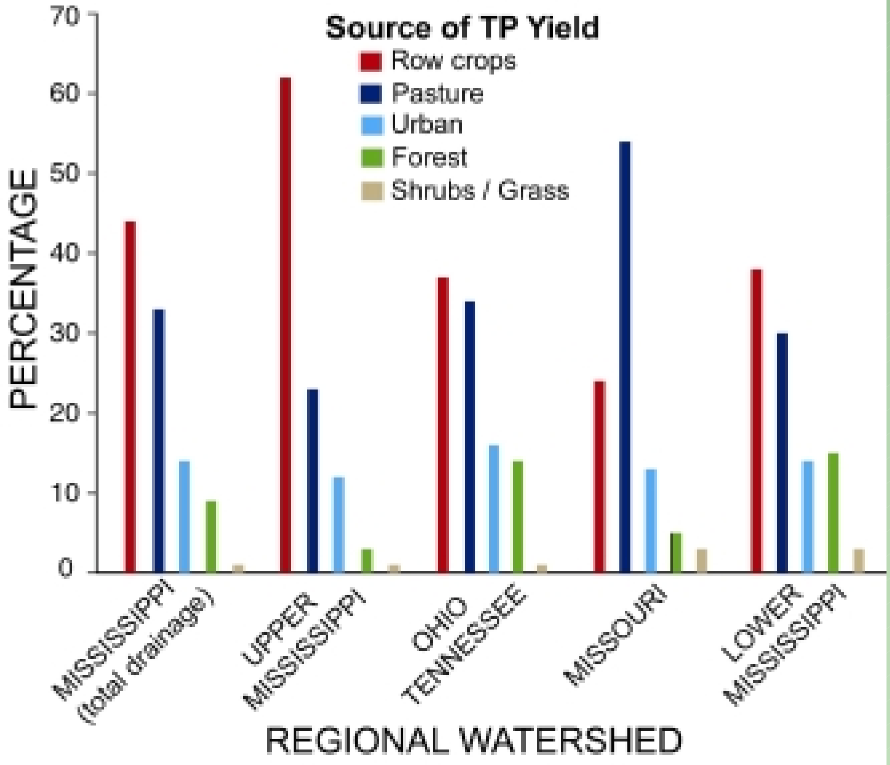
Mississippi River Basin
Total Phosphorus Yield



Mississippi River Basin

Watershed Land Use and Source Percentages





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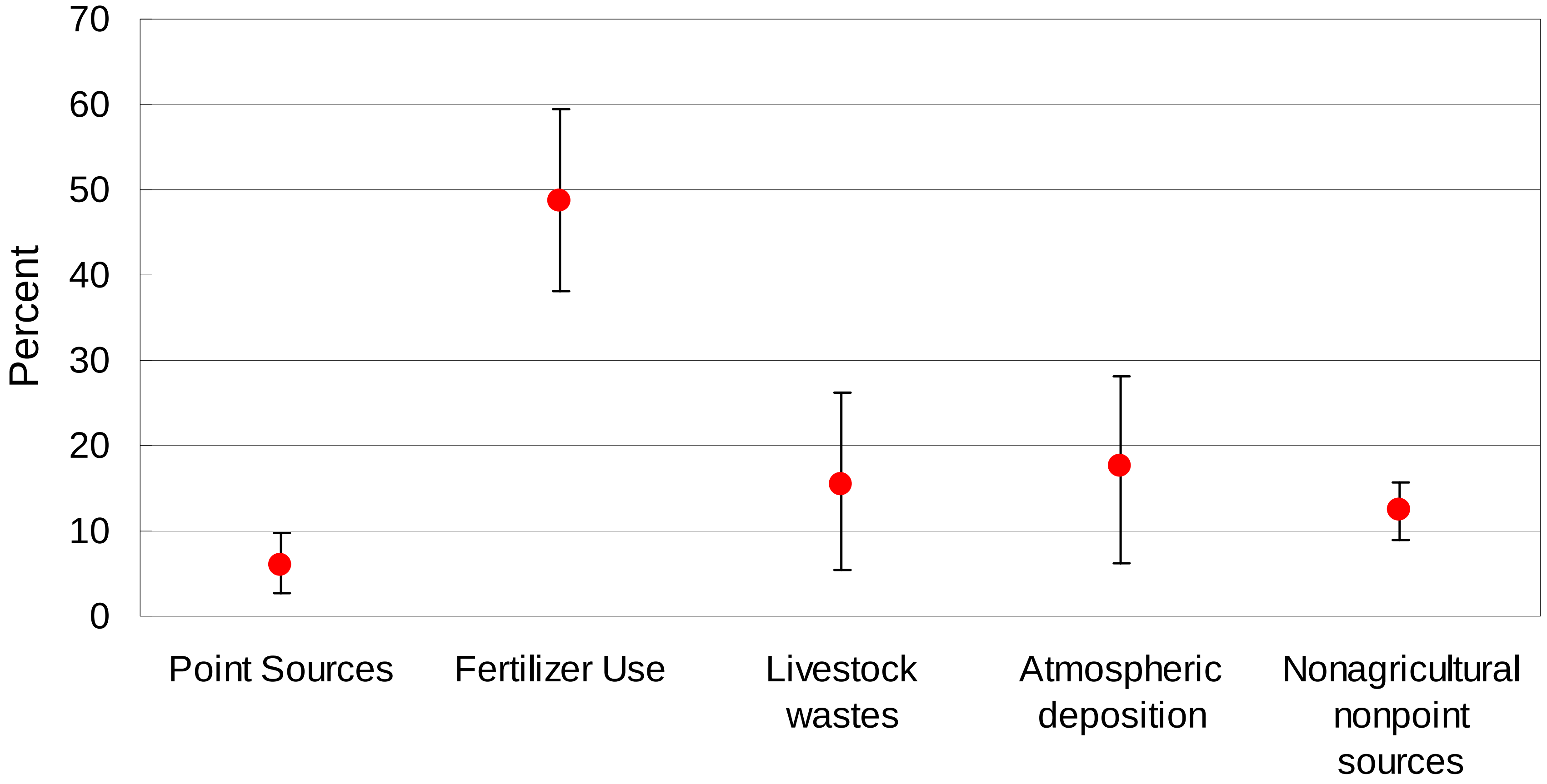
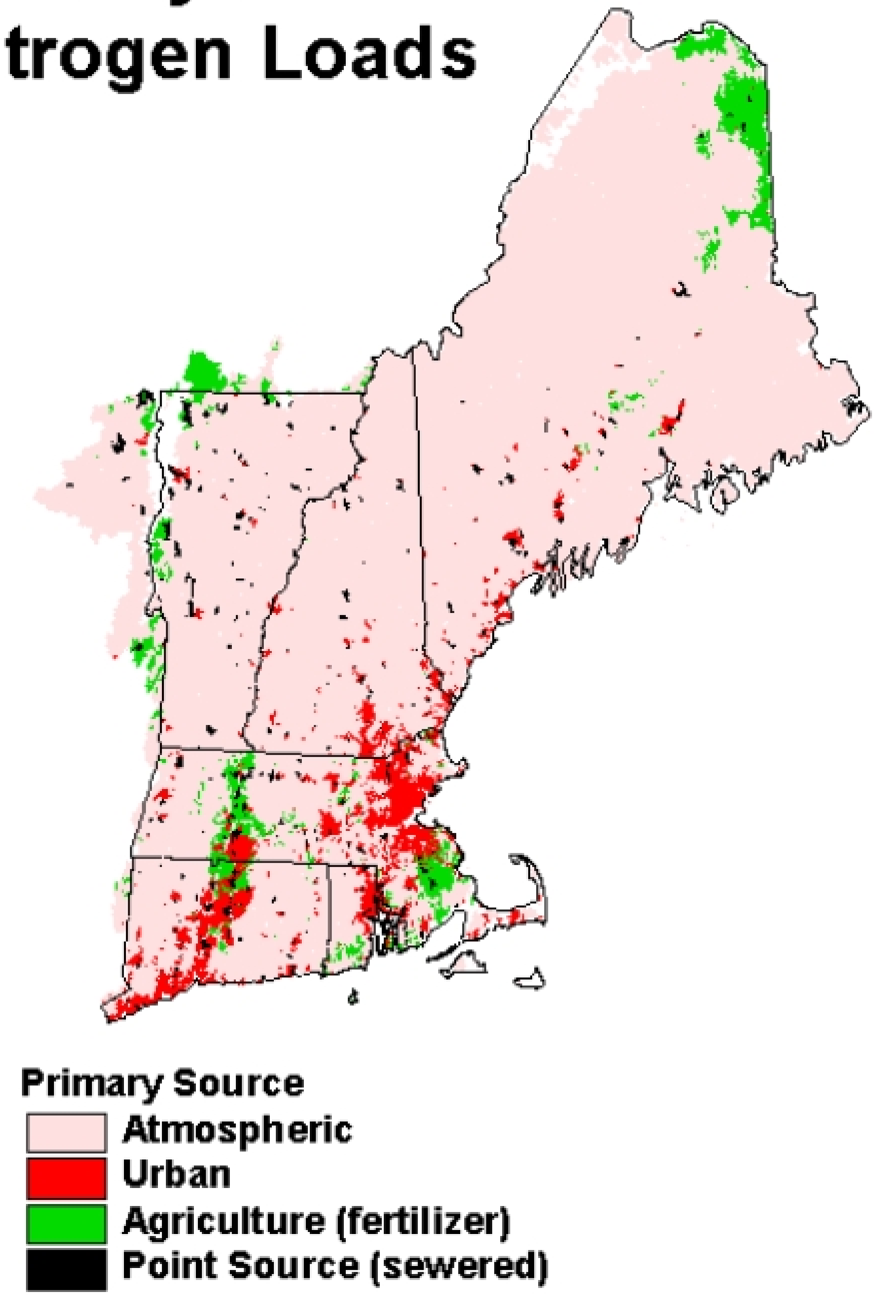
Contaminant sources and budgets Mississippi River basin

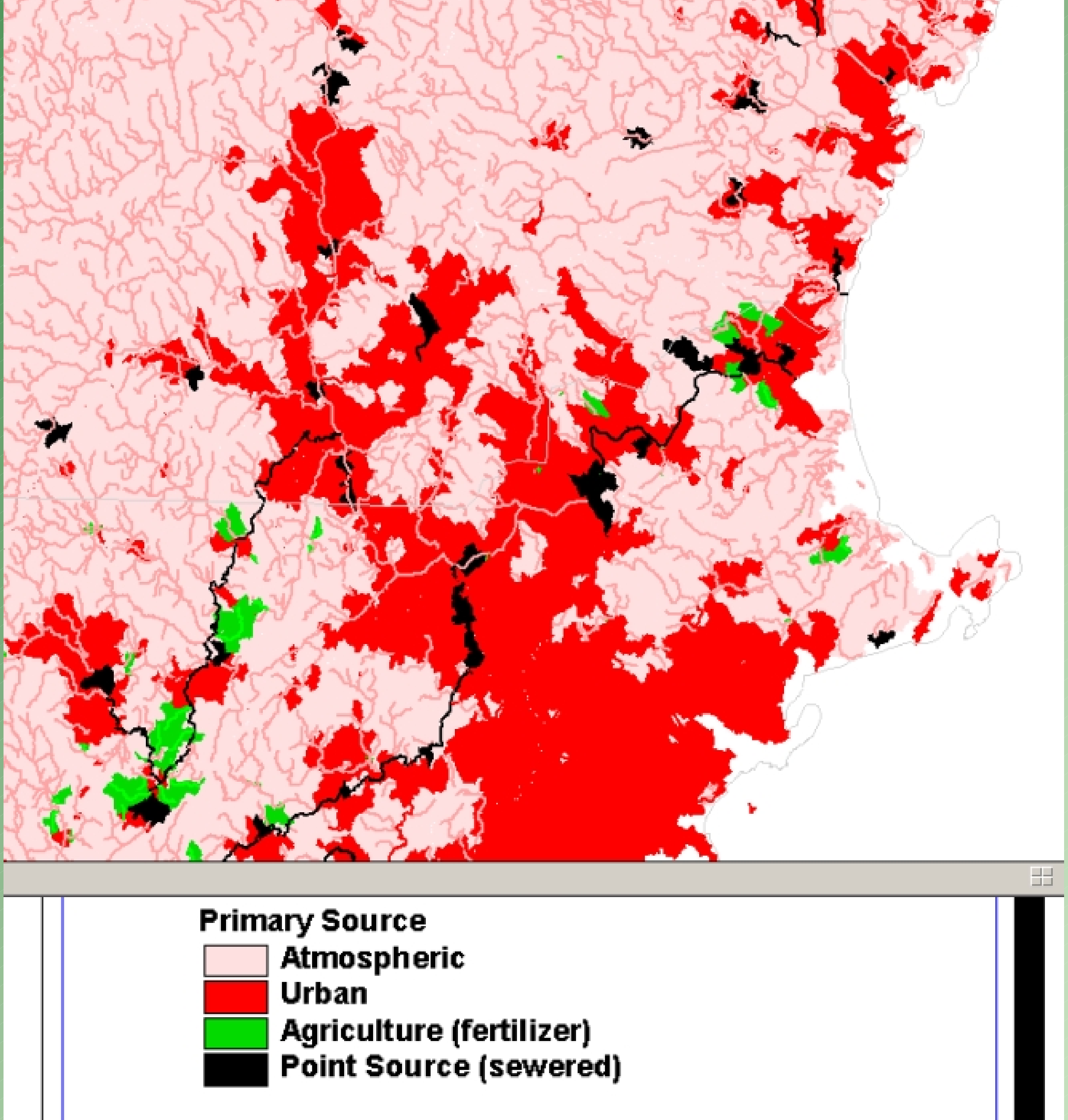
Sources of Total Nitrogen at the Mississippi River Outlet to the Gulf



Contaminant sources and budgets New England Coastal basins

Primary Sources of Nitrogen Loads





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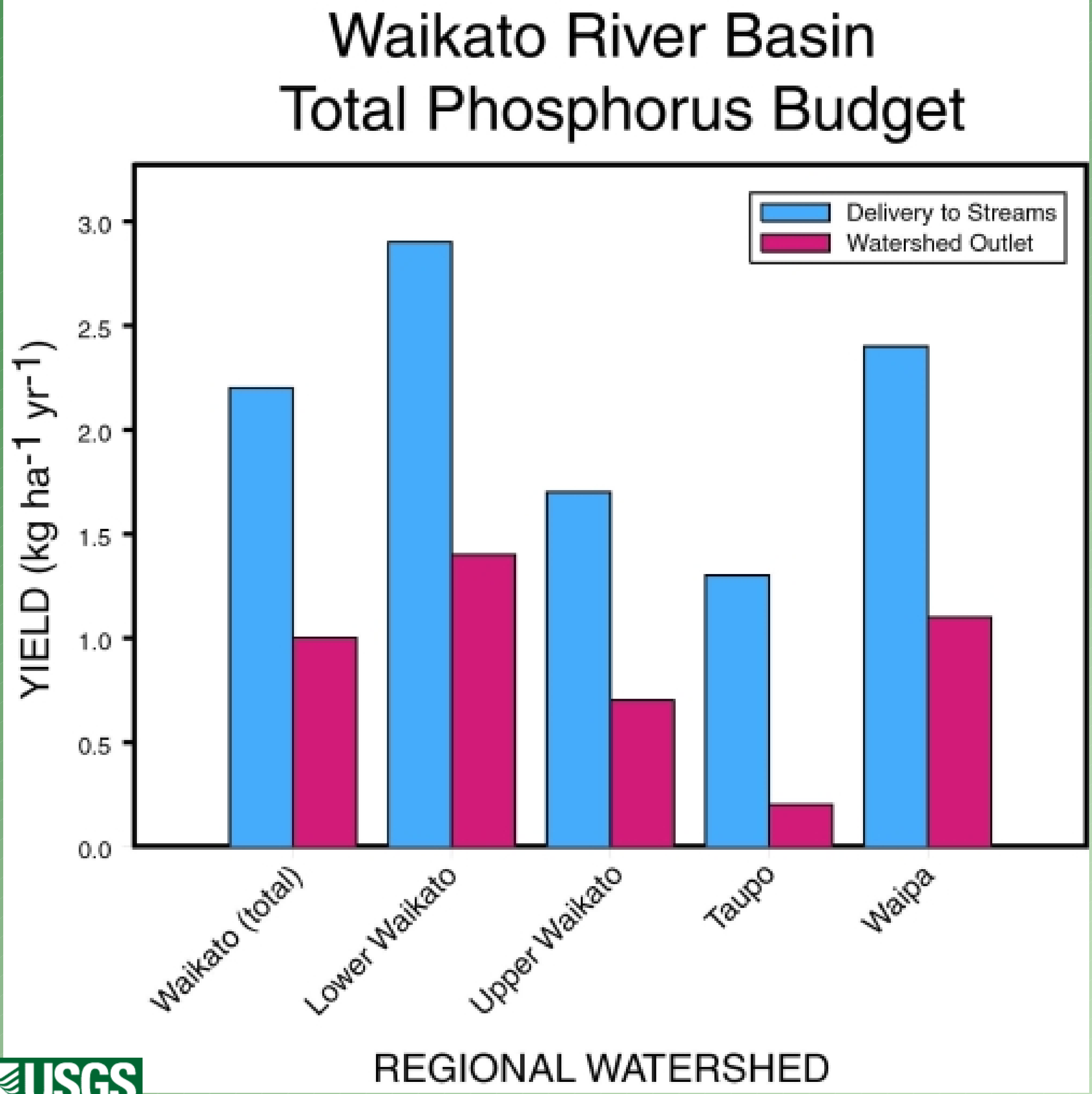
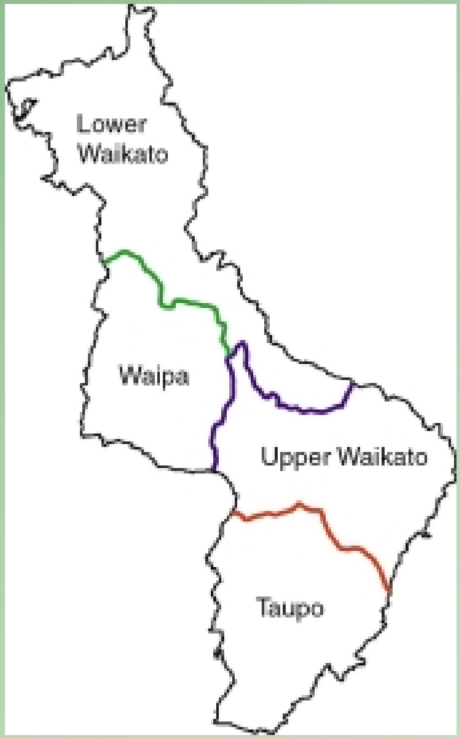
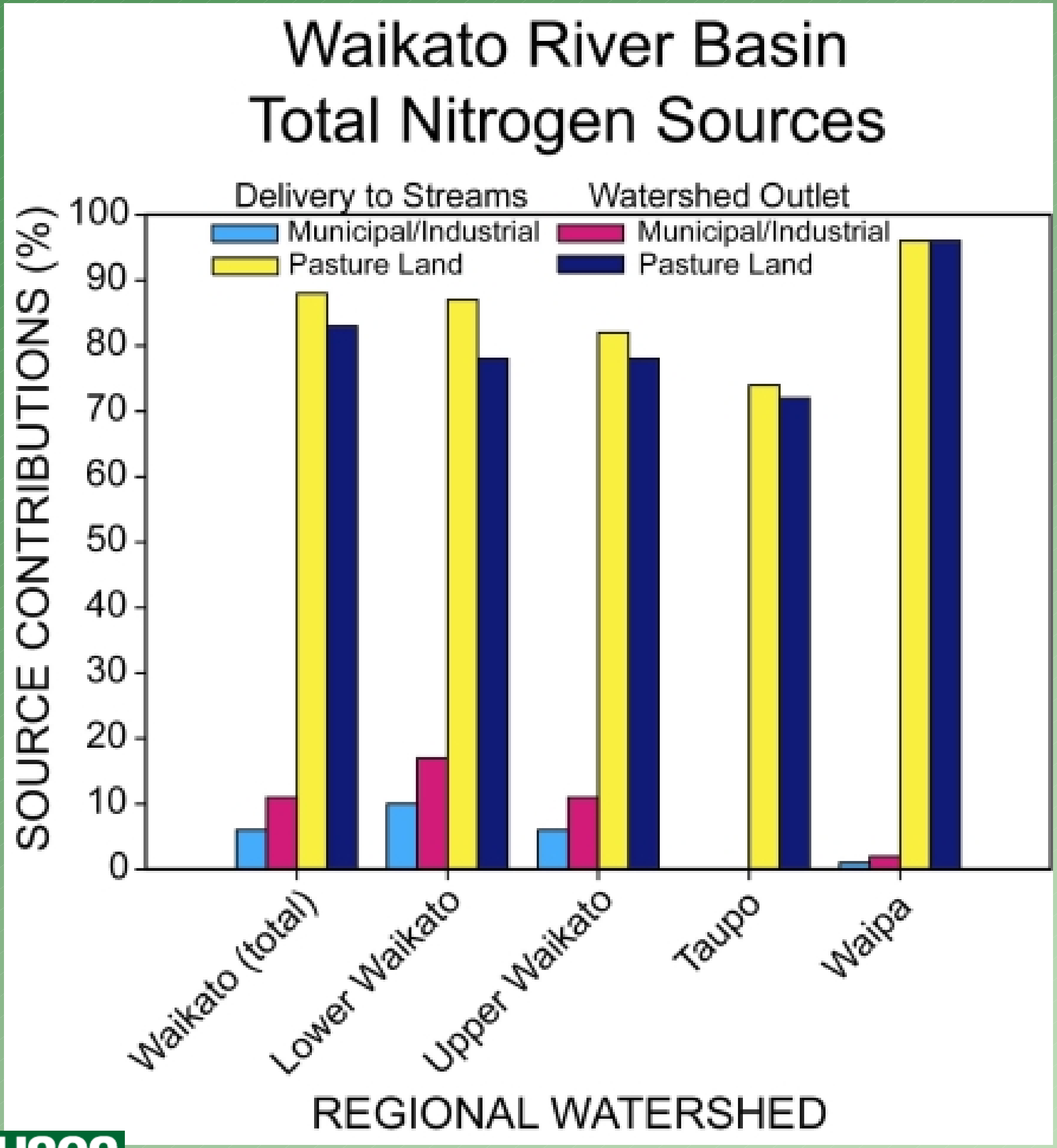
Contaminant sources and budgets New Zealand


Waikato River Basin
Total Phosphorus Budget
Delivery to Streams
Watershed Outlet
YIELD (kg ha-1 yr-1)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Waikato (total)
Lower Waikato
Upper Waikato
Taupo
Waipa
REGIONAL WATERSHED

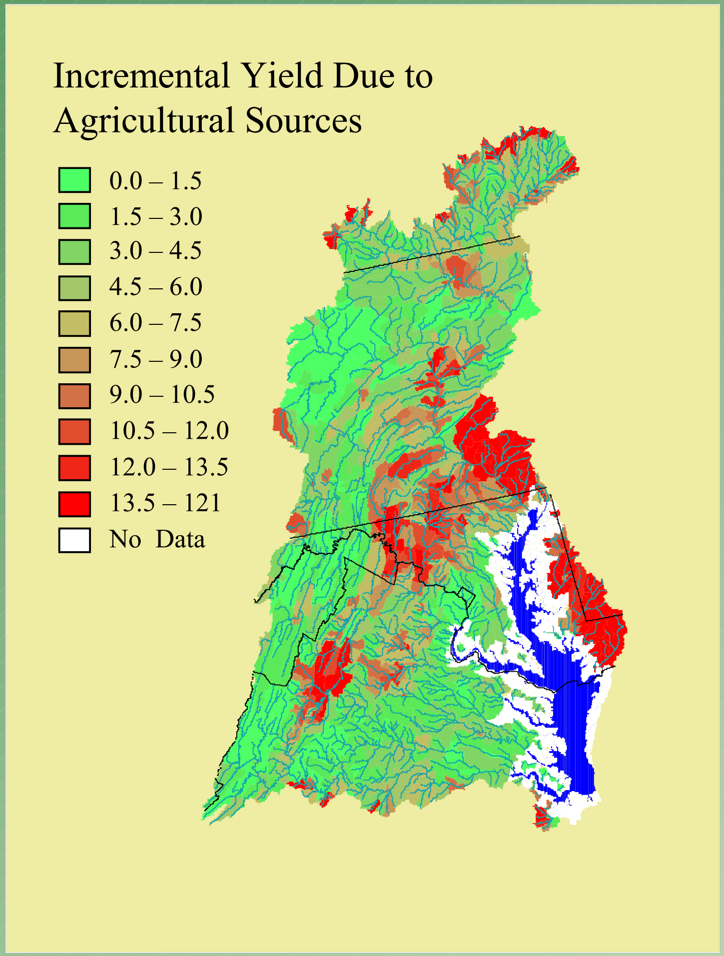

Lower Waikato
Waipa
Upper Waikato
Taupo

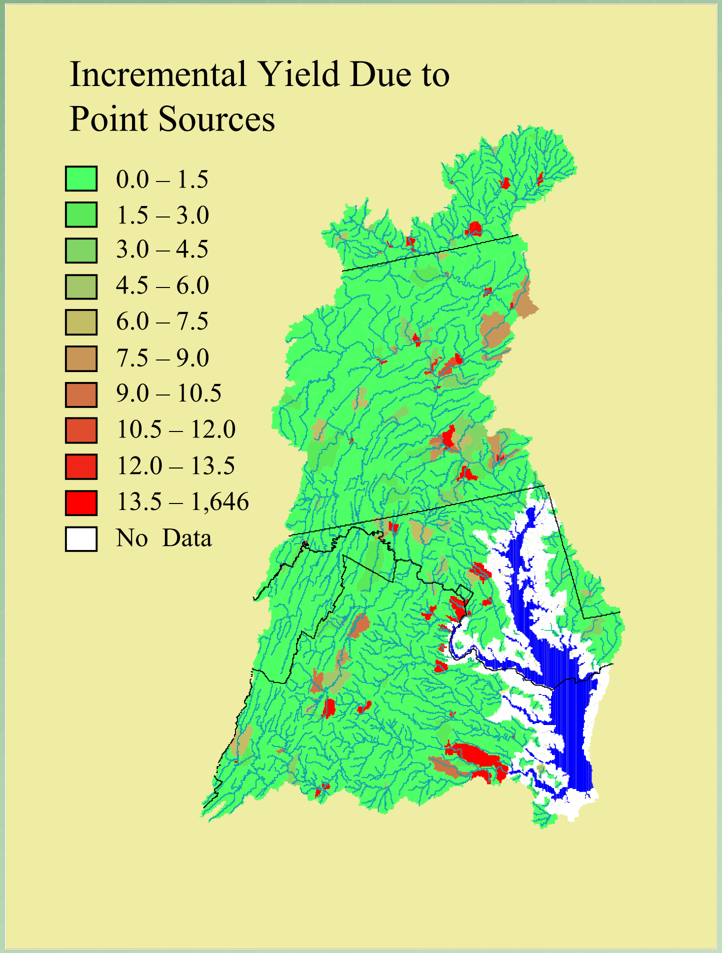

Waikato River Basin
Total Nitrogen Sources
Delivery to Streams
Watershed Outlet
Municipal/Industrial
Pasture Land
Municipal/Industrial
Pasture Land
SOURCE CONTRIBUTIONS (%)
100
90
80
70
60
50
40
30
20
10
0
Waikato (total)
Lower Waikato
Upper Waikato
Taupo
Waipa
REGIONAL WATERSHED


Lower Waikato
Waipa
Upper Waikato
Taupo

Contaminant sources and budgets Chesapeake Bay

Chesapeake Bay Watershed
Nitrogen Yield (kg/ha-yr)





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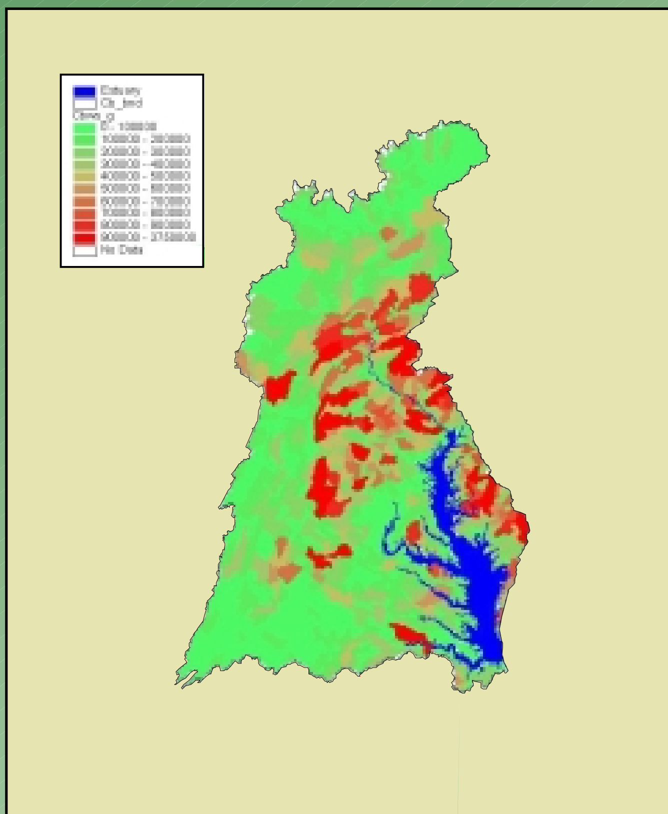
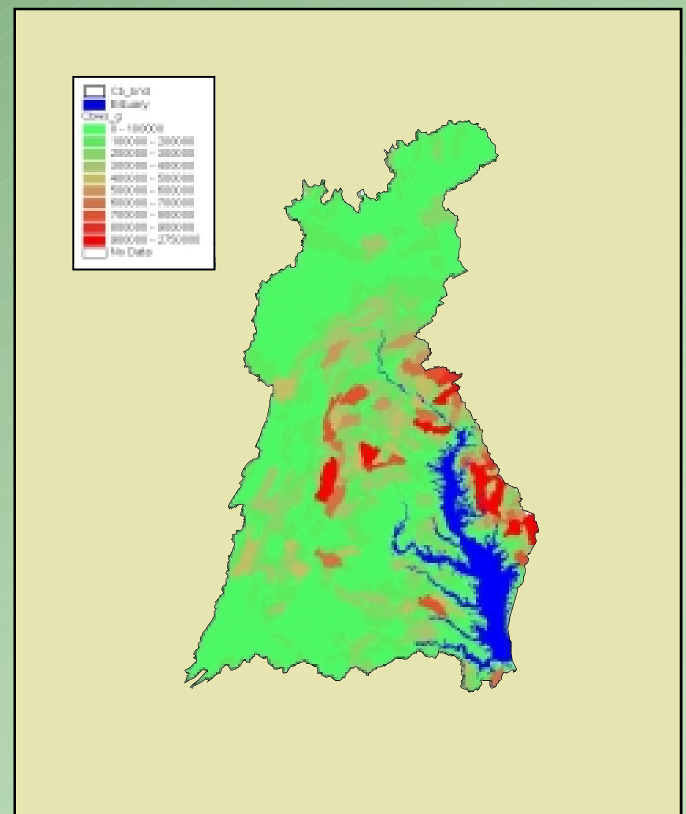
Fertilizer Nitrogen Data Sets

SPARROW Version I

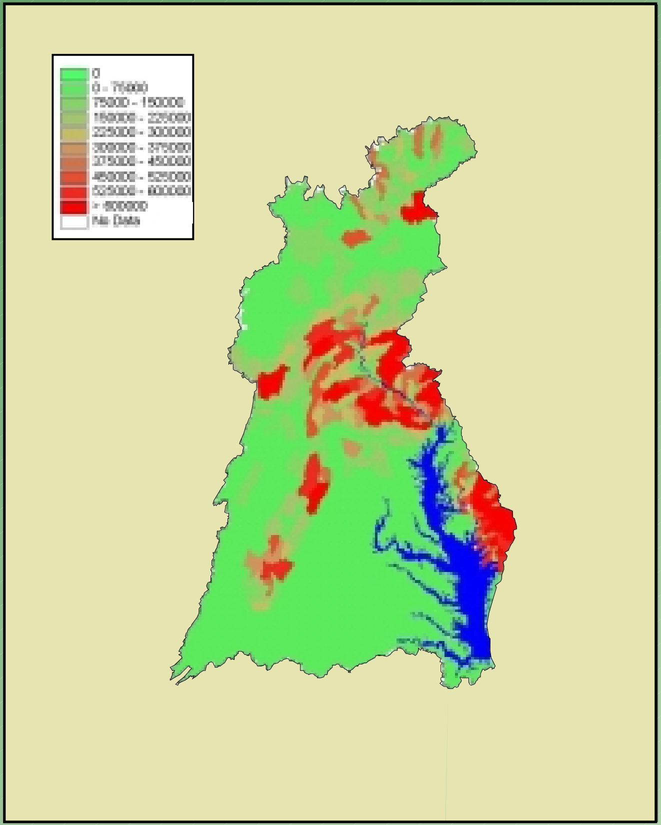


Fertilizer Sales

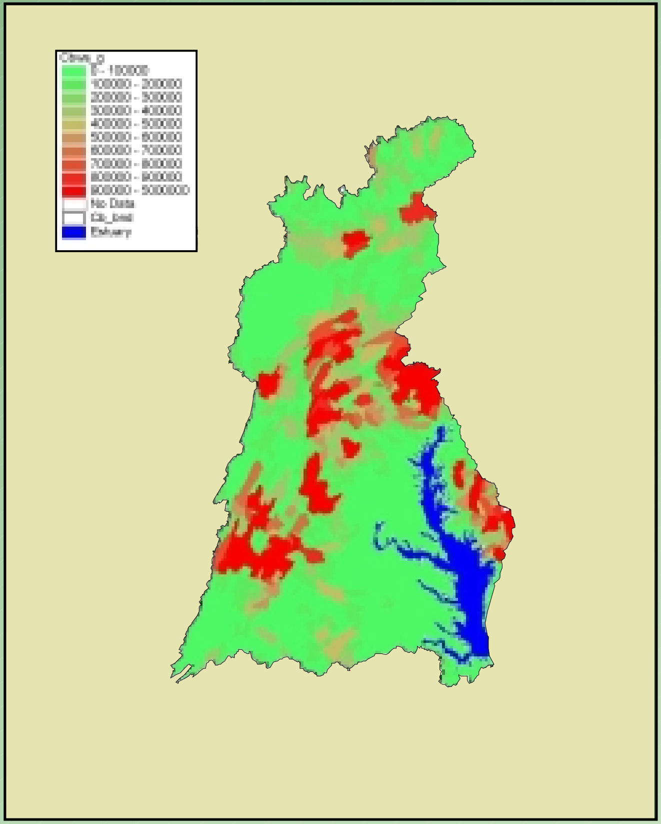


Manure Nitrogen Data Sets

SPARROW Version I

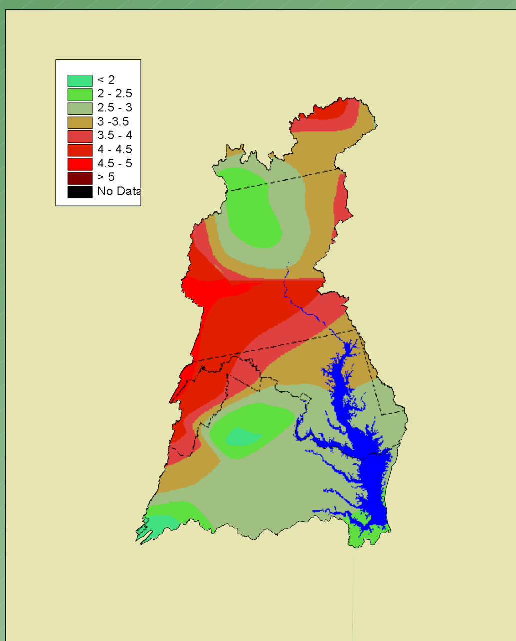


Census of Agriculture

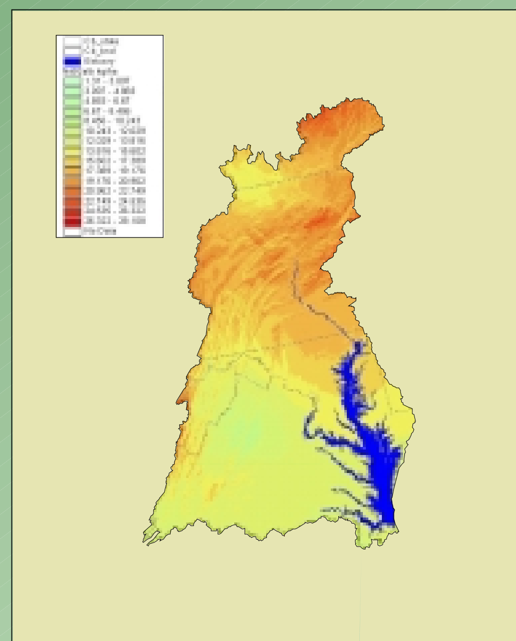


Nitrate Wet-Deposition Data Sets

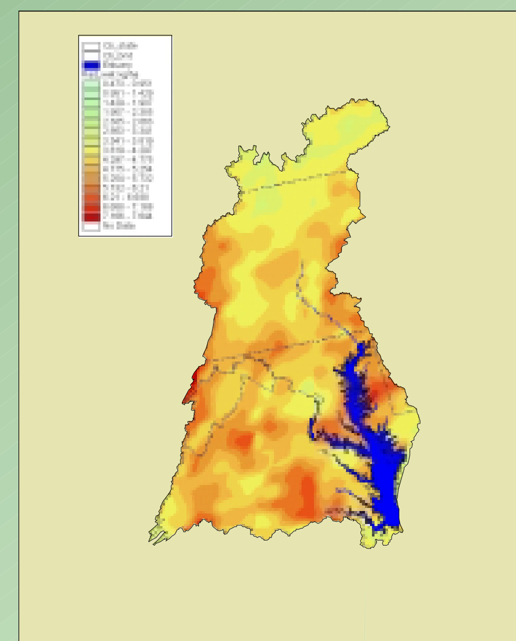
Interpolated
NADP
Data



Penn State
Extrapolated
NADP Data

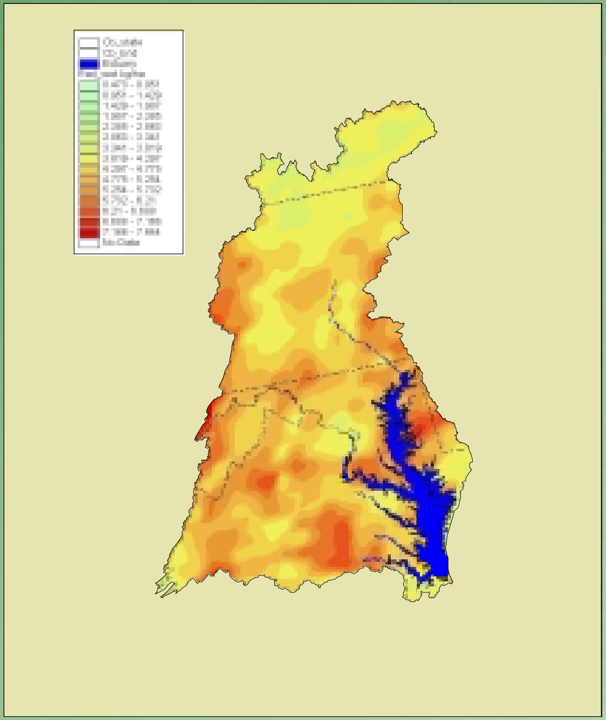


RADM
Model

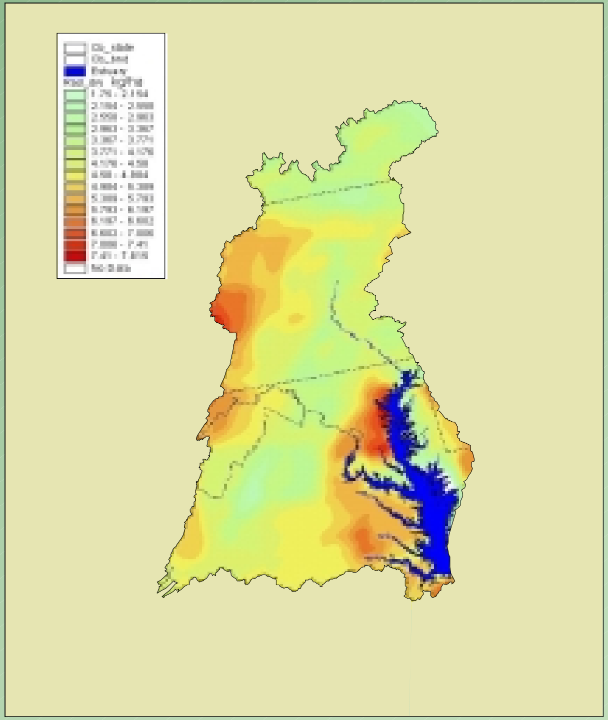


RADM Wet / Dry Nitrate Deposition Data Sets

Wet
Deposition



Dry
Deposition



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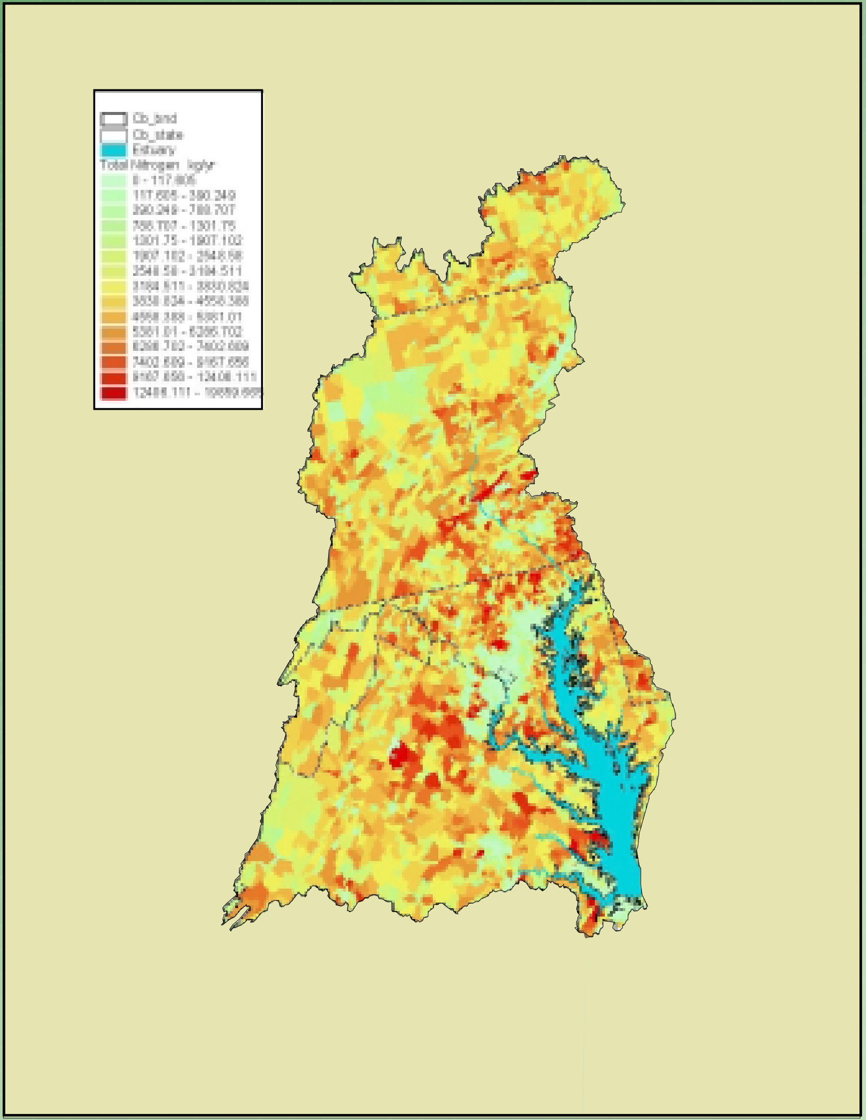
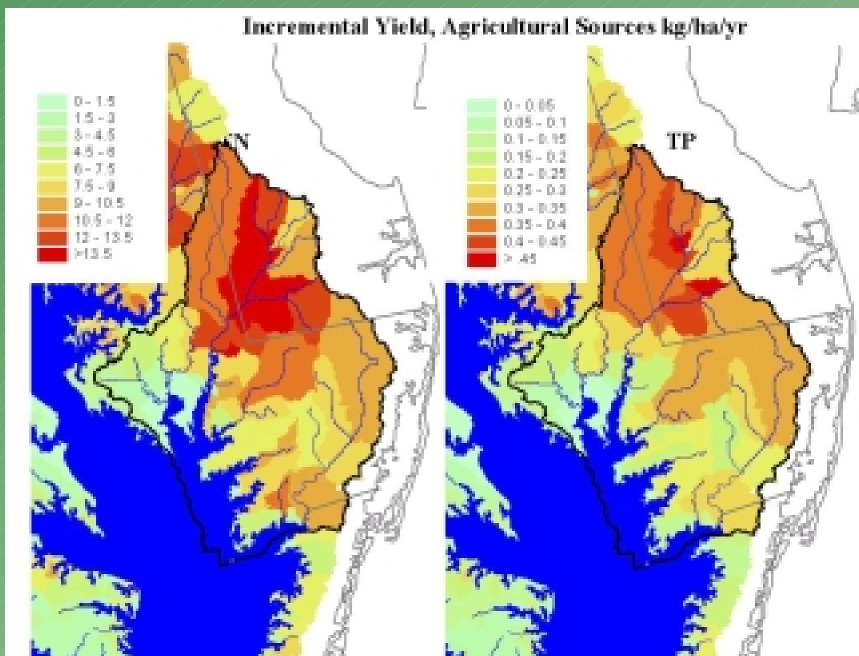
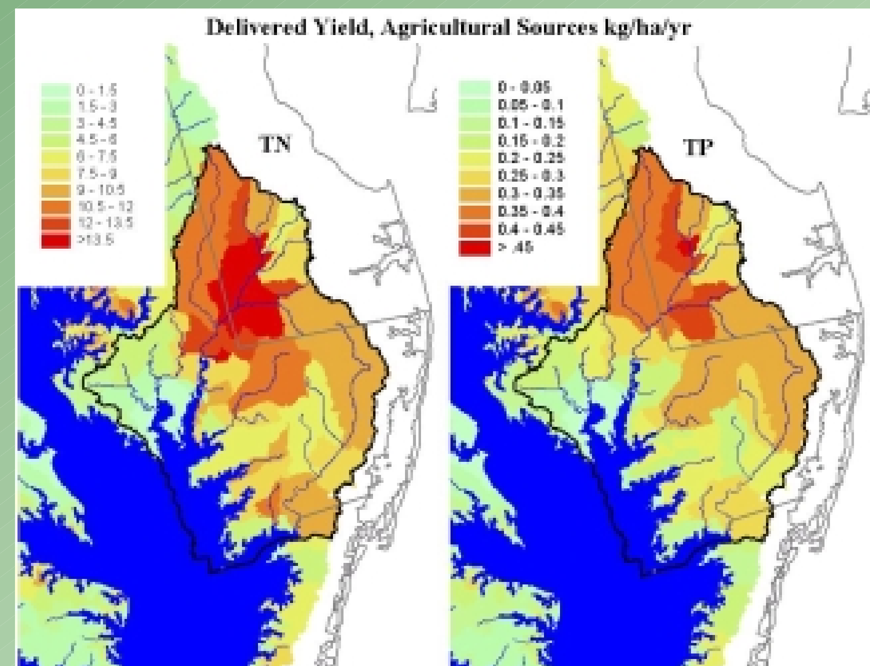
Septic Tank Loading Data

Derived
From
Census Information



Agricultural Yields





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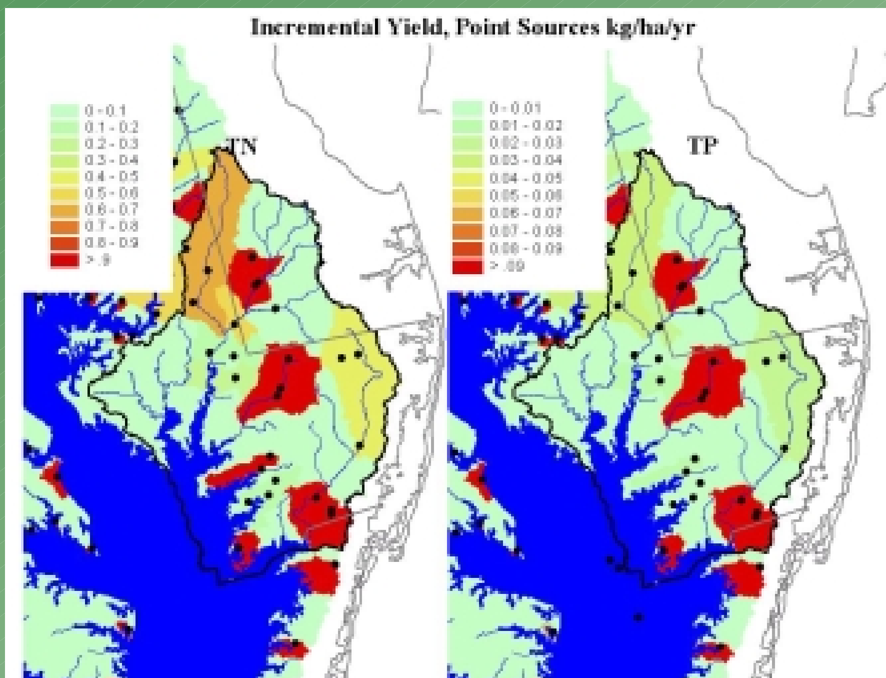
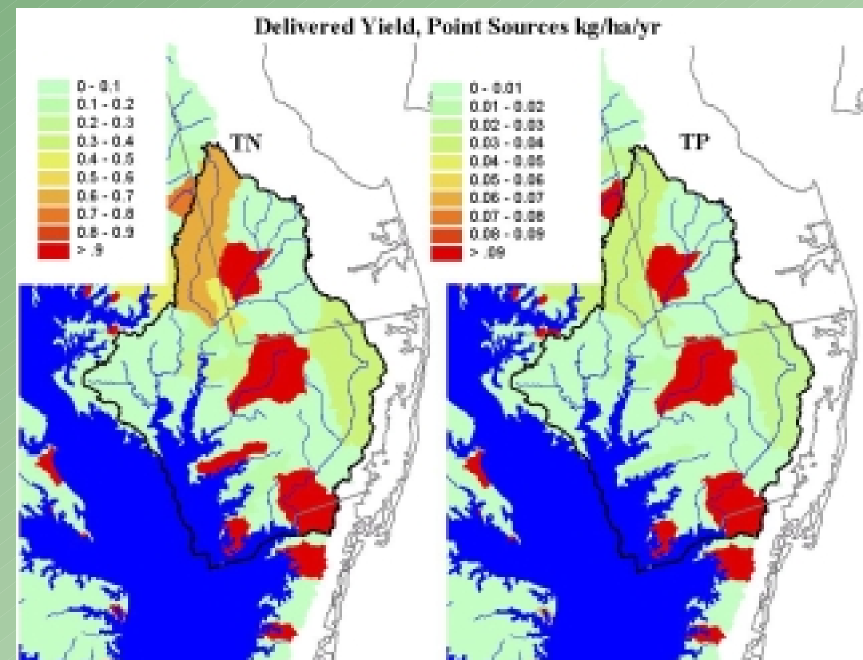
Point Source Yields





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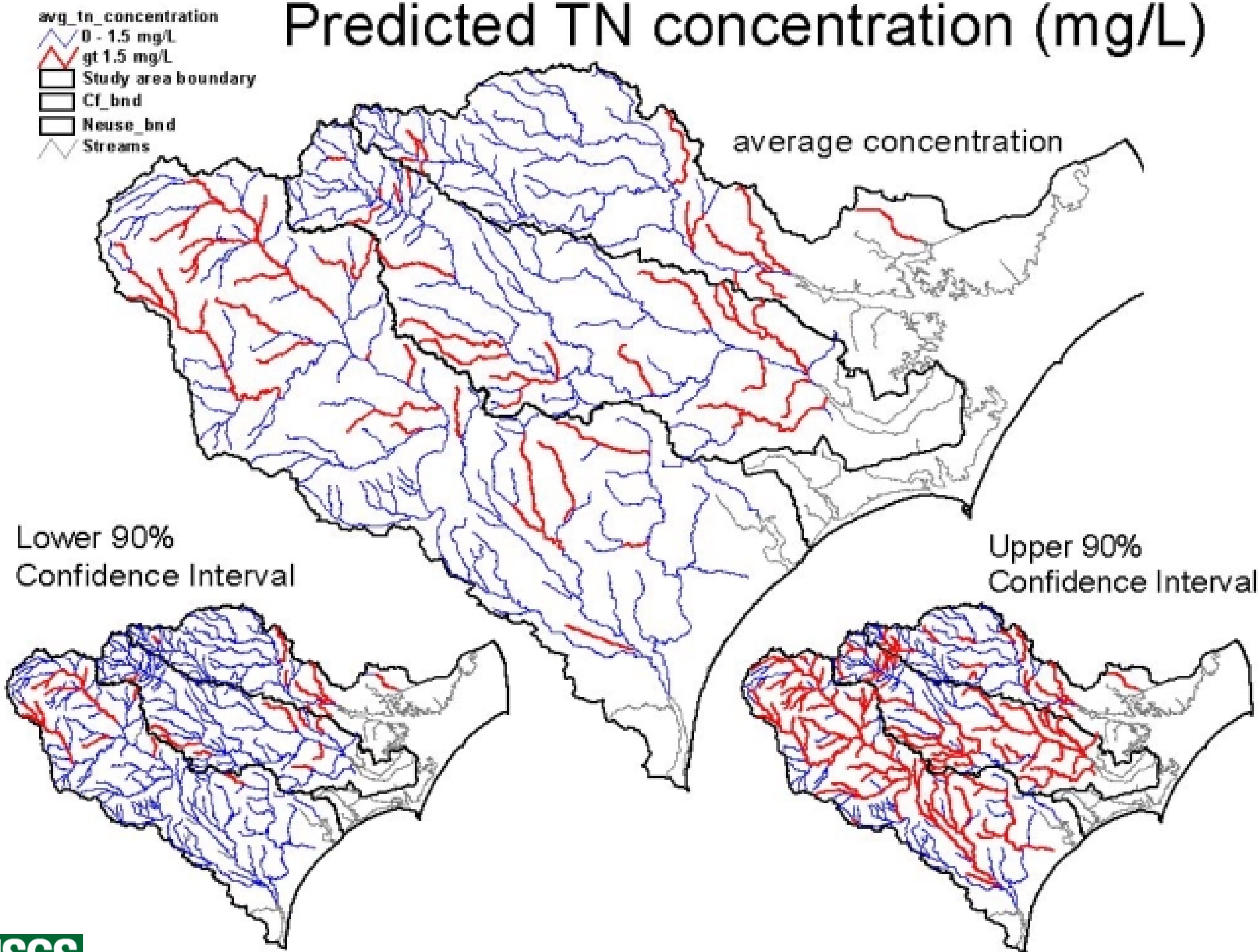
SPARROW Prediction Statistics
(Mean & Percentiles)

- Loads/yields exported from watersheds
- Contaminant losses in streams and reservoirs
- Loads/yields delivered to downstream sites (e.g., estuaries, reservoirs)
- Contaminant sources and budgets
- Concentration
- Probability of exceeding environmentally relevant load/concentration thresholds

Predicting concentration Coastal North Carolina

Predicted TN concentration (mg/L)



SPARROW Prediction Statistics
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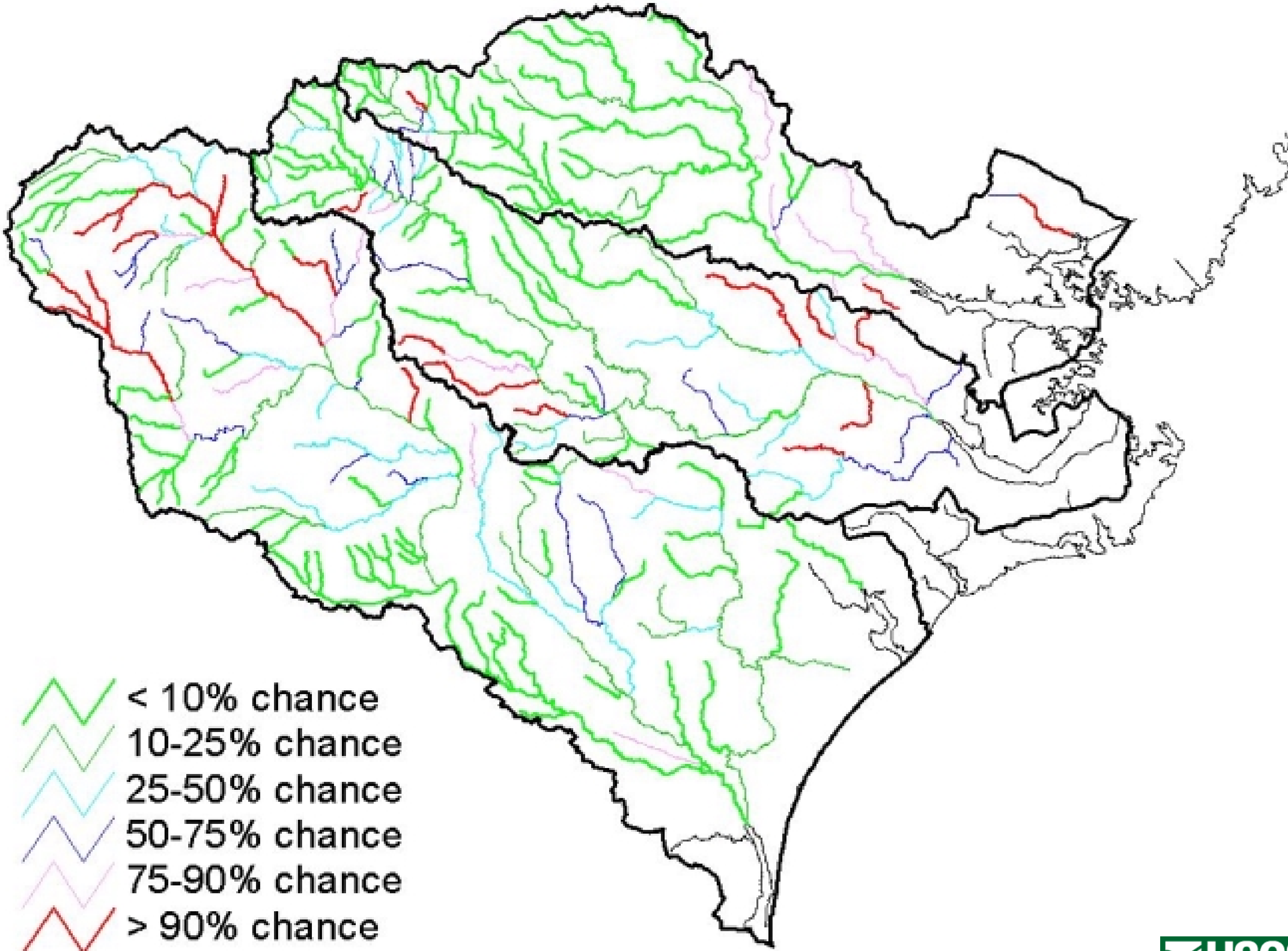
Probability of exceeding thresholds
Coastal North Carolina



< 10% chance
10-25% chance
25-50% chance
50-75% chance
75-90% chance
> 90% chance

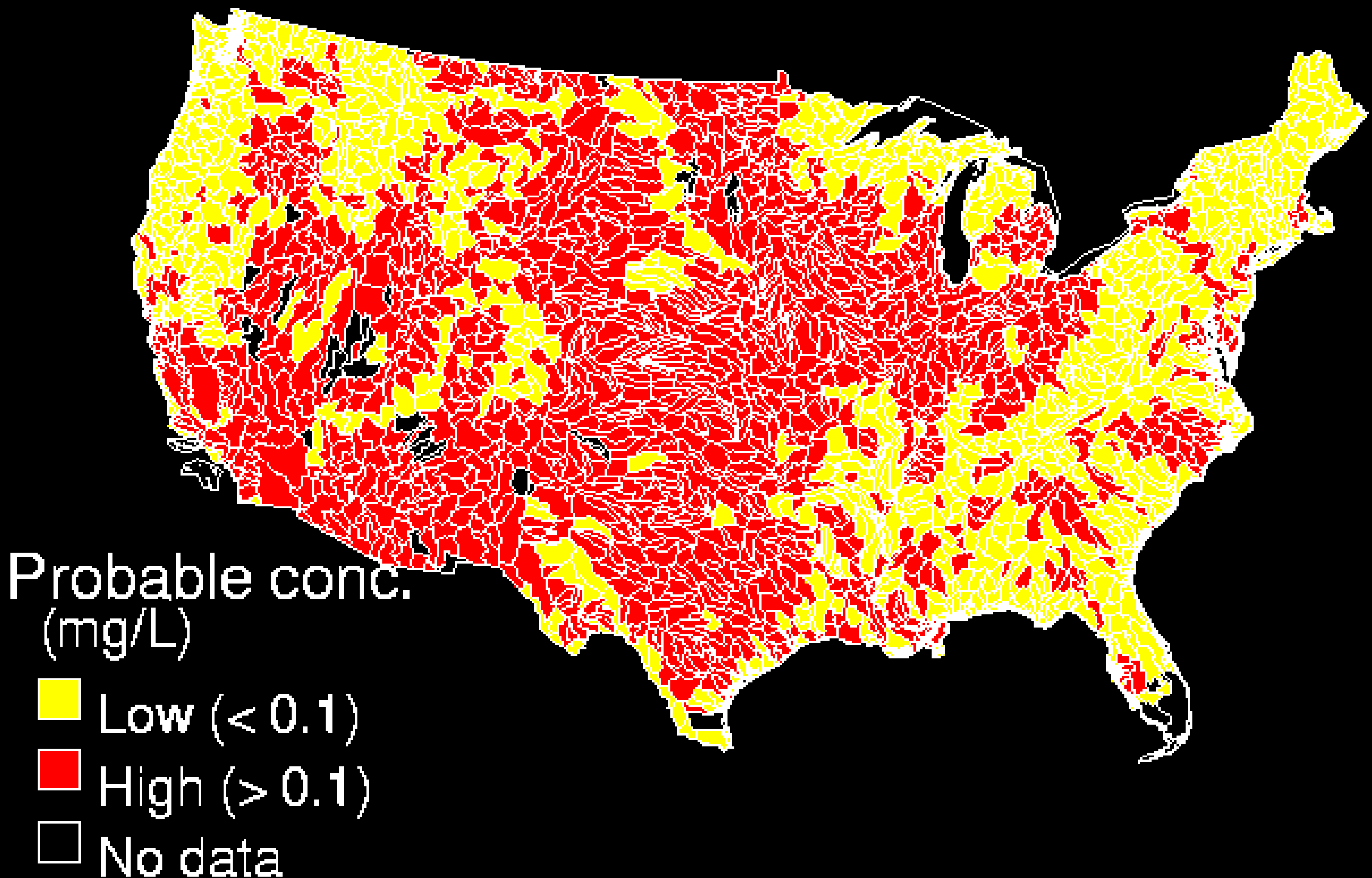
SPARROW Management Applications

- 305-b Water Quality Assessment
- TMDL
- Studying change over time
- Targeting of nutrient controls
- Natural background
- Atmospheric deposition
- Drinking water quality
- Network design

<u>305b Water Quality Assesssment</u>

Estimating proportion of watersheds satisfying water quality criteria

CLASSIFICATION OF PREDICTED TP CONCENTRATION IN HUCs



Proportion of Hydrologic Units with TP Concentration < 0.1 mg/L TP Criterion

Region	No. HUCs	Proportion	Lower 90% CI	Upper 90% CI
U.S.	2048	0.39	0.37	0.42
New England	52	0.84	0.75	0.90
Mid. Atlantic	88	0.60	0.53	0.67
Upper Miss.	131	0.19	0.15	0.23

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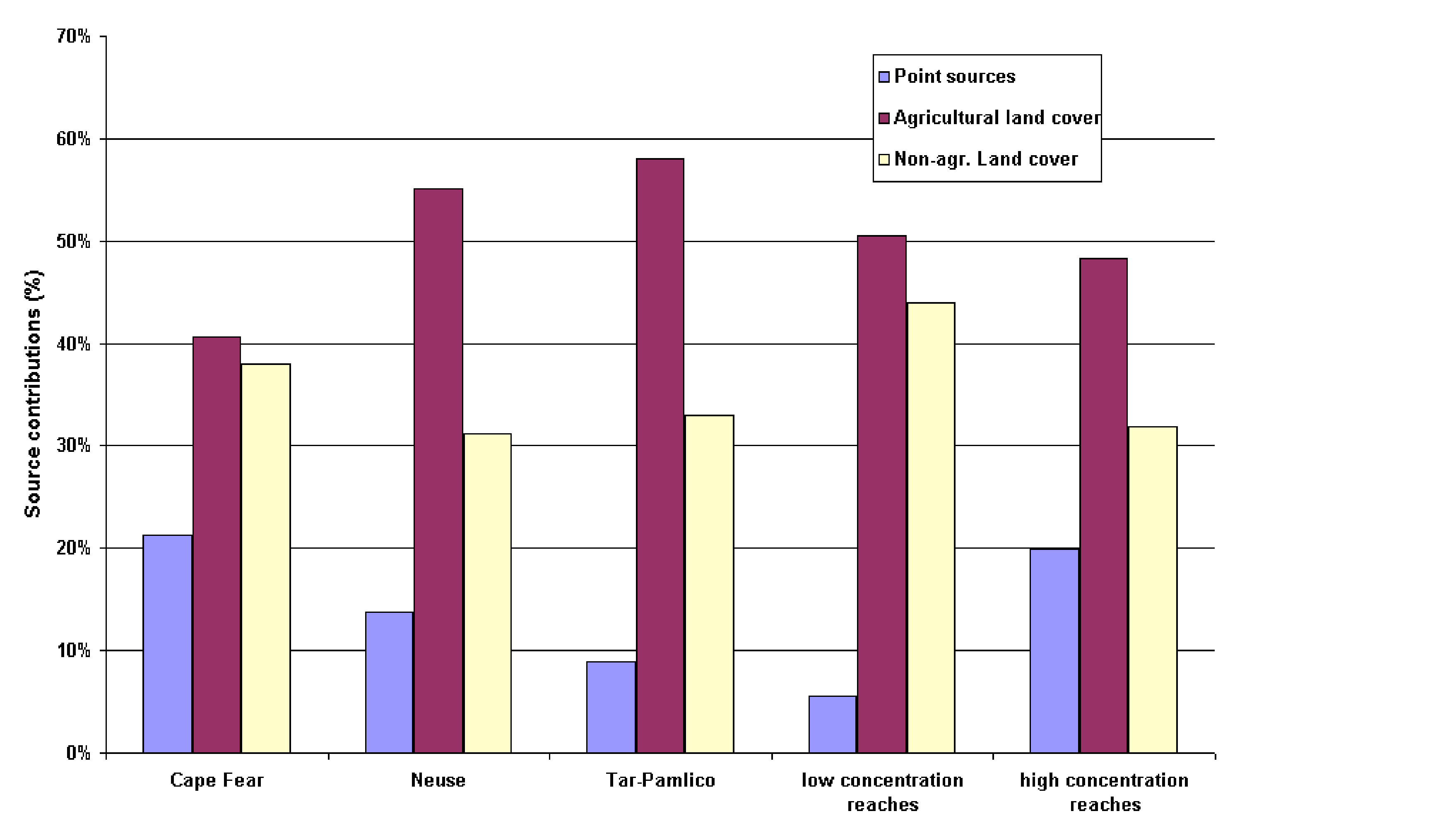
SPARROW Management Applications

- 305-b Water Quality Assessment
- TMDL
- Studying change over time
- Targeting of nutrient controls
- Natural background
- Atmospheric deposition
- Drinking water quality
- Network design

TMDL
Baseline TN loads
Coastal North Carolina

Understanding baseline nitrogen source contributions



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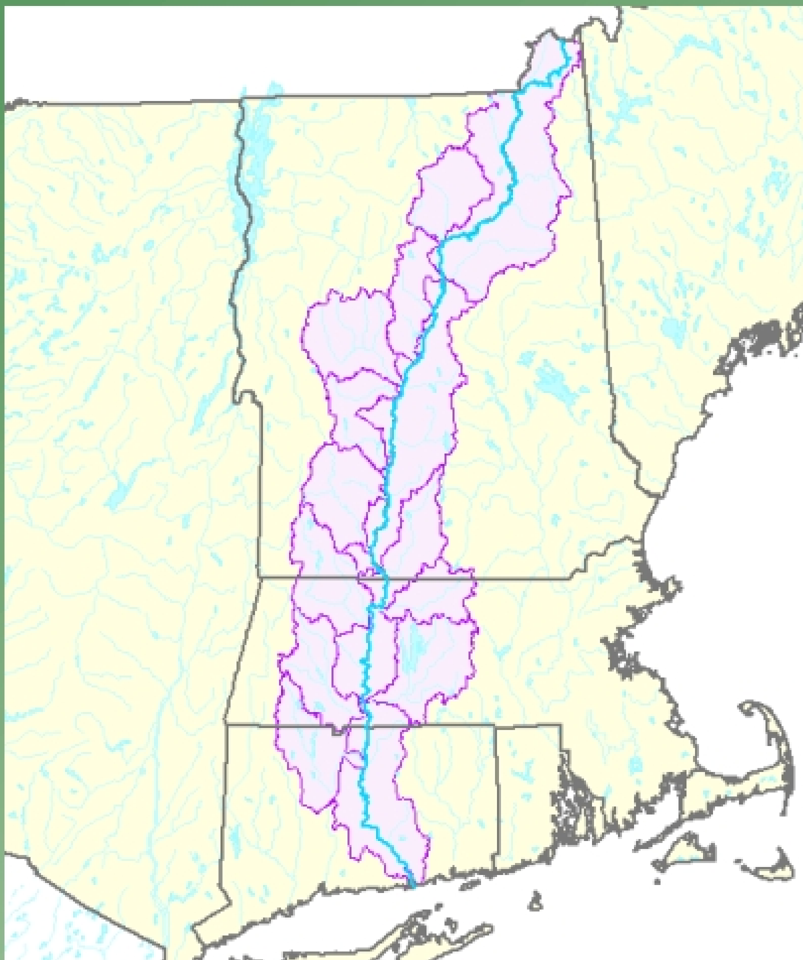
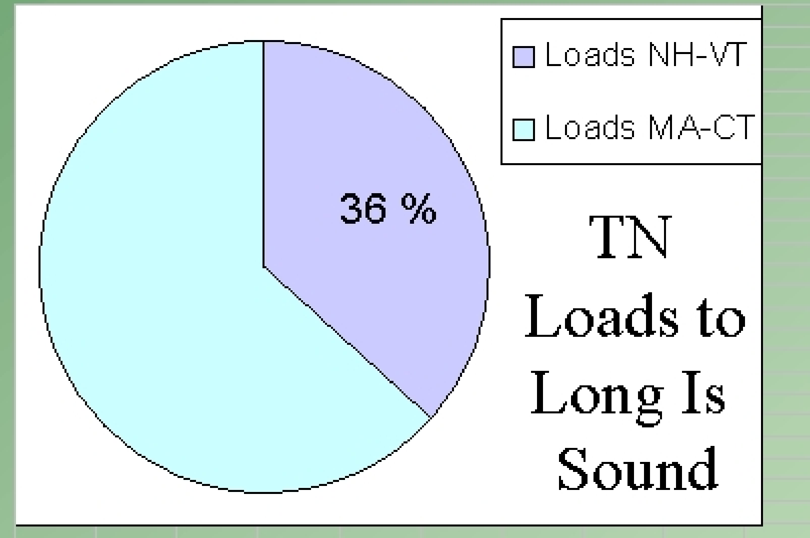
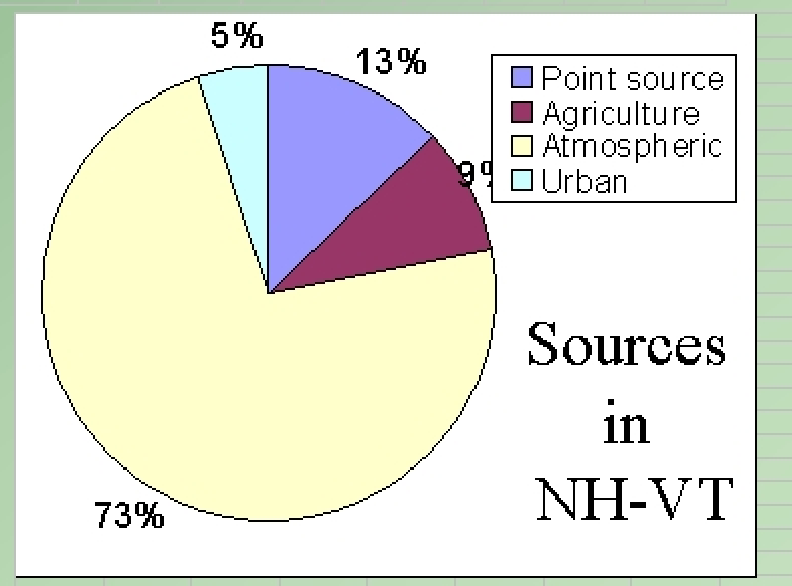
TMDL
Baseline TN loads
New England Coastal basins

Utility of New England SPARROW Model Results for TMDL Applications –
An Example from the Connecticut River Basin



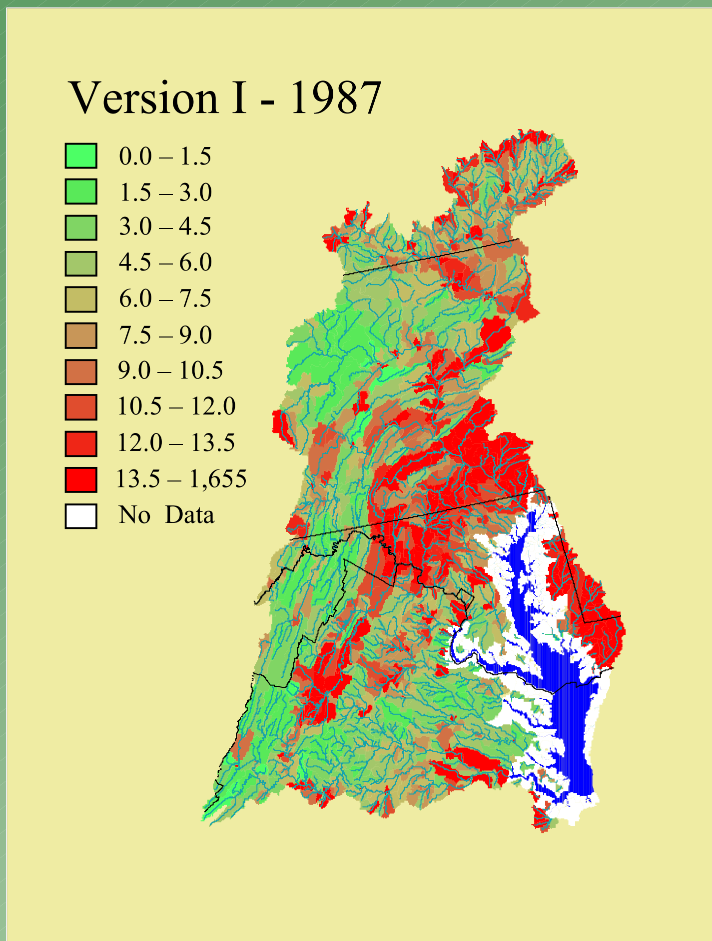


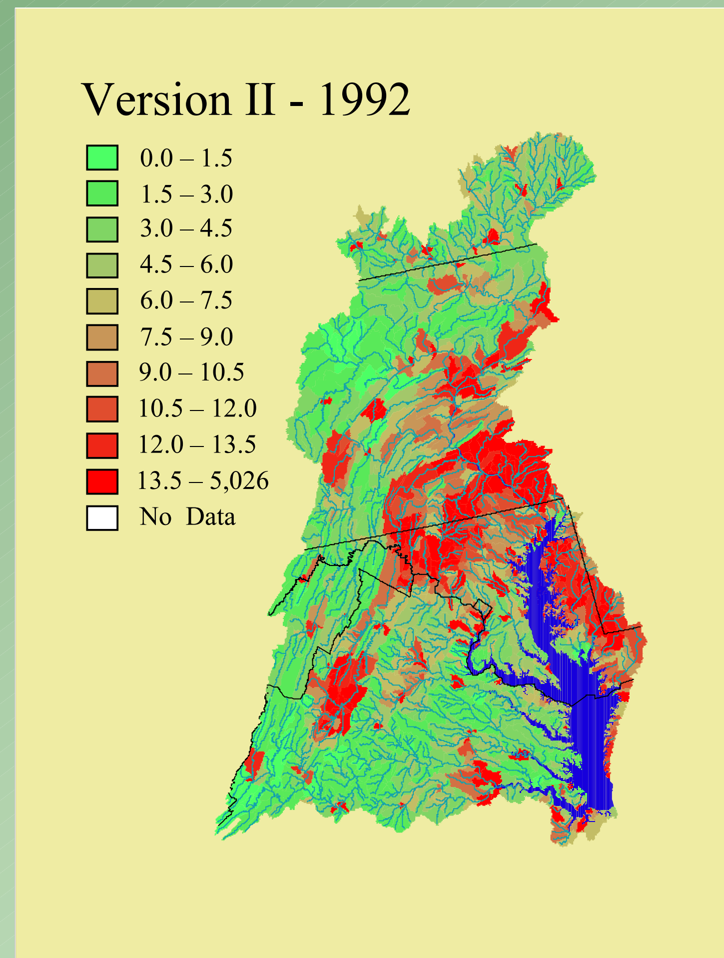


SPARROW Management Applications

- TMDL
- Studying change over time
- Targeting of nutrient controls
- Natural background
- Atmospheric deposition
- Drinking water quality
- Network design

Chesapeake Bay Watershed
Total Nitrogen – Incremental Yield (kg/ha-yr)





SPARROW Management Applications

- TMDL
- Studying change over time
- Targeting of nutrient controls
- Natural background
- Atmospheric deposition
- Drinking water quality
- Network design

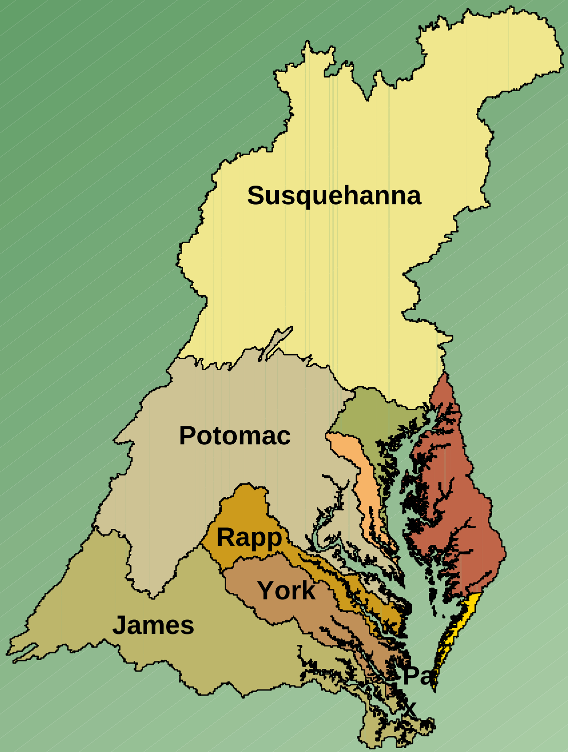
Chesapeake Bay

Establishing Nutrient-Load Allocations

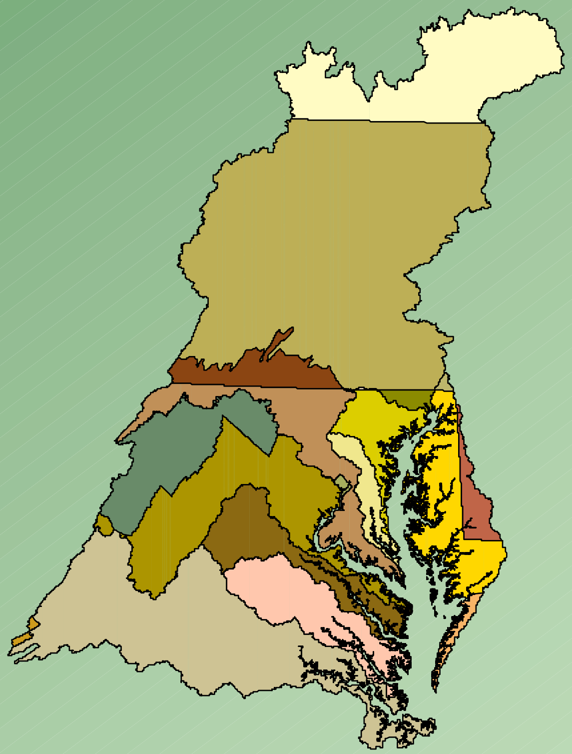
Joint Application of SPARROW and HSPF

Setting Load Allocations

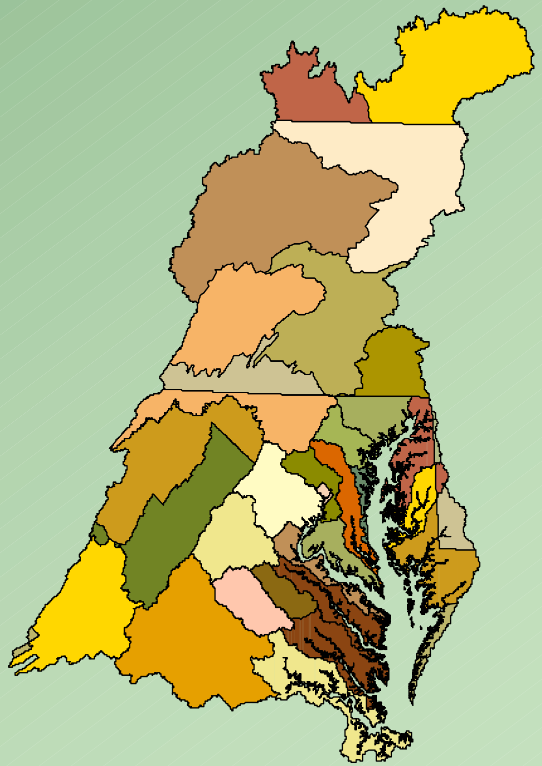
Allocate Loading Caps to the 9 Major Basins



Further allocate cap load responsibilities to each state



Further allocate major tributary basin load caps to 37 state defined sub-basins



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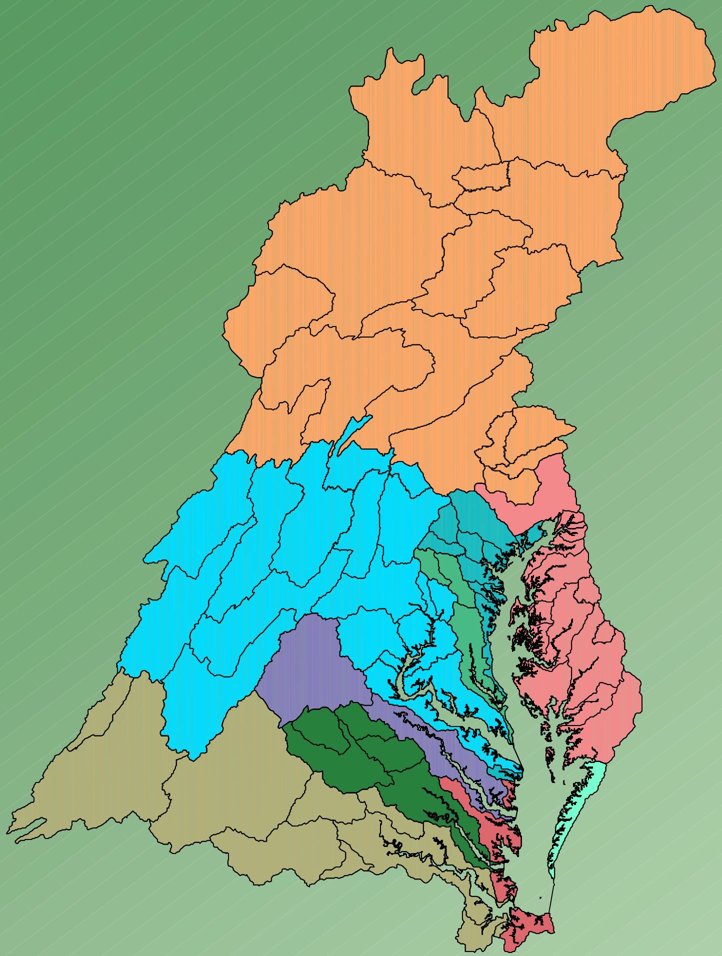
Chesapeake Bay Program Watershed Model - HSPF



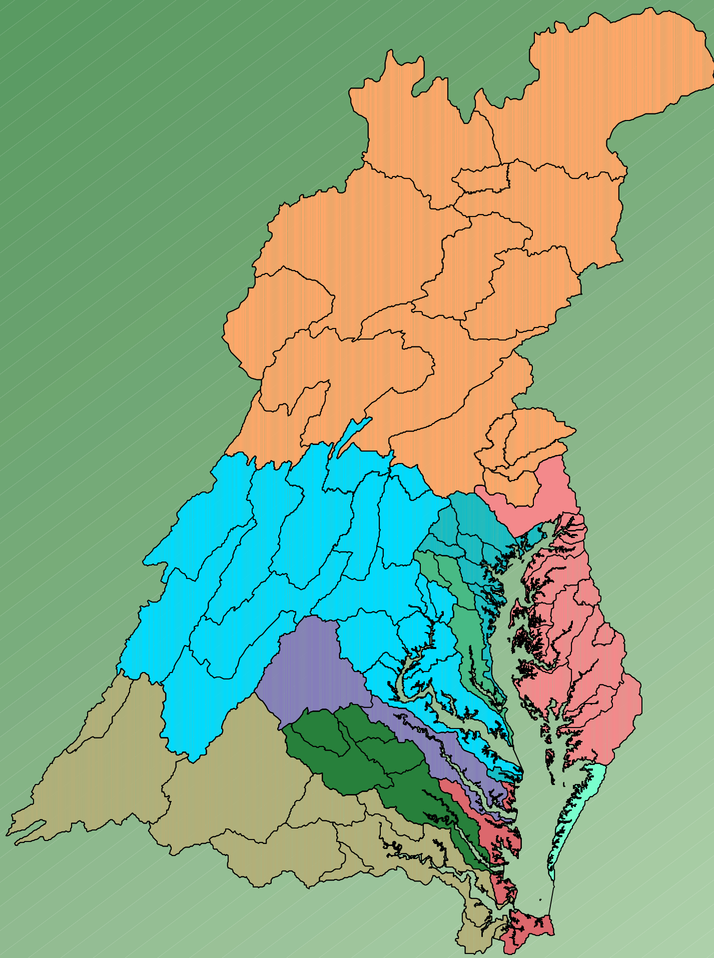
Description of Modeling Framework

- Deterministic
- Process Oriented
- Spatially and Temporally Defined
- Temporally Detailed

Chesapeake Bay Application

- Deliver Nutrient and Sediment Loads to Separate Estuarine Water-Quality Model
- Establish Nutrient and Sediment Allocations by Drainage Area and Land Use Type
- Develop Stream Load Predictions for Various Scenarios of Management-Practice Implementation

Chesapeake Bay Program Watershed Model - HSPF



Limitations of Modeling Framework

- Over-Parameterized
- Labor-Intensive Manual Calibration
- Spatial Coarseness
- No Systematic Method of Assessing Error

Why is HSPF Necessary?

- Designed for Studying the Relations of Human Activities on the Landscape to Nutrient and Sediment Loads of Streams
- Allows Simulation of "ALL" Human Activities that Affect Stream Loads
- Allows the Simulation of Management-Practices to Assess Their Effectiveness and Optimize the Efficient Use of Resources

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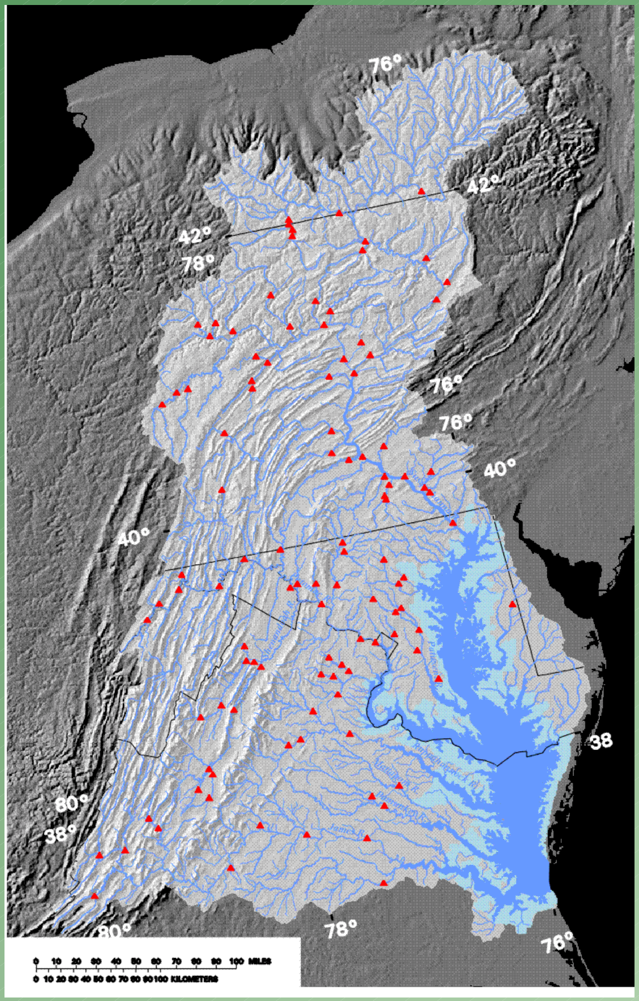
U.S. Geological Survey - SPARROW



Description of Modeling Framework

- Statistical
- Designed to Define Spatial Relations Between Contaminant Sources and Stream Loads
- Spatially Defined Only
- Spatially Detailed

Chesapeake Bay Application

- Provide Framework for Relating Various Types of Detailed Geographic Data to Stream Nutrient Loads
- Statistically Identify the Environmental Factors that are Most Closely Related to Stream Loads
- Provide Spatially Detailed Estimates of Stream Load for Targeting and Other Uses

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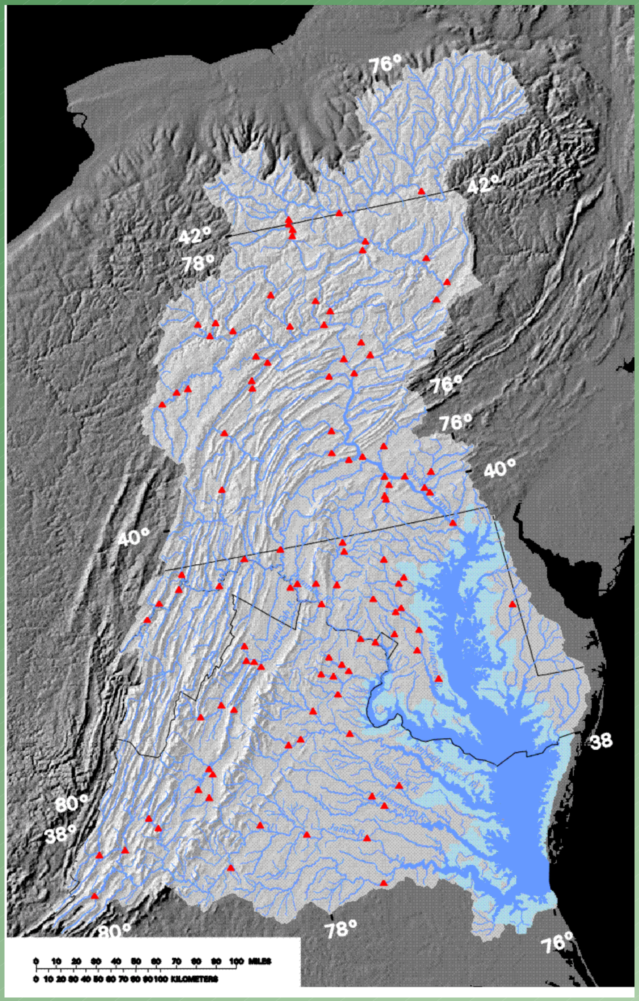
U.S. Geological Survey - SPARROW



Limitations of SPARROW

- No Temporal Definition
- Extremely Data Intensive
- Predictions Based Only on Statistically Significant Variables

Why is SPARROW Useful?

- Provides a Statistical Basis for Watershed Modeling and Estimates of Error Associated With All Predictions
- Provides Spatially Detailed Predictions of Stream Loads
- Provides a Basis for Spatially Detailed Assessment of the Relative Importance of Factors Affecting Stream Loads

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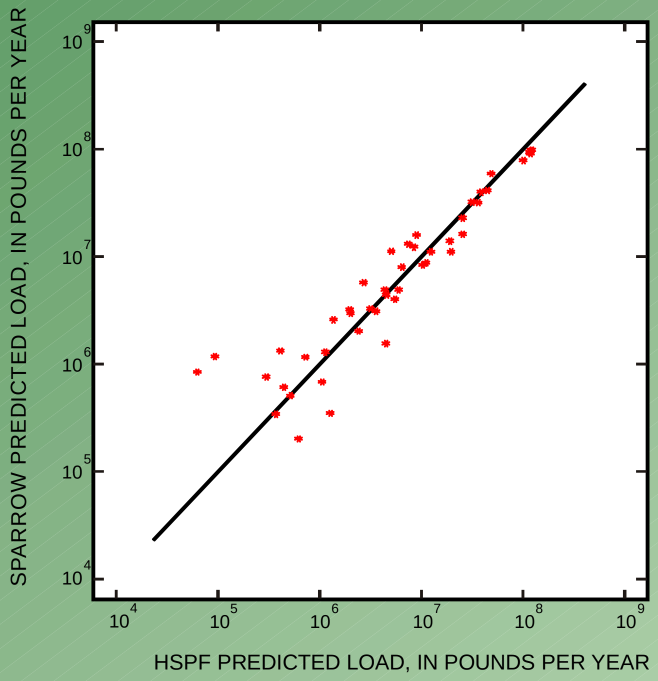
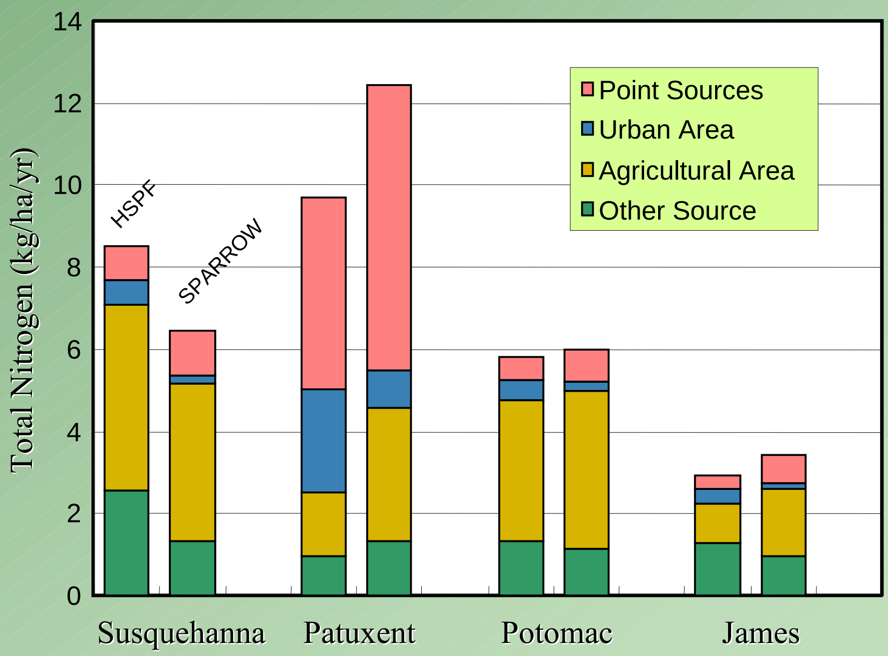
Chesapeake Bay Watershed

SPARROW / HSPF Comparison





Joint Application of SPARROW and HSPF in the Chesapeake Bay Watershed

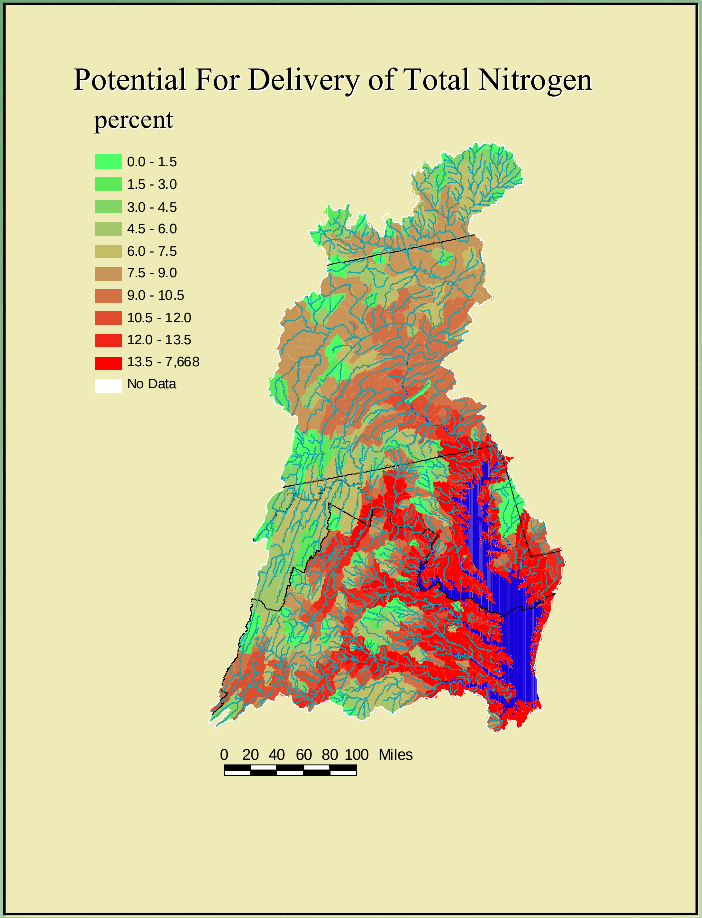
1. Feedback Between SPARROW and HSPF

2. Use of SPARROW for Targeting / HSPF for Evaluating
   Tributary Specific Management Plans

3. Use of SPARROW for Targeting / HSPF for Evaluating
   Load Allocations Among Large Basins
   for Criteria Attainment

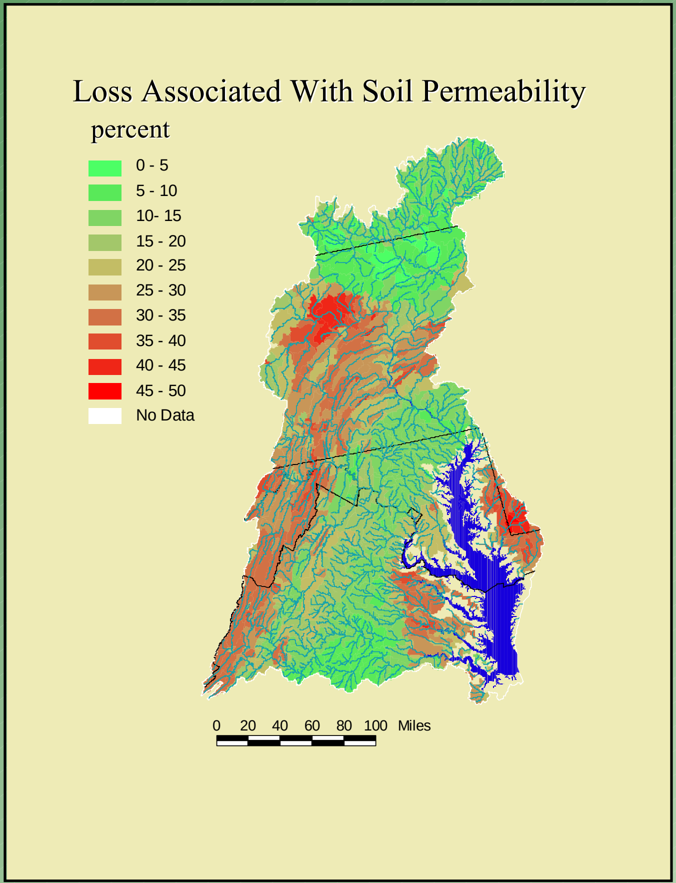
Joint Application of SPARROW and HSPF

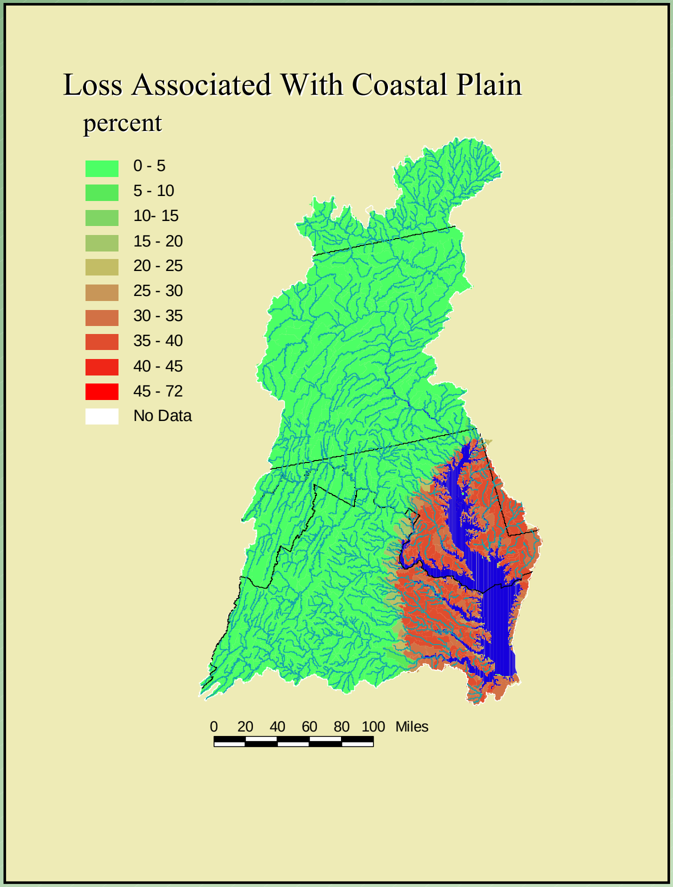
Model Feedback - Instream Loss Rates



Joint Application of SPARROW and HSPF

Model Feedback – Identification of Significant Variables





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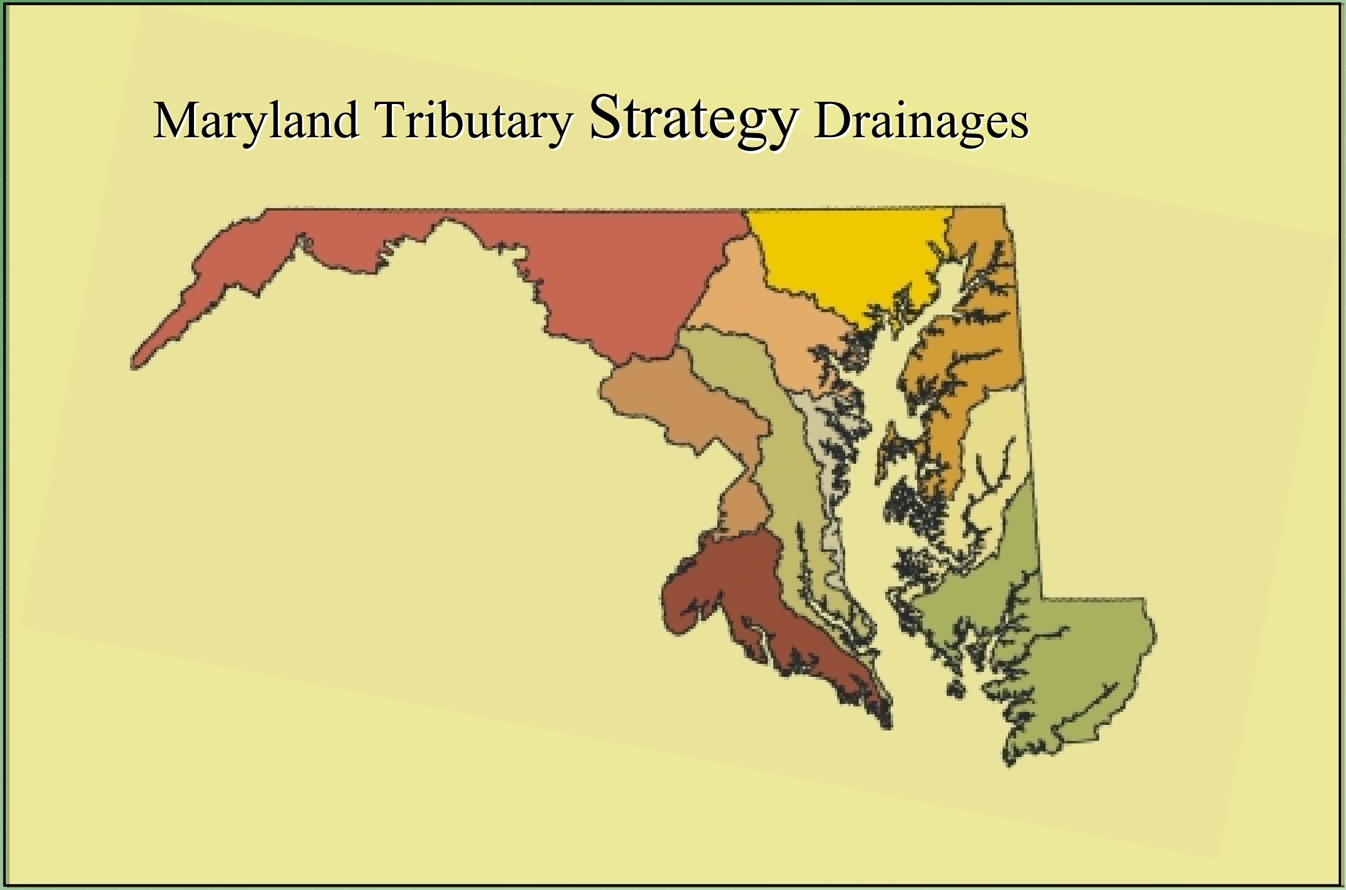
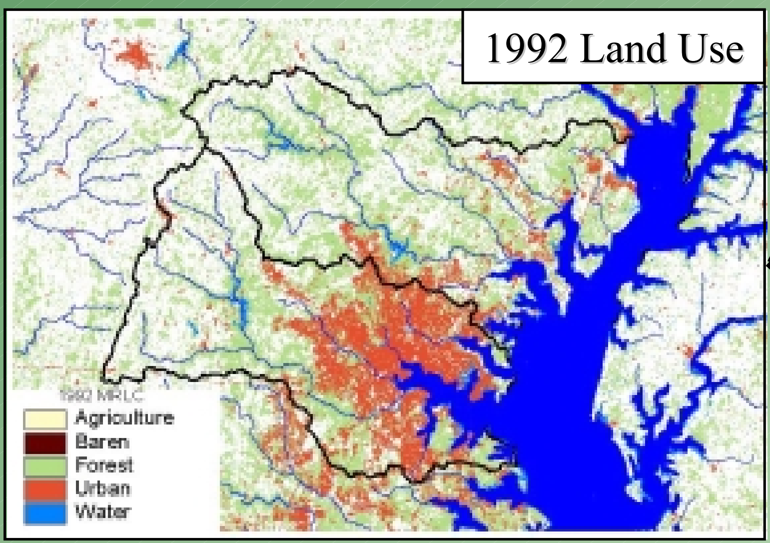
Joint Application of SPARROW and HSPF

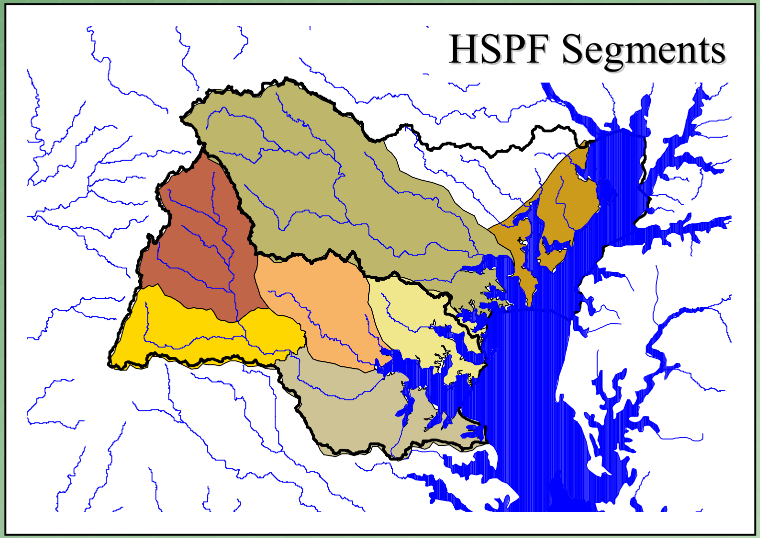
Targeting – Area Specific Management Plans

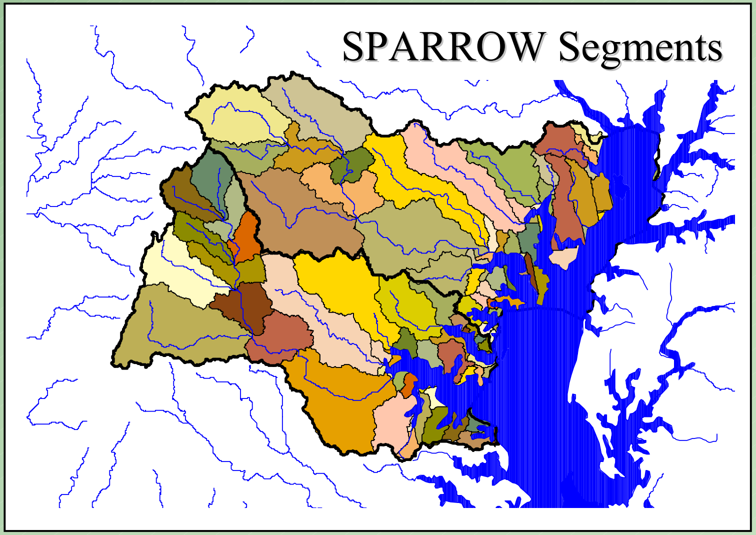


Joint Application of HSPF and SPARROW

Targeting – Area Specific Management Plans

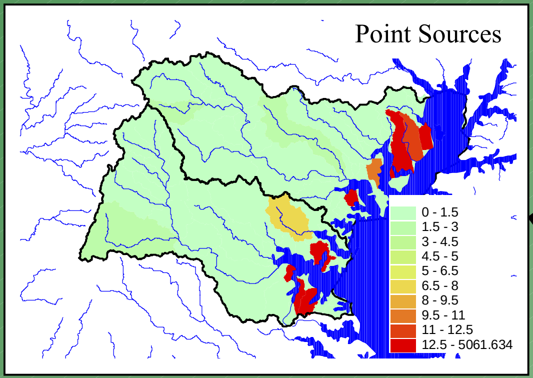


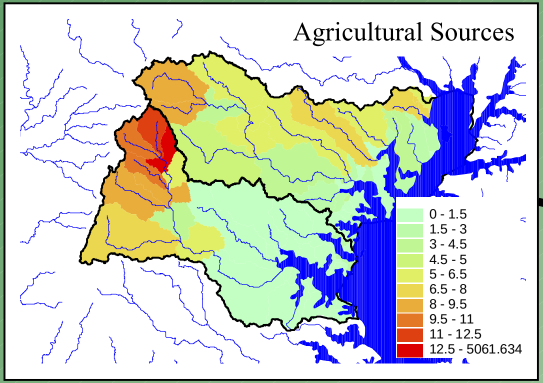


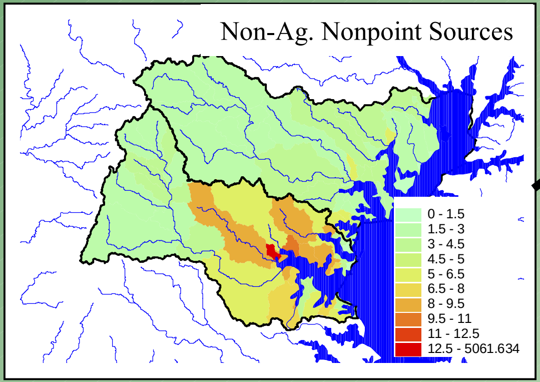


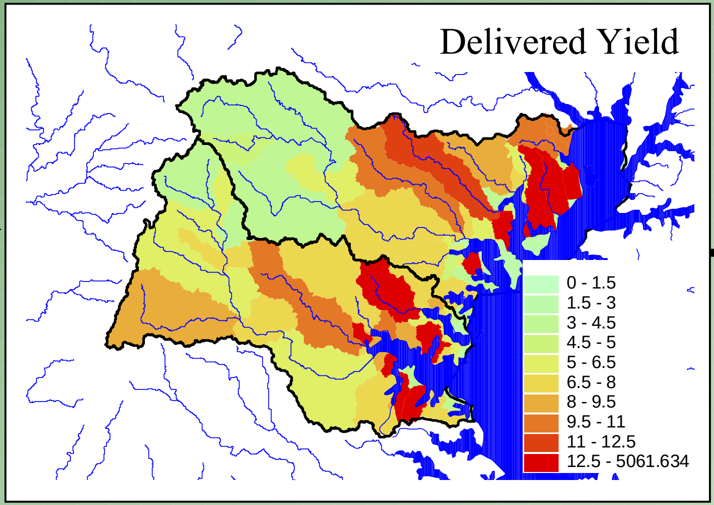
Joint Application of SPARROW and HSPF

Targeting – Area Specific Management Plans







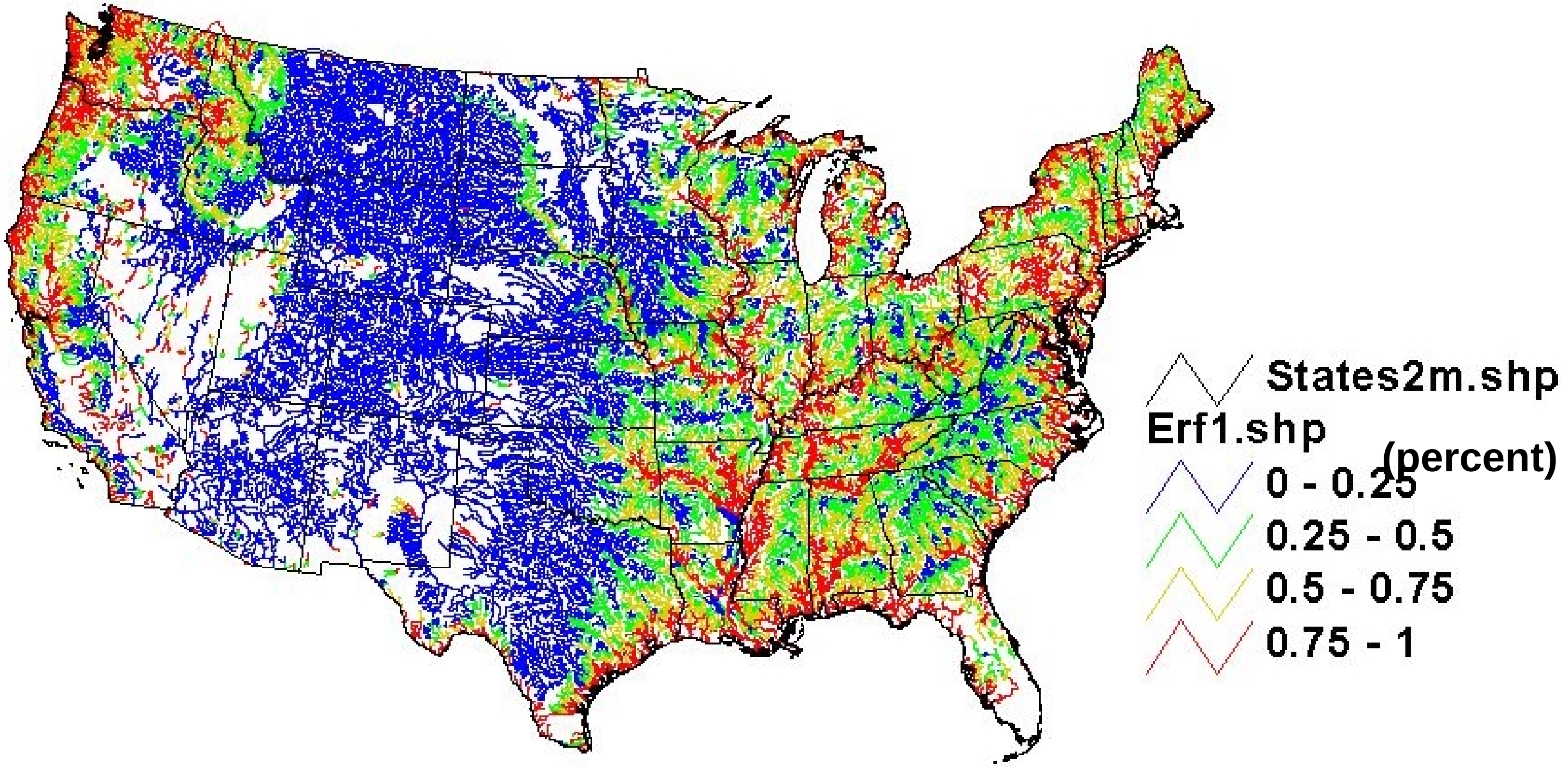


Management Scenario

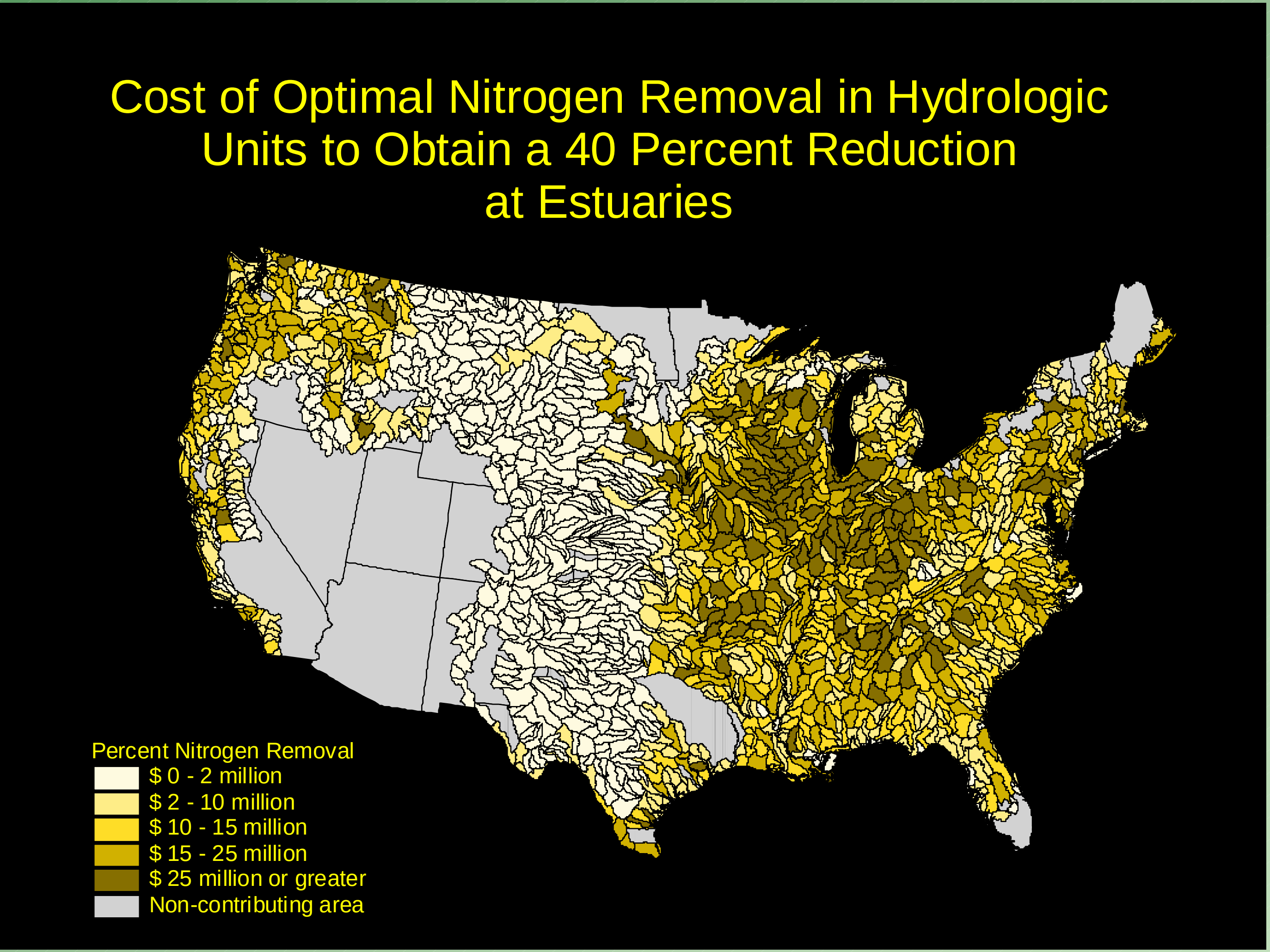
Test With HSPF

Economically Efficient Targeting of Nutrient Controls

Percentage of N Export Delivered to the Coast



Application of SPARROW to Evaluate Control Strategies for Reducing Nitrogen Flux to Estuaries



Differences in in-stream decay rates make it more efficient to control watersheds near large rivers.

The cost of the optimal strategy is 40% less than the cost of a uniform strategy.

SPARROW Management Applications

- TMDL
- Studying change over time
- Targeting of nutrient controls
- Natural background
- Atmospheric deposition
- Drinking water quality
- Network design

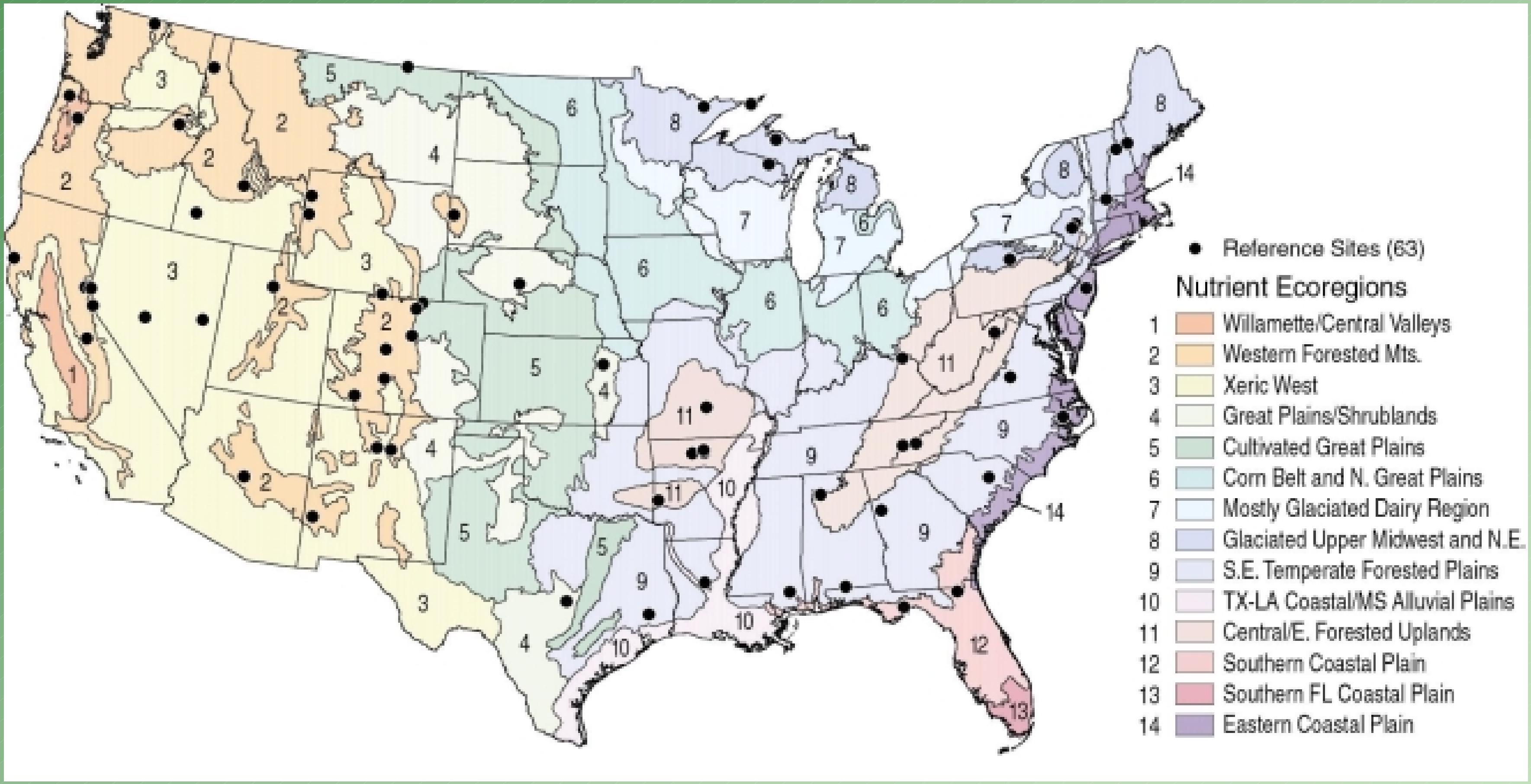
Objective: Develop models to correct for limitations of data from reference sites

1. Few sites; none in some ecoregions
2. Effect of atmospheric deposition
3. Effect of natural factors, esp. runoff
4. Effect of stream size

Approach

1. Calibrate regression models of background TN and TP yield from headwater stream reference sites as functions of runoff, basin size, atmospheric TN deposition, and regional factors.

US EPA Nutrient Ecoregions & USGS Reference Sites



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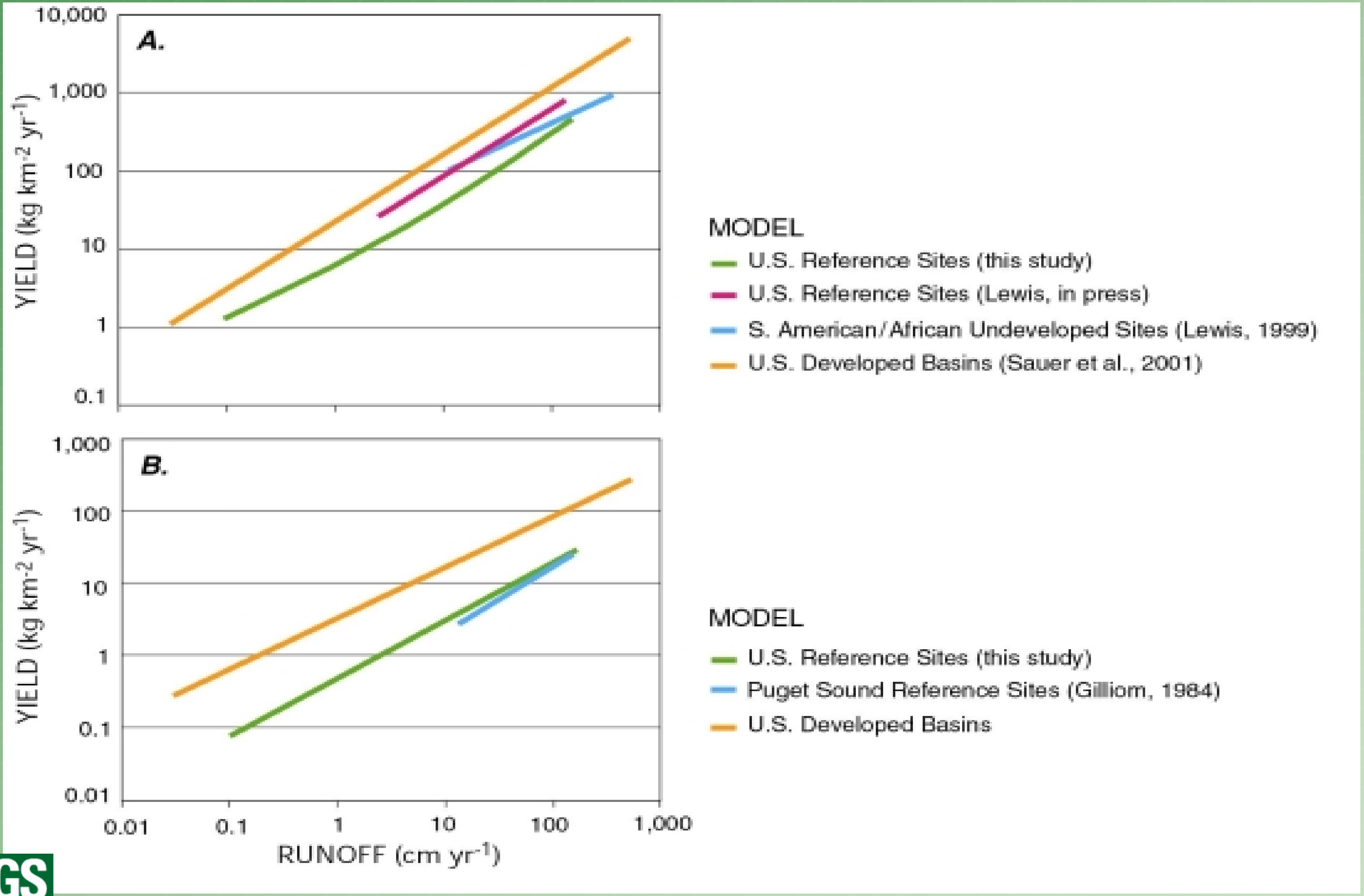
Comparison with Other Models

(A. = TN; B. = TP)



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Approach (cont.)

2. Use the atmospheric deposition term in the reference site regression model to correct for this source of TN.

3. Use the regression models to estimate background nutrient loadings to larger streams and rivers (defined as RF1 reaches).

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Approach (cont.)

3. Use previously calibrated SPARROW models to predict the effects of transport in larger streams and rivers on background nutrient concentrations.

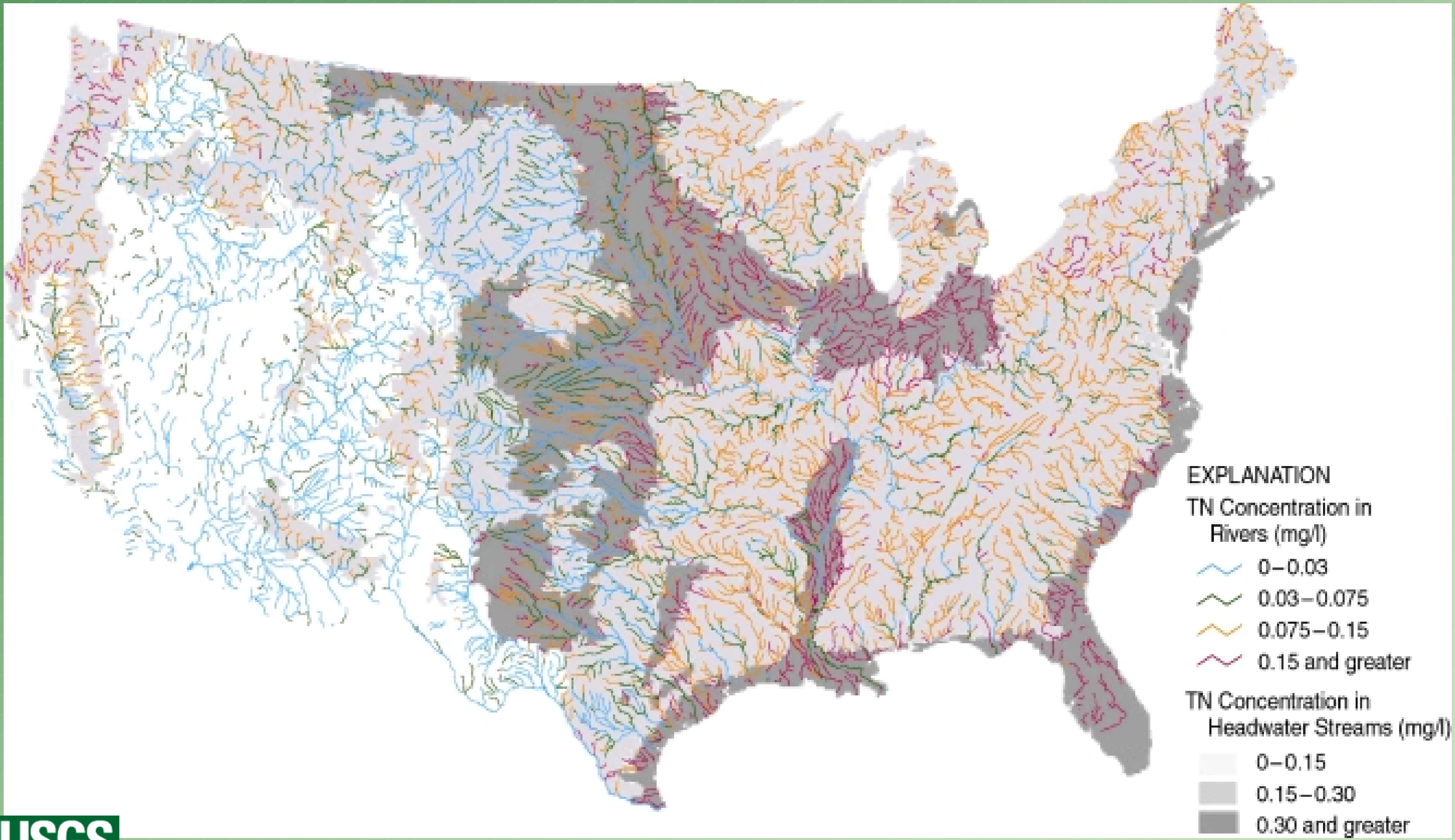
SPARROW Transport Equation

$$L_i = \sum_{j \in J(i)} Y_j A_j [\exp(-\mathbf{k}'\mathbf{T}_{i,j})]$$

Approach (cont.)

4. Also, use the reservoir sedimentation term in the SPARROW transport model to “correct” for the effect of dams on total P concentrations.

Estimated Background TN Concentrations in RF1 Streams and Rivers



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Estimated Background TP Concentrations in RF1 Streams and Rivers

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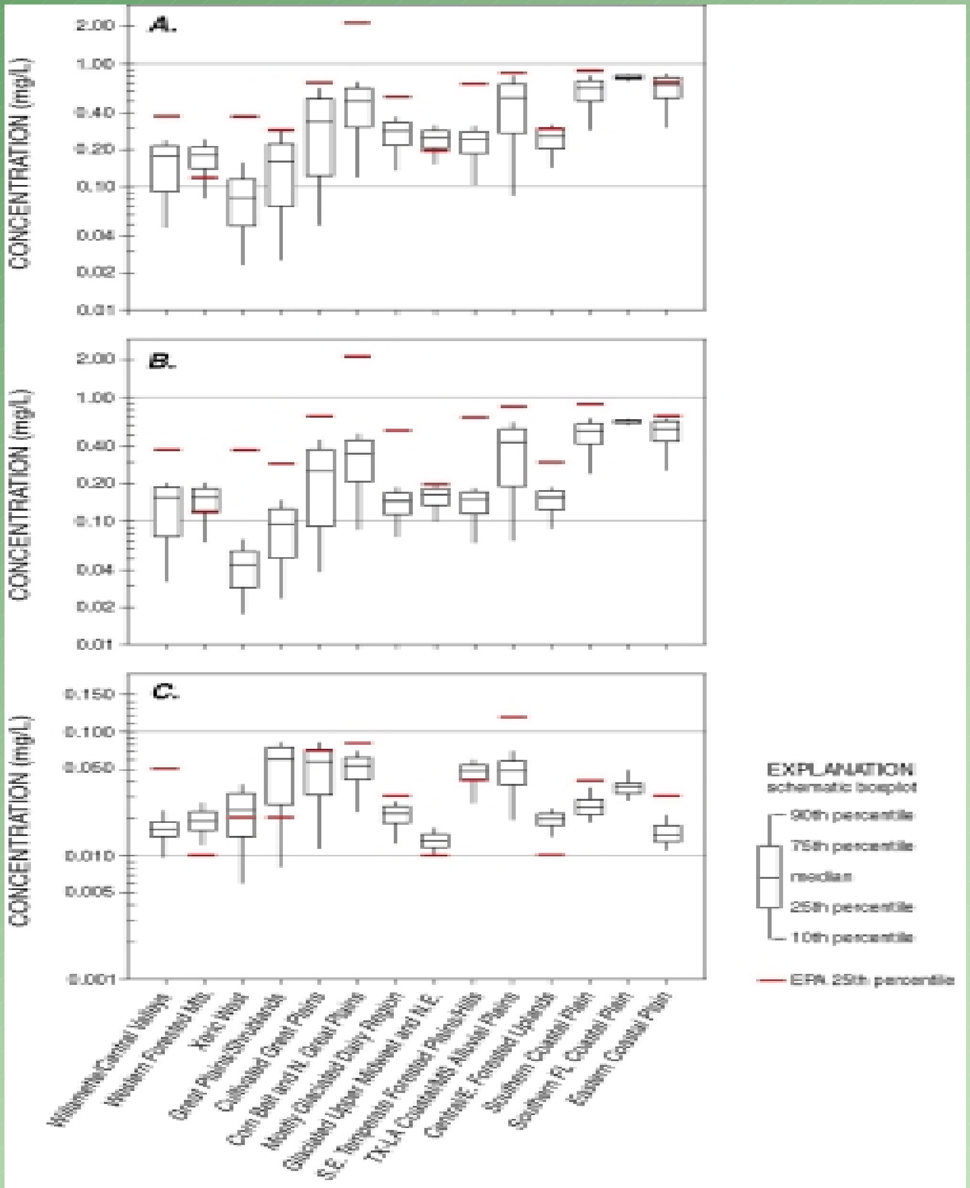
Background Nutrient Concentrations in RF1 Streams and Rivers

TN Concentration

Deposition-adjusted TN Concentration

TP Concentration



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Conclusions

- Actual (i.e. current) TN concentrations (Dodds *et al*, 1998) exceed background levels by a much larger factor than do actual TP concentrations.

- Reasons: nutrient loadings, pollution controls, dams and reservoirs.

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Conclusions (cont.)

- As much as a 10X variation in natural background concentrations of TN and TP within EPA nutrient ecoregions.

- Predicted background TP concentrations exceed EPA 25th percentile values in many streams (52% nationwide).

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Conclusions (cont.)

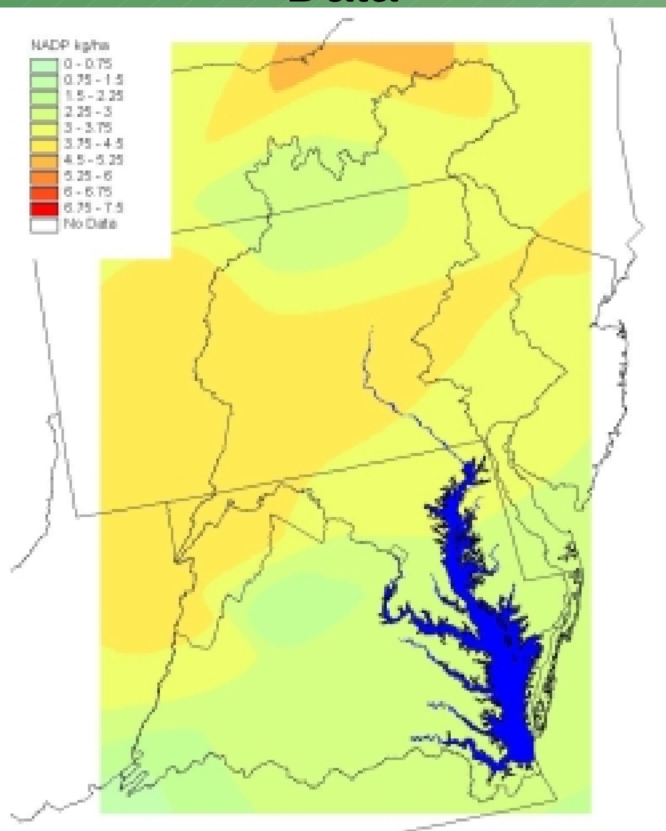
- Fundamental problem for setting nutrient criteria: large local variation in background concentrations due to runoff and stream-river junctions.
- Localized variation hinders solving this problem through sub-division of major eco-regions.

SPARROW Management Applications

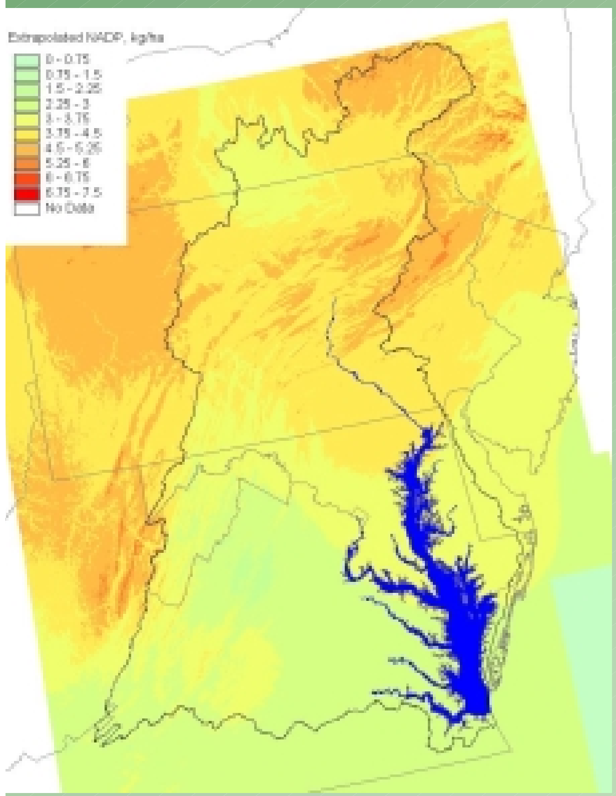
- TMDL
- Studying change over time
- Targeting of nutrient controls
- Natural background
- Atmospheric deposition
- Drinking Water Quality
- Network design

Nitrate Wet-Deposition Data Sets Chesapeake Bay Region

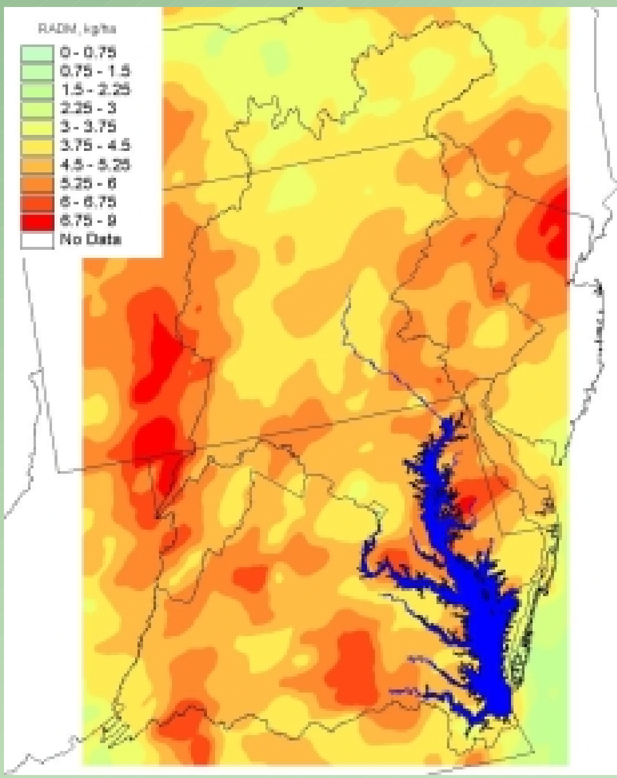
Interpolated NADP Data



Penn State Modeled NADP Data



RADM Model



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CB Total Nitrogen SPARROW (1992)
Five Models Evaluated

Sources:

Atmospheric deposition:

- NADP wet nitrate
- Penn St. wet nitrate
- RADM (wet, dry, total)

Municipal / industrial point

Septic systems

Urban runoff

Fertilizer

Livestock waste

Results:

- Model fits similar (R^2=0.98); statistically inseparable
- Source contributions to stream TN flux similar
  - Modest differences in atmospheric & fertilizer sources

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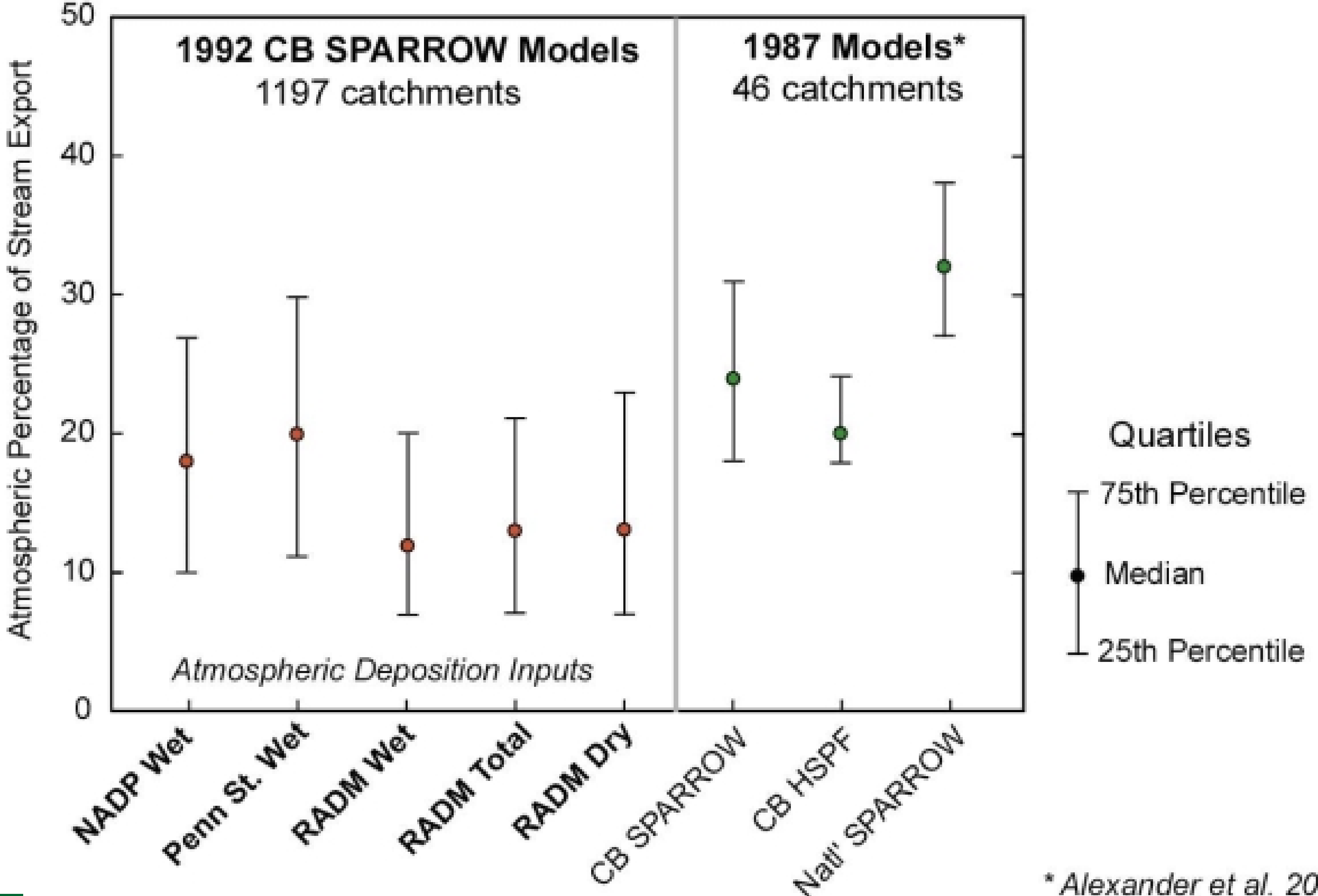
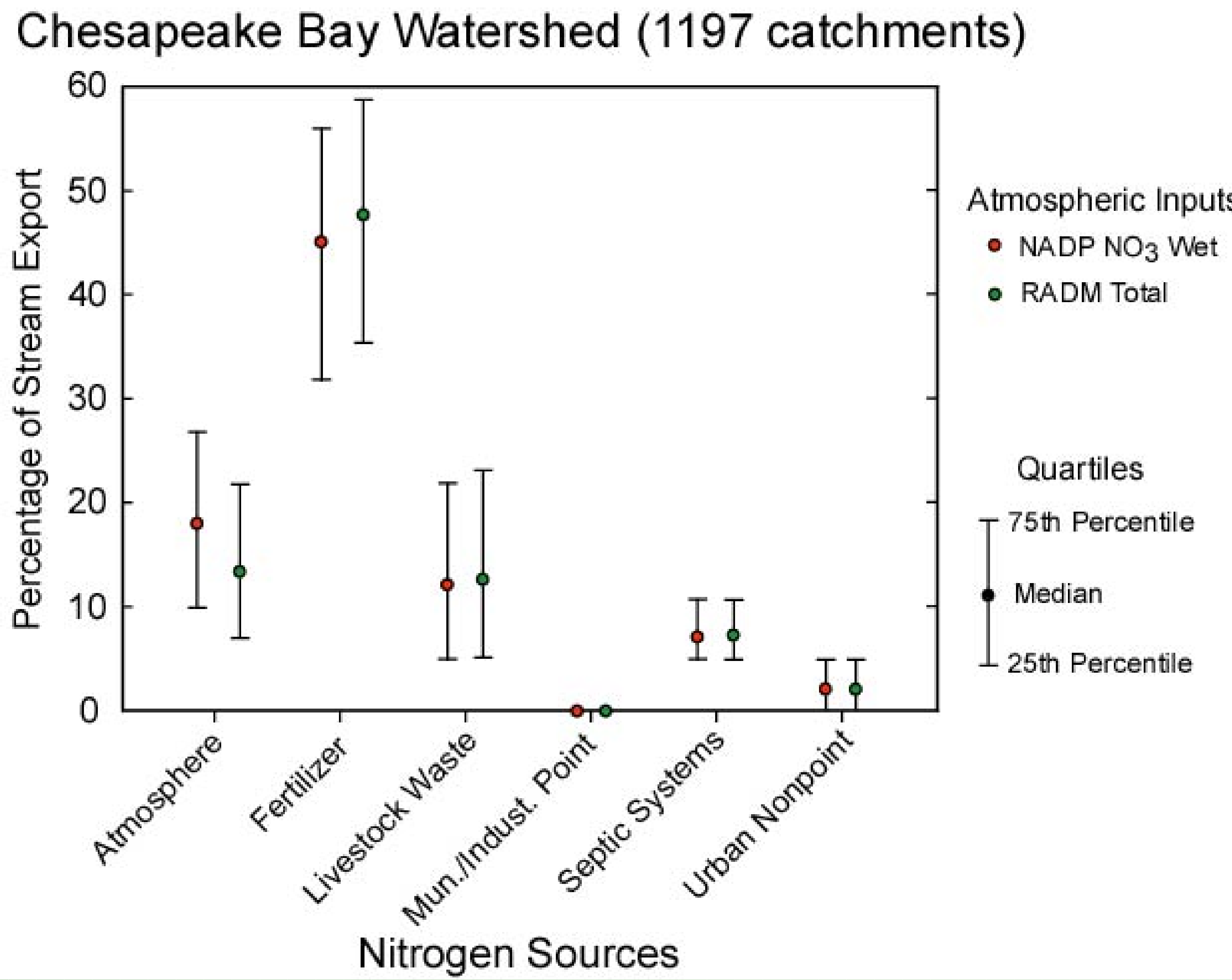
Chesapeake Bay Watershed
Atmospheric Contributions to Stream TN Export



* Alexander et al. 2001

CB SPARROW 1992 Estimates of Source Contributions to Stream TN Export



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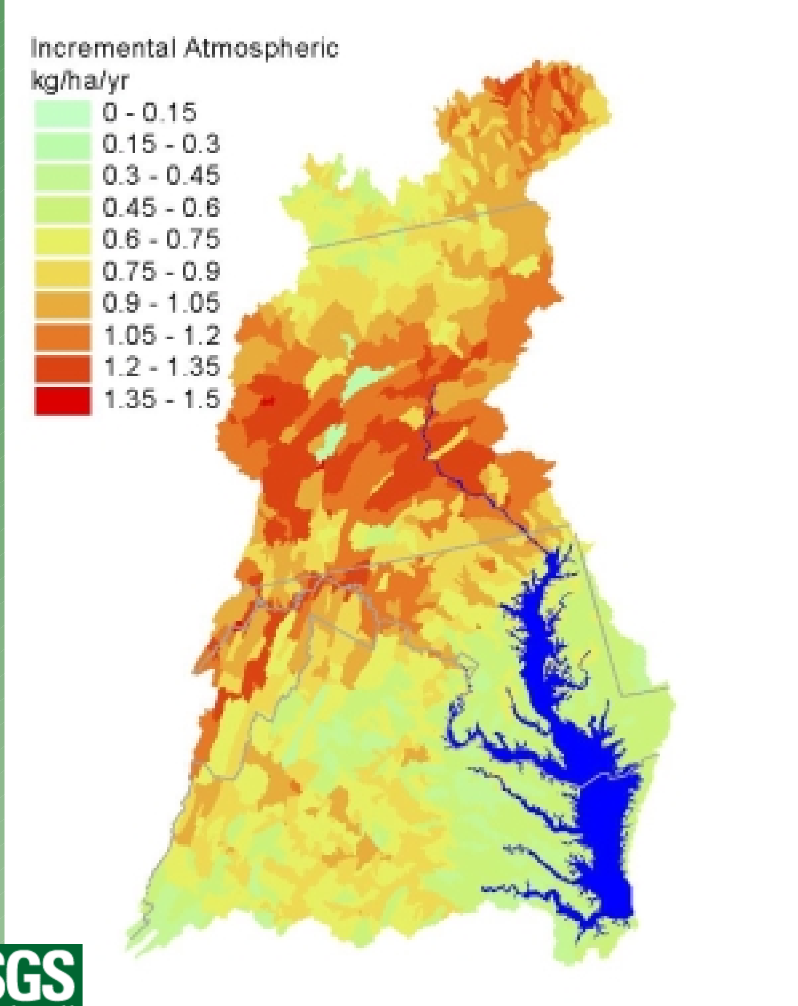
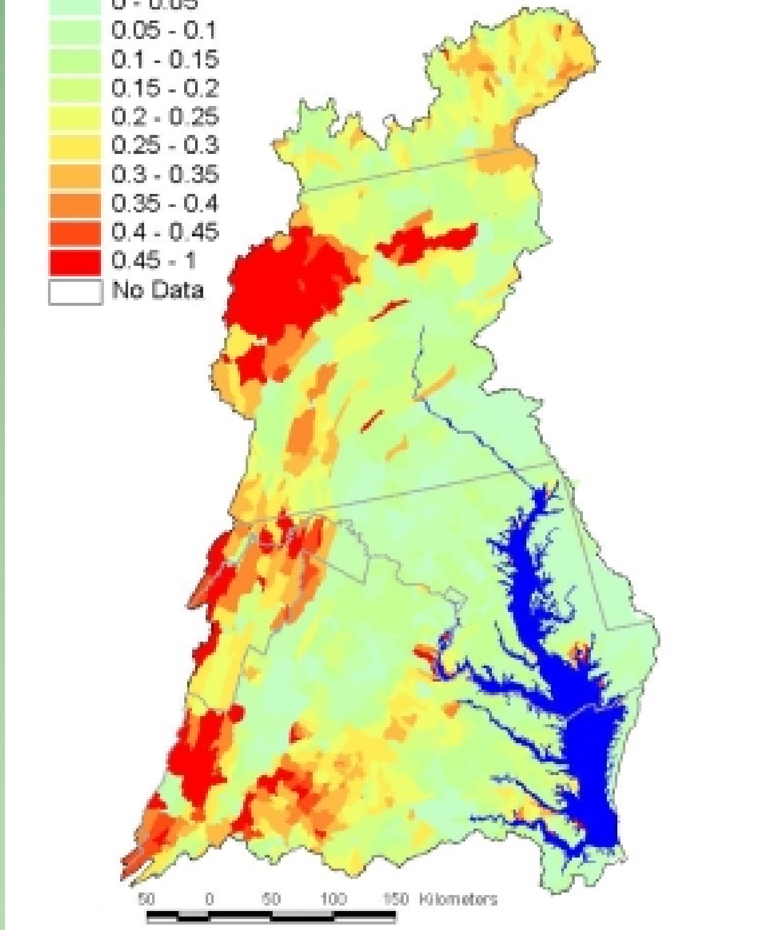
CB SPARROW Atmospheric Contributions Exported from Reach Catchments

(Based on Interpolated NADP Wet NO_3 Deposition)

TN Yield



Fraction of All Sources



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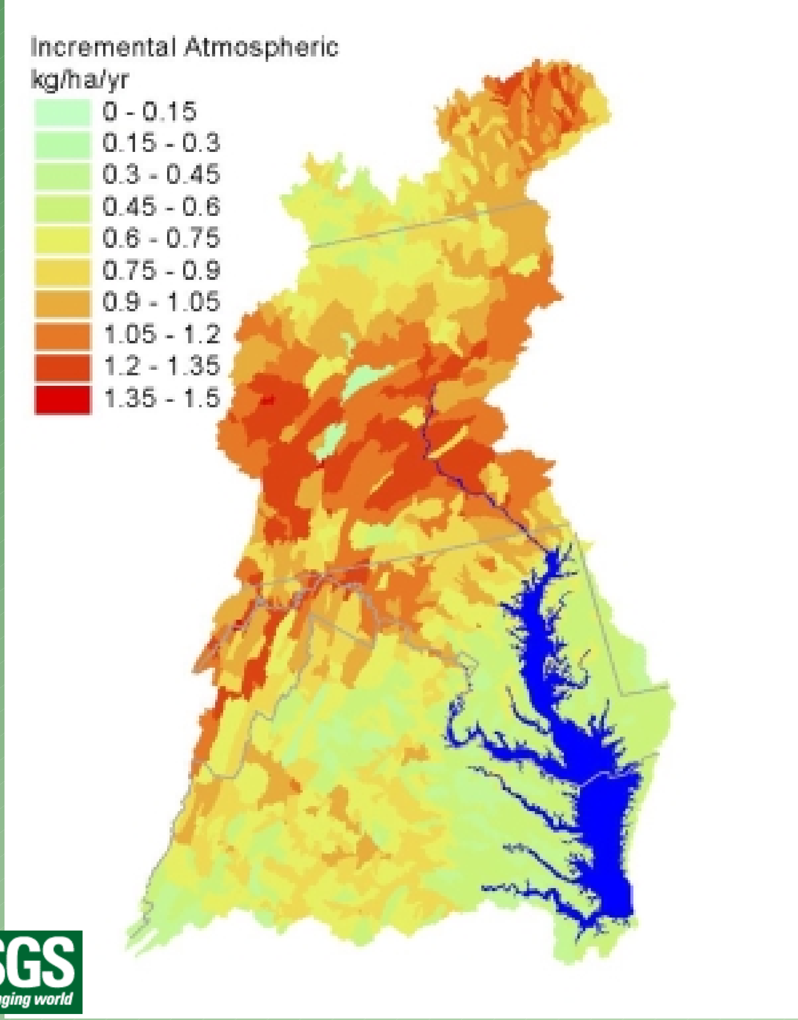
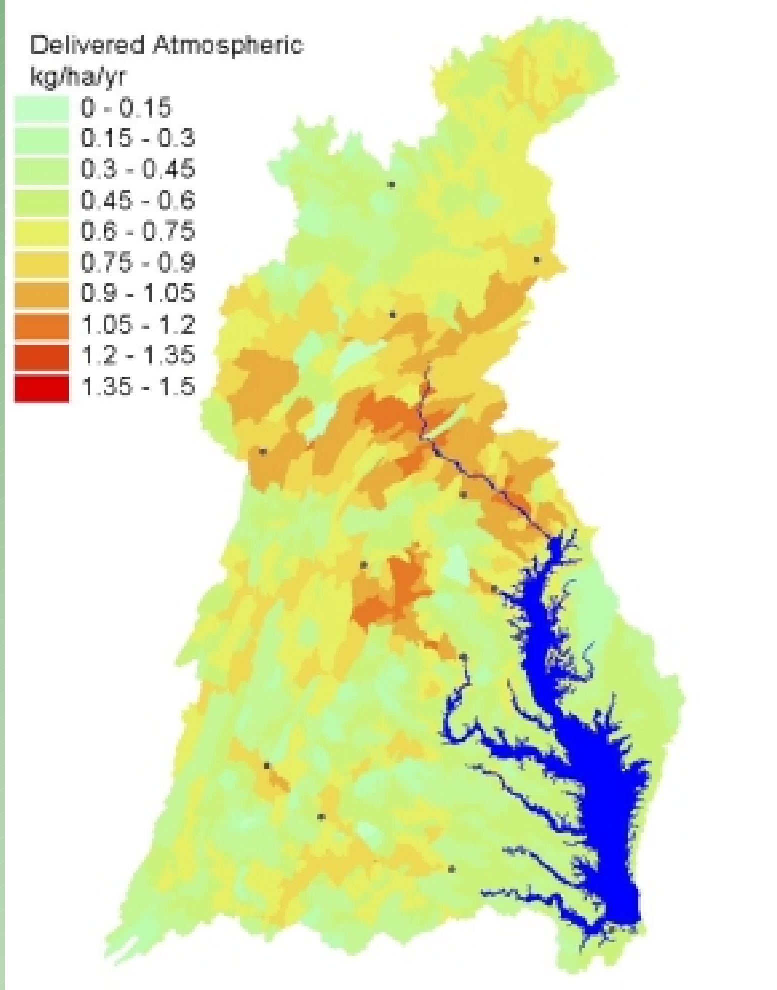
CB SPARROW Atmospheric Contributions Exported from Catchments & Delivered to Bay

(Based on Interpolated NADP Wet NO_3 Deposition)

TN Yield



Delivered TN Yield



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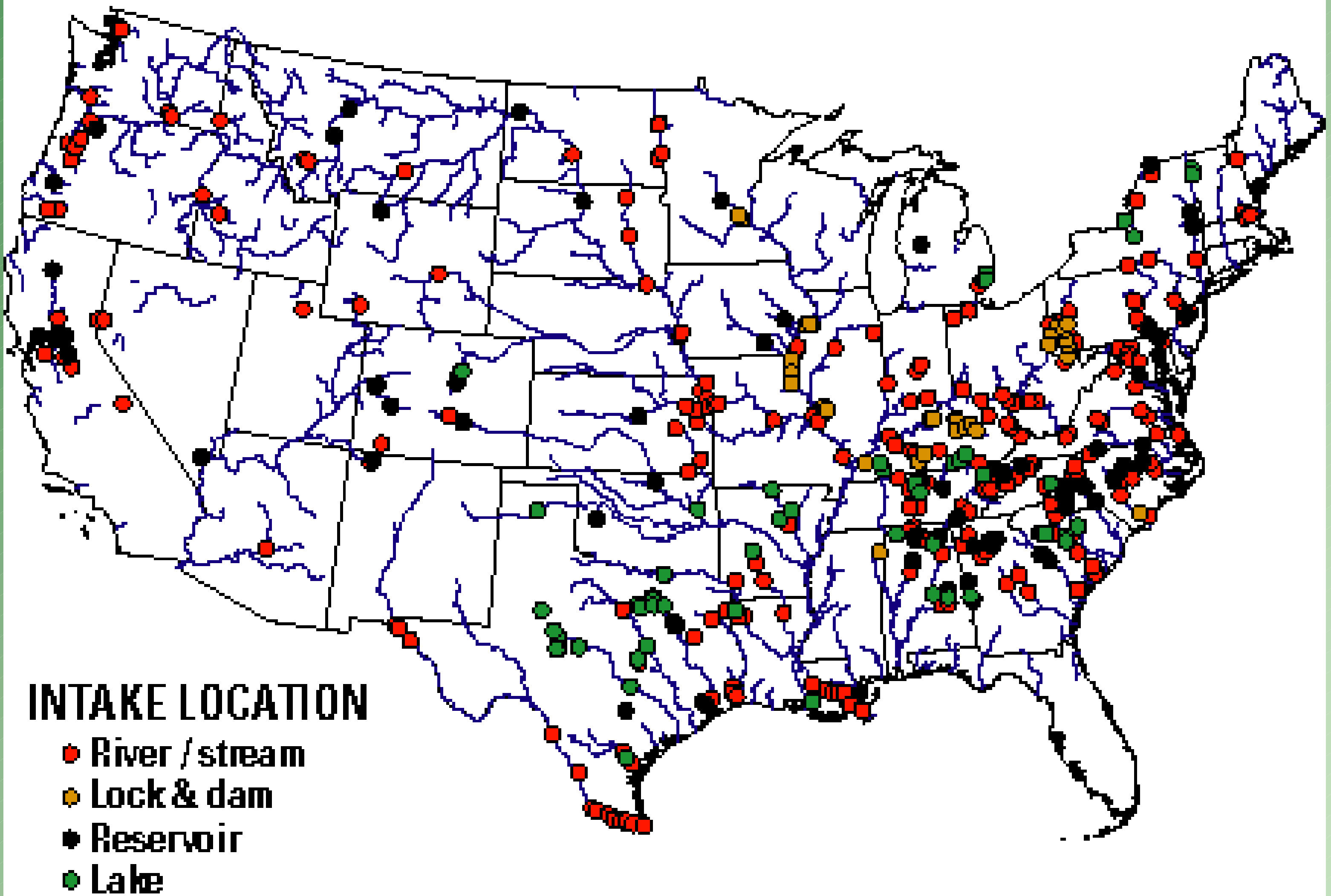
SPARROW Management Applications

- TMDL
- Studying change over time
- Targeting of nutrient controls
- Natural background
- Atmospheric deposition
- Drinking Water Quality
- Network design

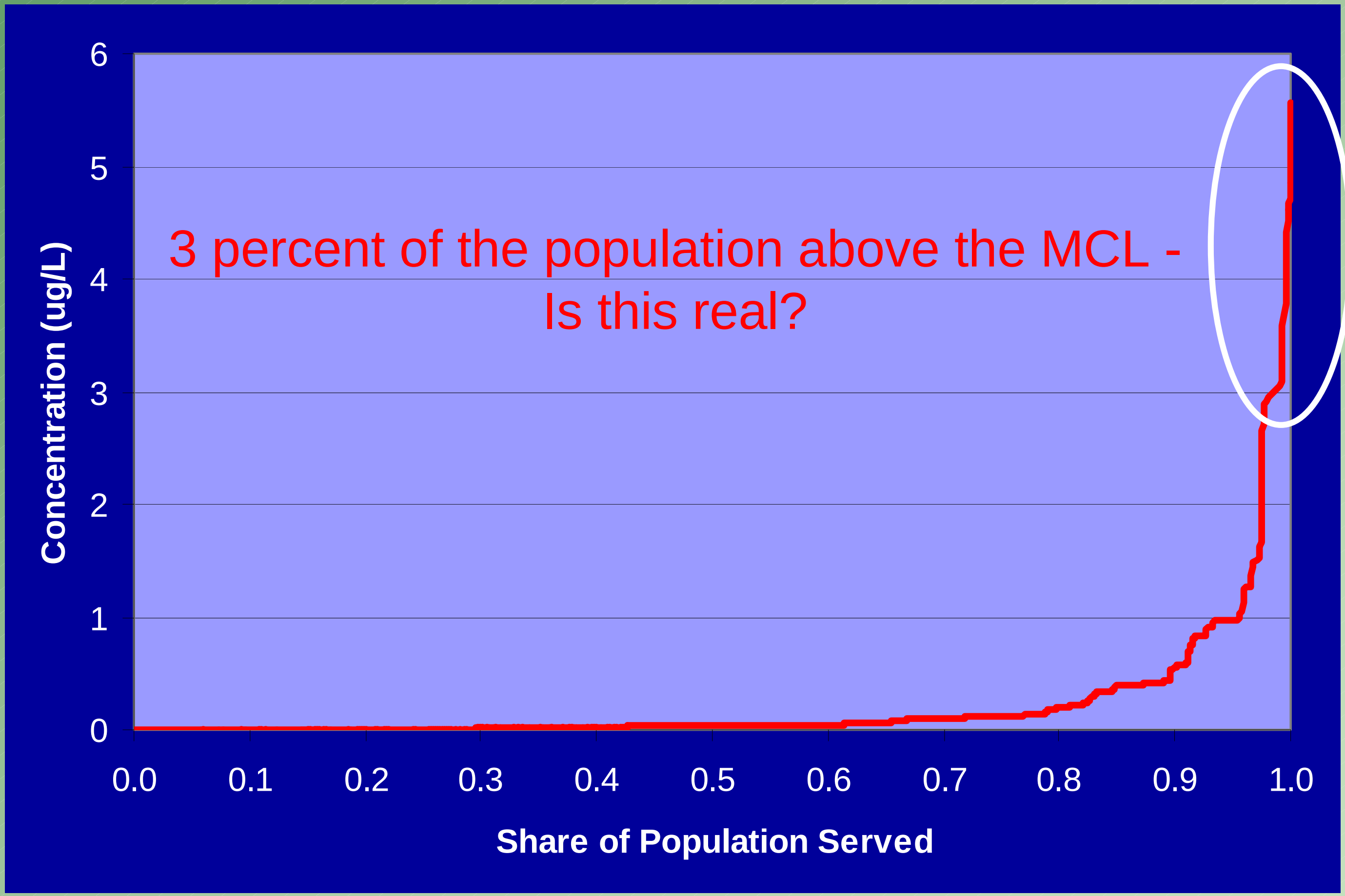
SURFACE-WATER INTAKES IN THE UNITED STATES

Serving Populations above 10,000 in Watersheds Greater than 1,000 Sq. Km.



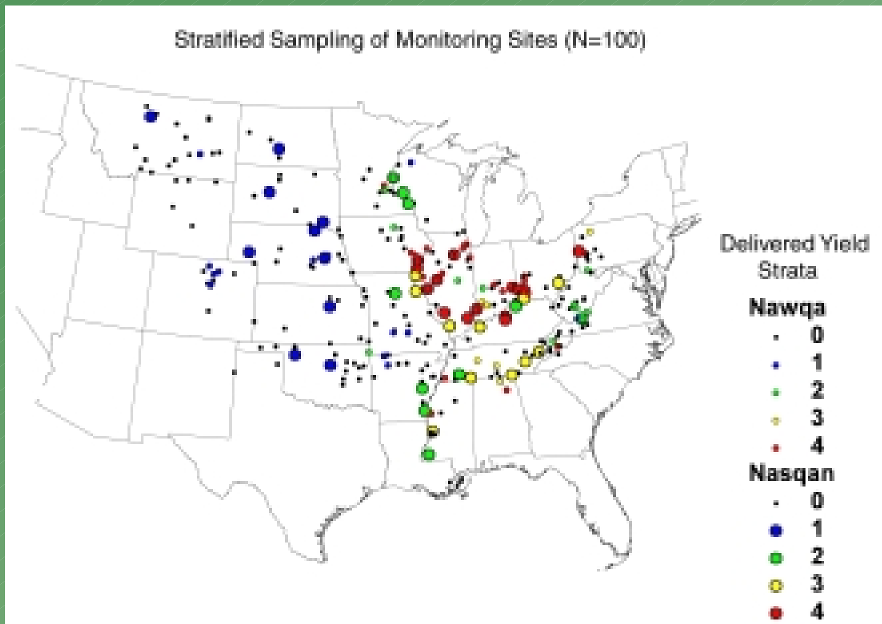
Cumulative Population with Atrazine Exposure Below Given Concentration

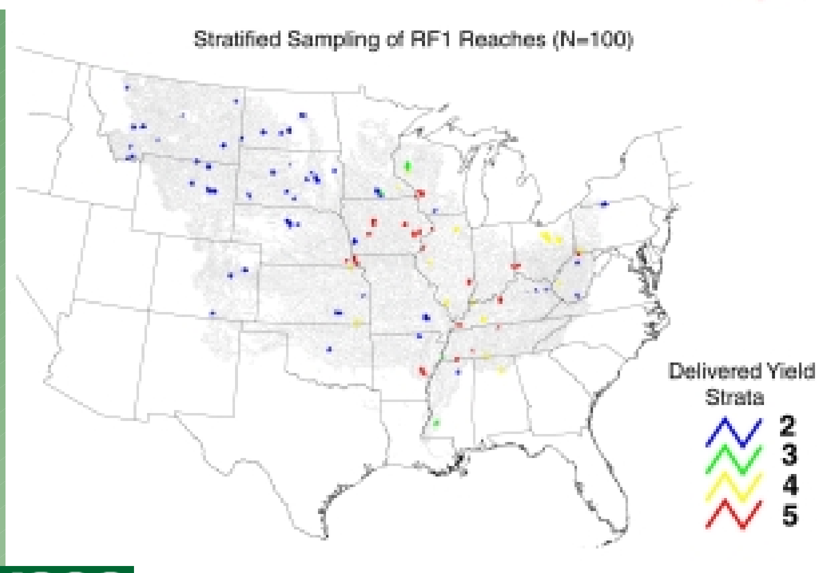
(567 intakes serving 60 million people)



Network design
Optimal network design to predict TN yield to Gulf of Mexico

Network Design Using SPARROW

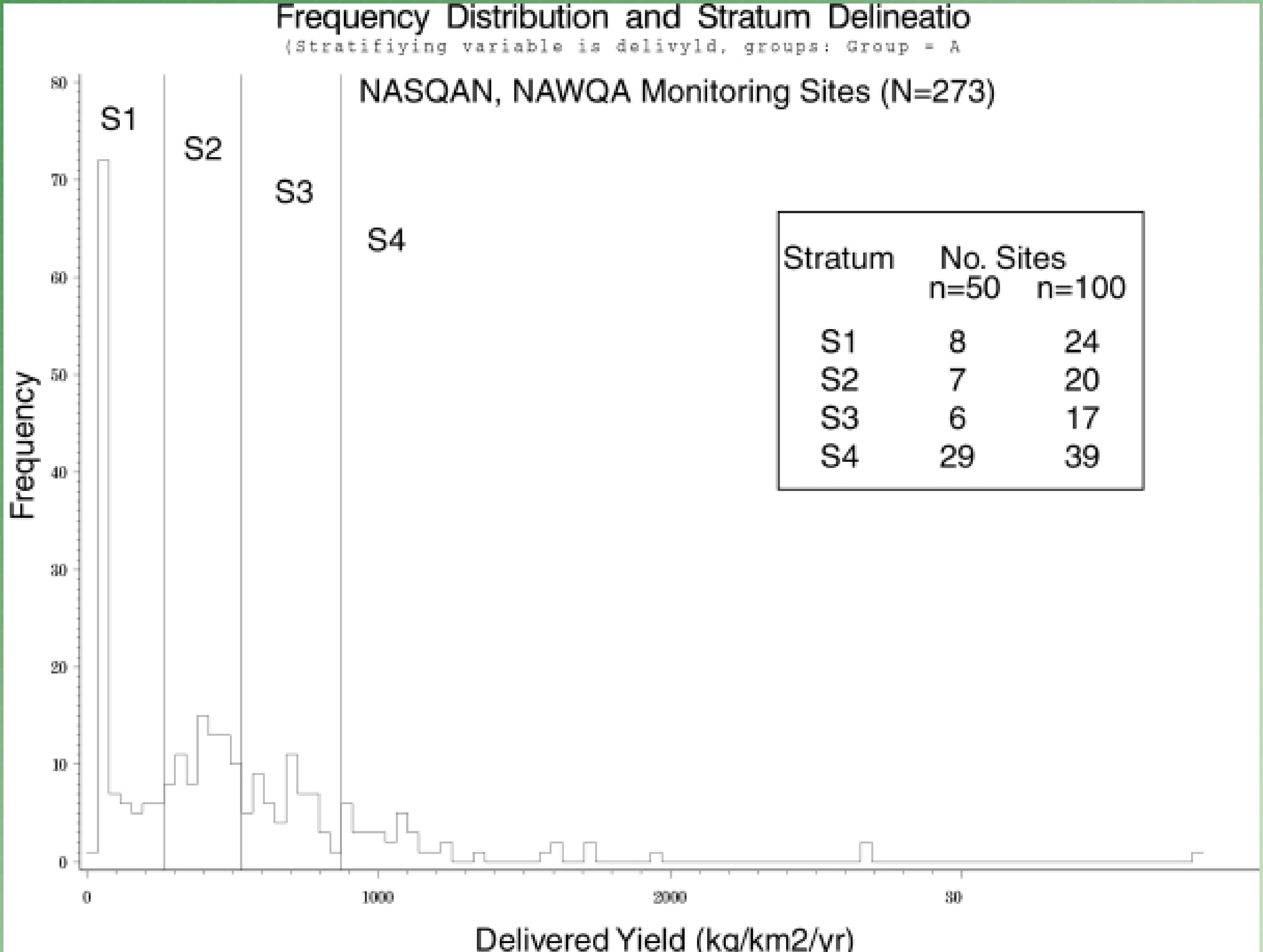




<u>Objective:</u> Select the "optimal" set of monitoring locations that improves the precision of model estimates of the "delivered TN yield" to the Gulf of Mexico

<u>Method:</u> (a) stratify the distribution of delivered yield for sites (273 NASQAN & NAWQA) and reaches; (b) determine the sample size from each strata that satisfies the objective; (c) randomly select 100 locations from the four strata

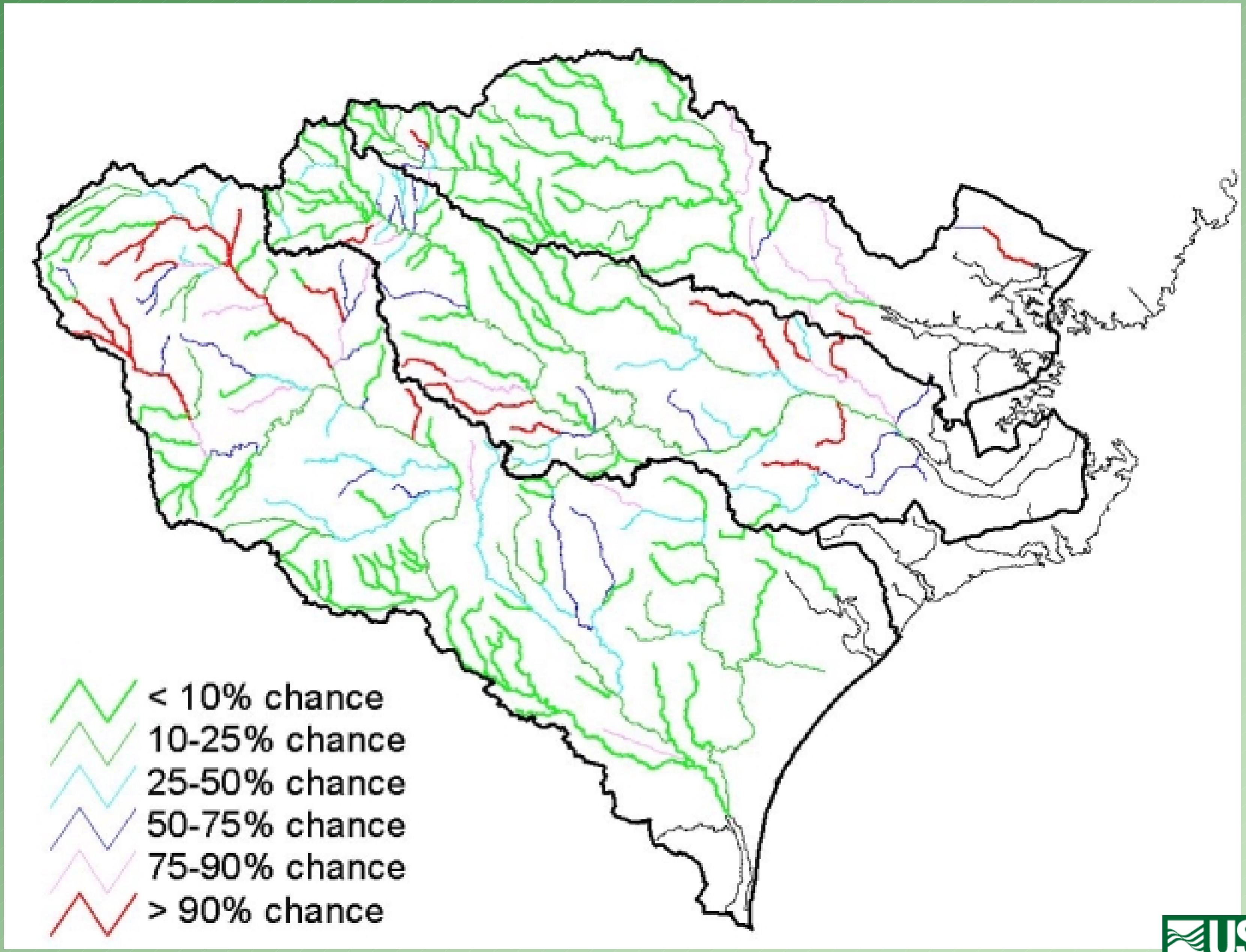
<u>Additional design scenarios possible:</u>
(a) alternate populations of streams having different attributes; (b) effect of station sample size; (c) different objective functions (e.g., concentration)



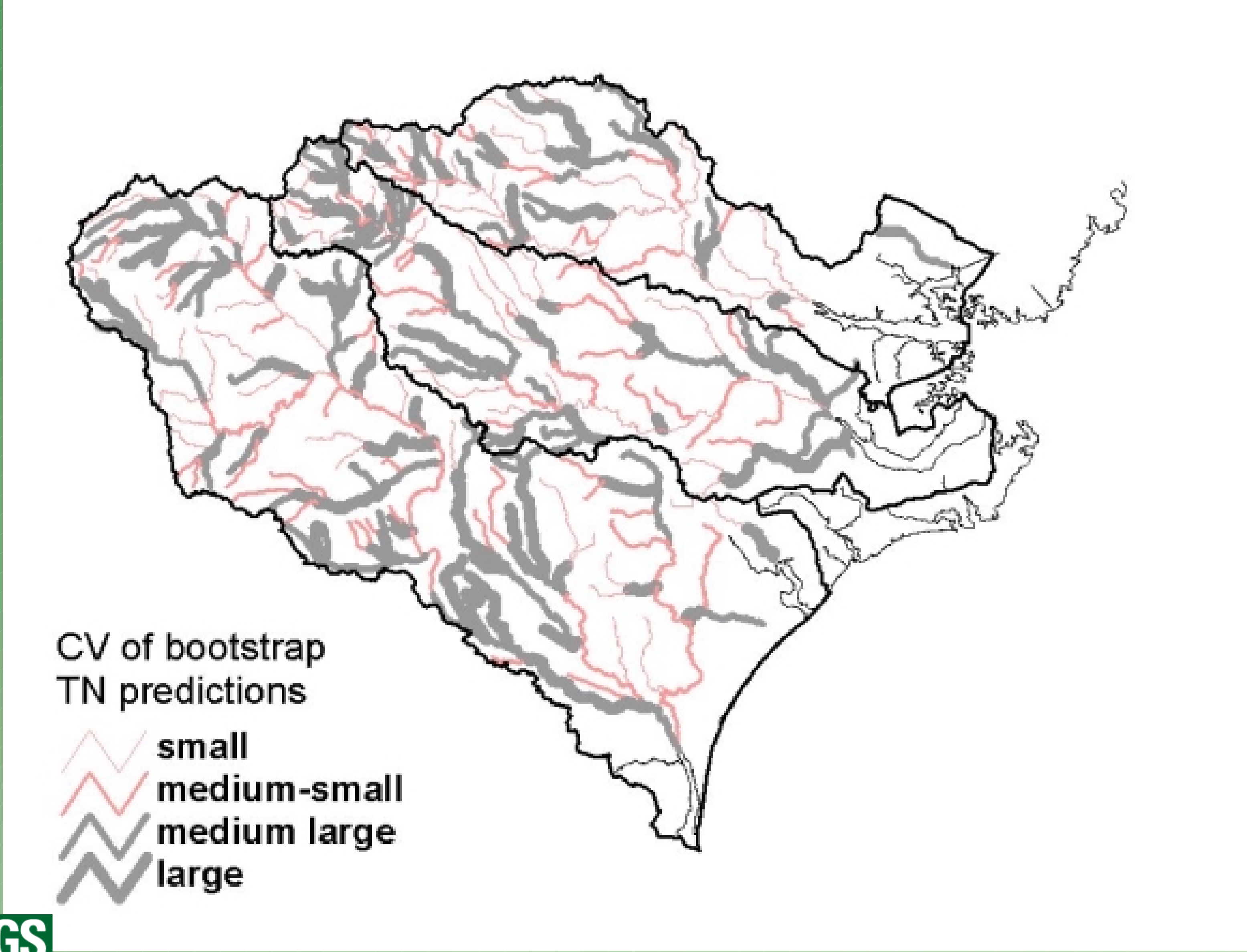
Frequency Distribution and Stratum Delineatio
(Stratifiying variable is delivyld, groups: Group = A
NASQAN, NAWQA Monitoring Sites (N=273)
S1
S2
S3
S4
Stratum No. Sites
n=50 n=100
S1 8 24
S2 7 20
S3 6 17
S4 29 39
Frequency
Delivered Yield (kg/km2/yr)
0
10
20
30
40
50
60
70
80
0
1000
2000
30

Network design
Using exceedence probability and prediction uncertainty to locate additional monitoring sites

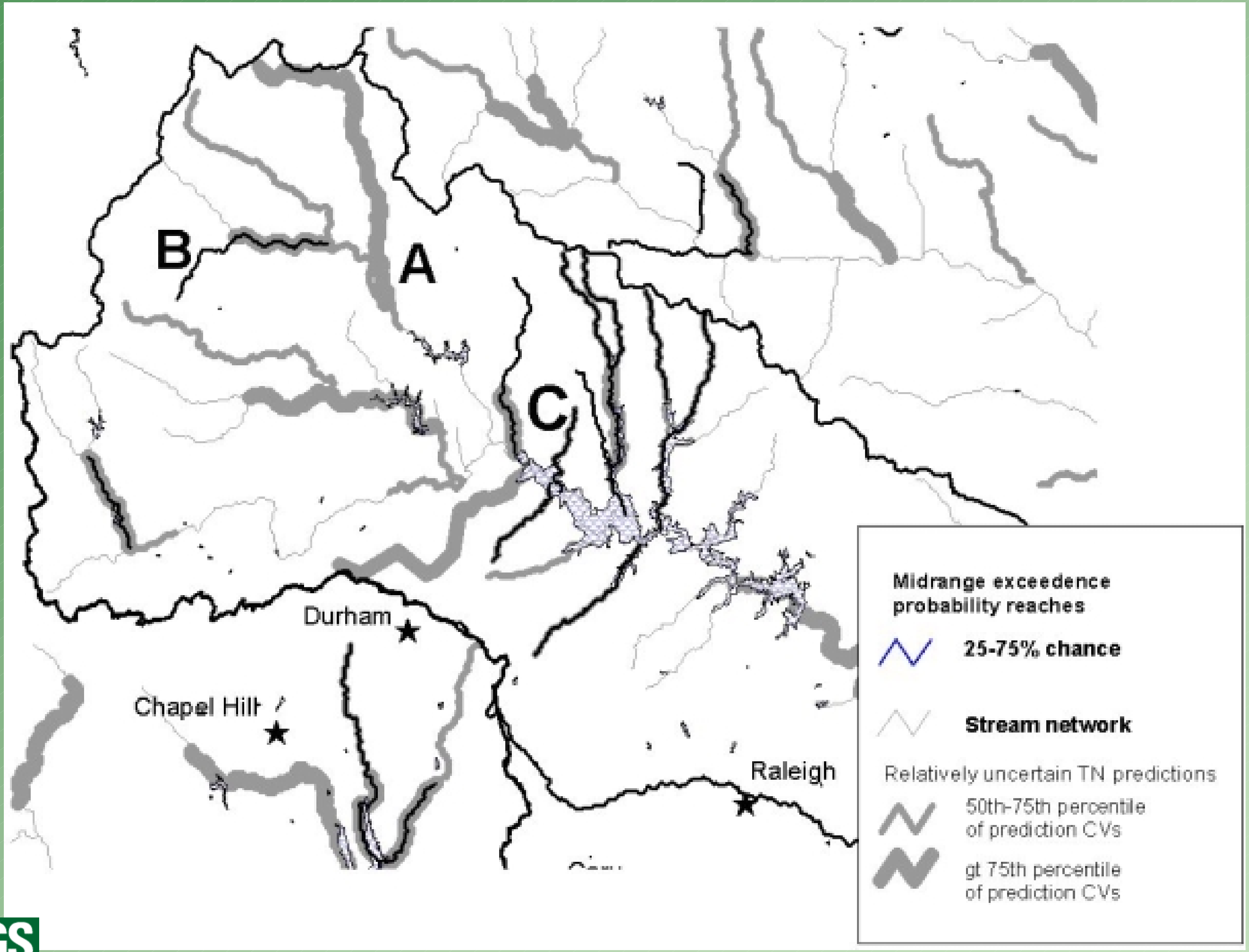
Probability of exceeding TN concentration of 1.5 mg/L



Relative variability of TN predictions



Identifying locations for further monitoring?



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Network design
Chesapeake Bay
Non-Tidal Monitoring Network Design

Key Aspects of the Non-Tidal Monitoring Program

* Non-Tidal Monitoring Funded Primarily by the States for Other Objectives

* Objectives of Non-tidal Monitoring for CBP
  Focus on How Watershed Activities
  Affect the Bay

* States Have Agreed to Work With the CBP
  to Make Modest Changes to Achieve
  All Objectives

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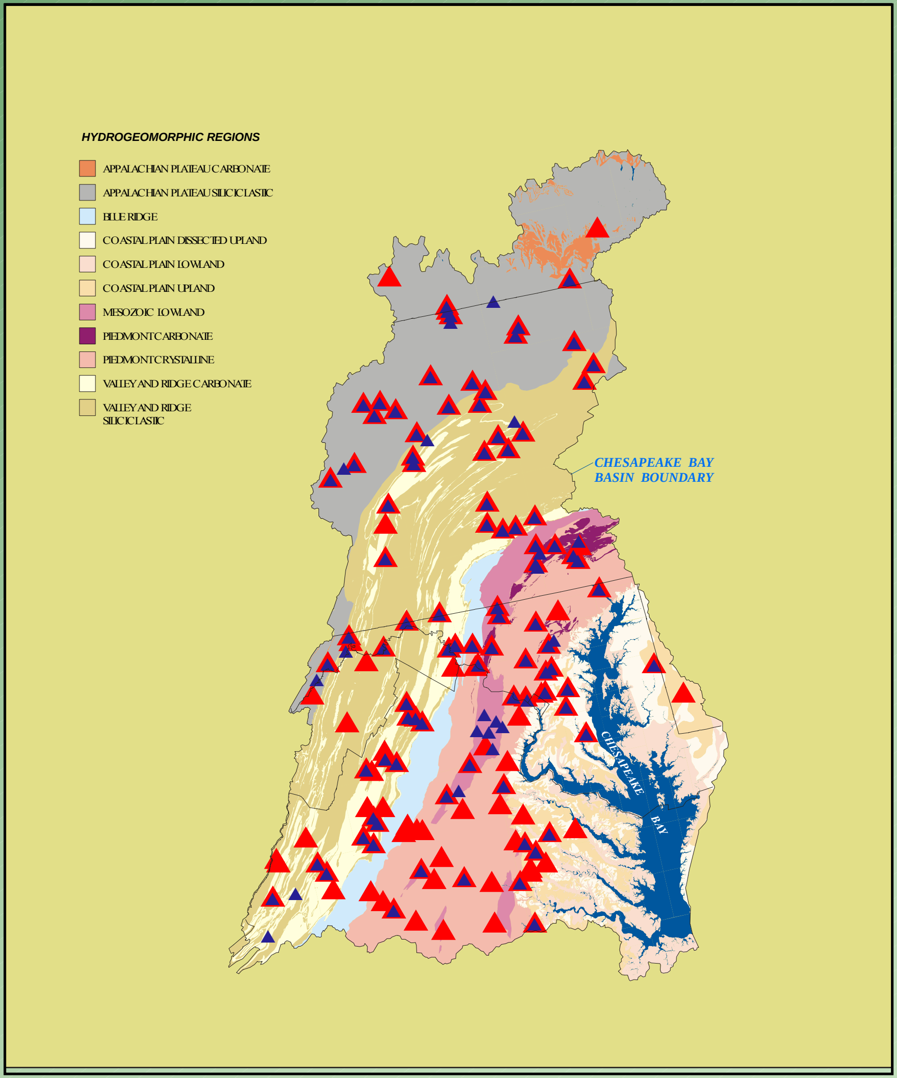
Chesapeake Bay SPARROW

Version II

HGMR / Load Site Distribution



▲ Version I - 1987

▲ Version II - 1992

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Criteria for Non-Tidal Site Inclusion

A. Load Estimation

- Must be associated with a stream gage
- Sites must represent broad range of watershed characteristics
- Minimum of 12 samples per year over 3 consecutive years

B. Temporal Trend Analysis

- Must be associated with a stream gage
- Sites must represent broad range of watershed characteristics
- Minimum of 4 samples per year over 10 consecutive years

C. HSPF Watershed Modeling

- Must be associated with a stream gage
- Sites must represent broad range of watershed characteristics
- Minimum record length of 5 consecutive years
- Sites must be located near segment boundary

Preliminary Results of Criteria Application

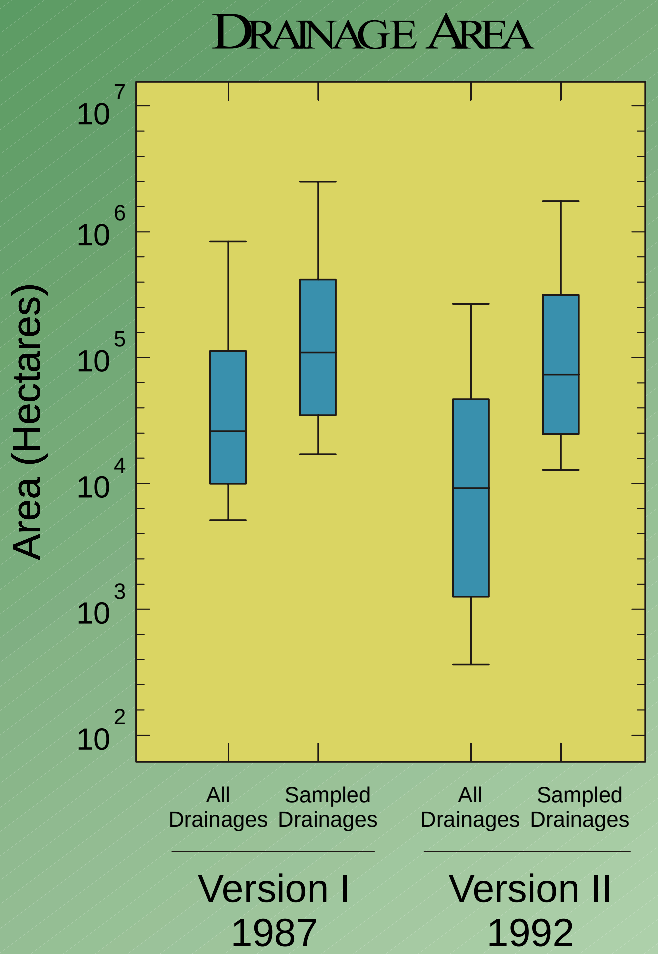
Langland and others, WRIR 95-4233

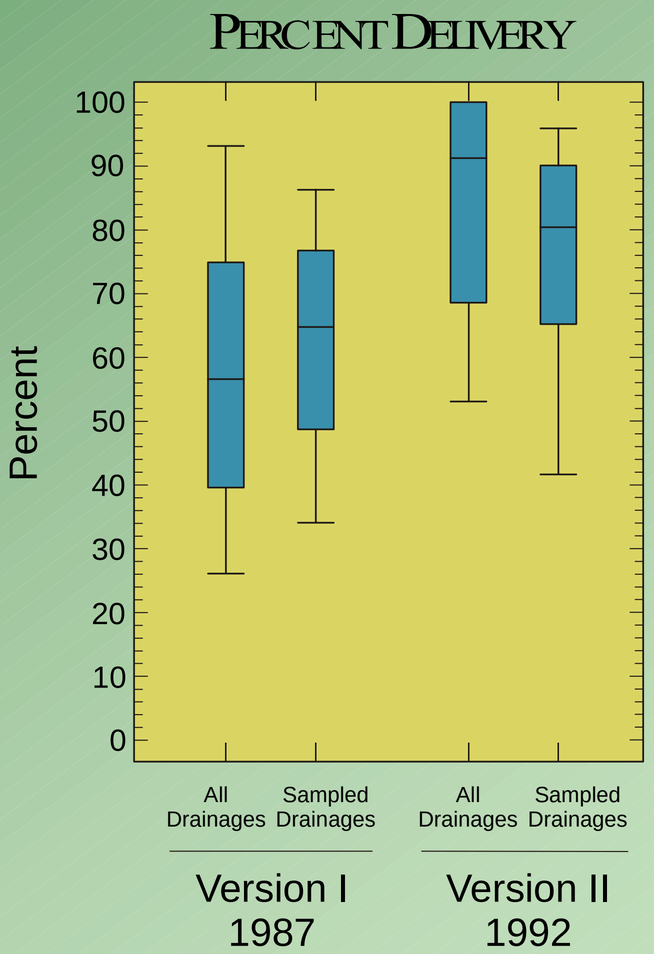
* A Total of 1,058 Sites With at Least 12 Nutrient or Sediment Samples Collected Over 3 Years or More

* Of the 1,058 Sites, 613 had at Least 50 Nutrient or Sediment Samples Collected Over 3 Years or More

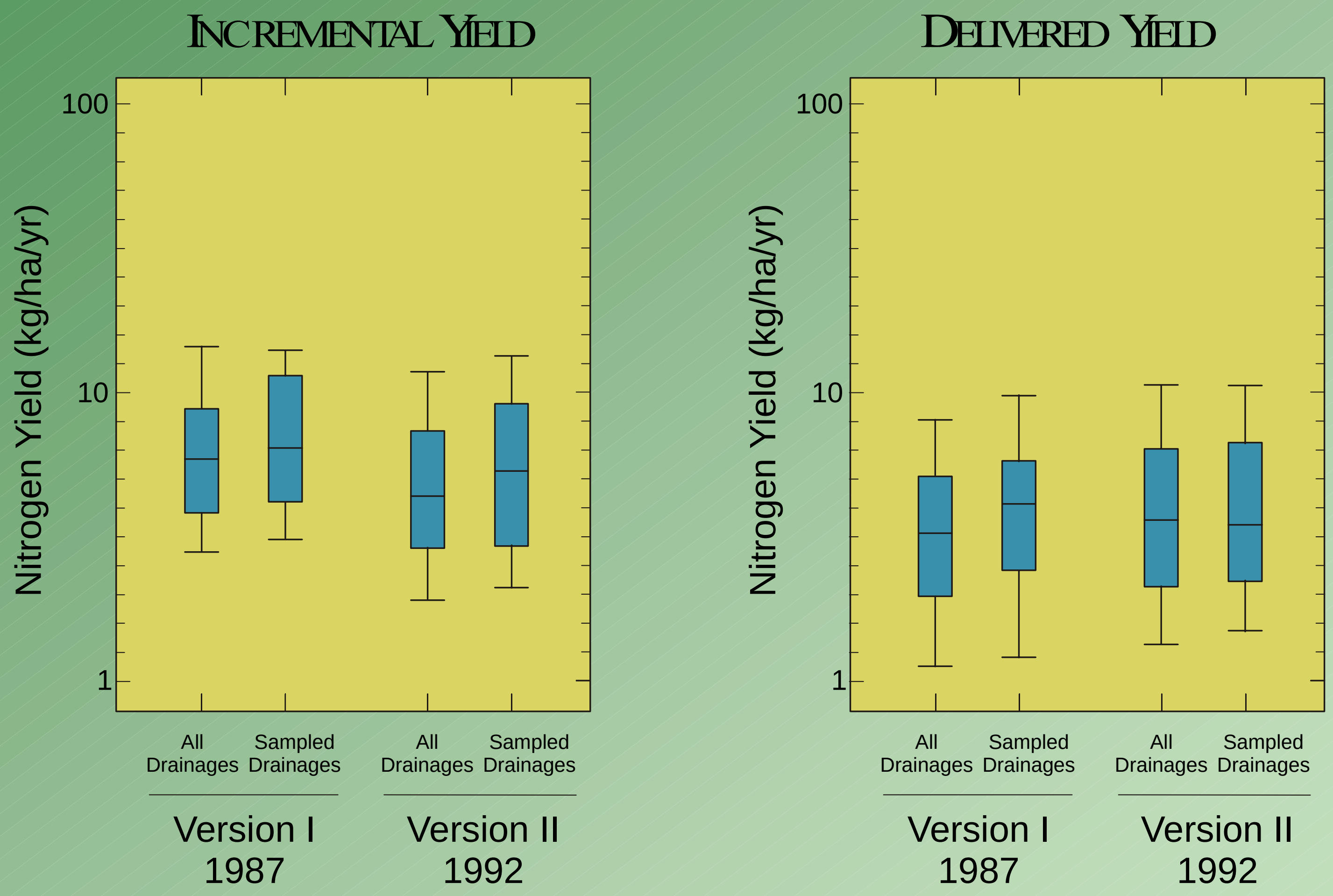
* Of the 613 Sites, Only127 Were Associated With a Flow Gage

MONITORING NETWORK REPRESENTATIVENESS



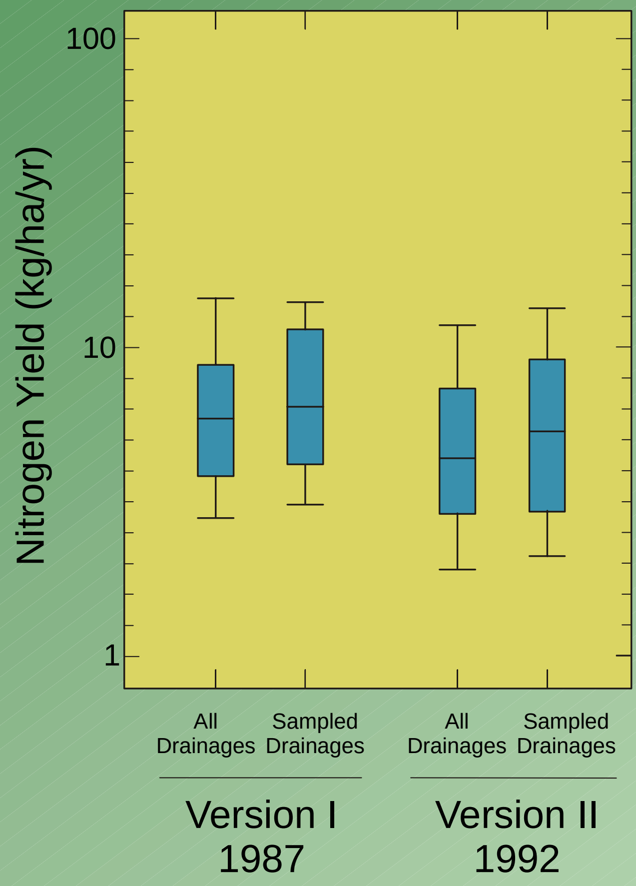


MONITORING NETWORK REPRESENTATIVENESS

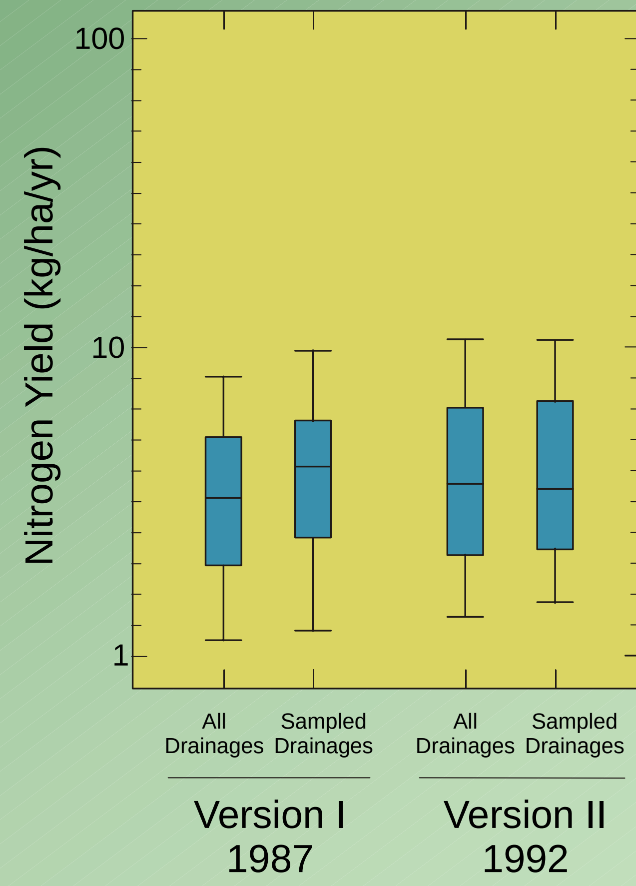


MONITORING NETWORK REPRESENTATIVENESS

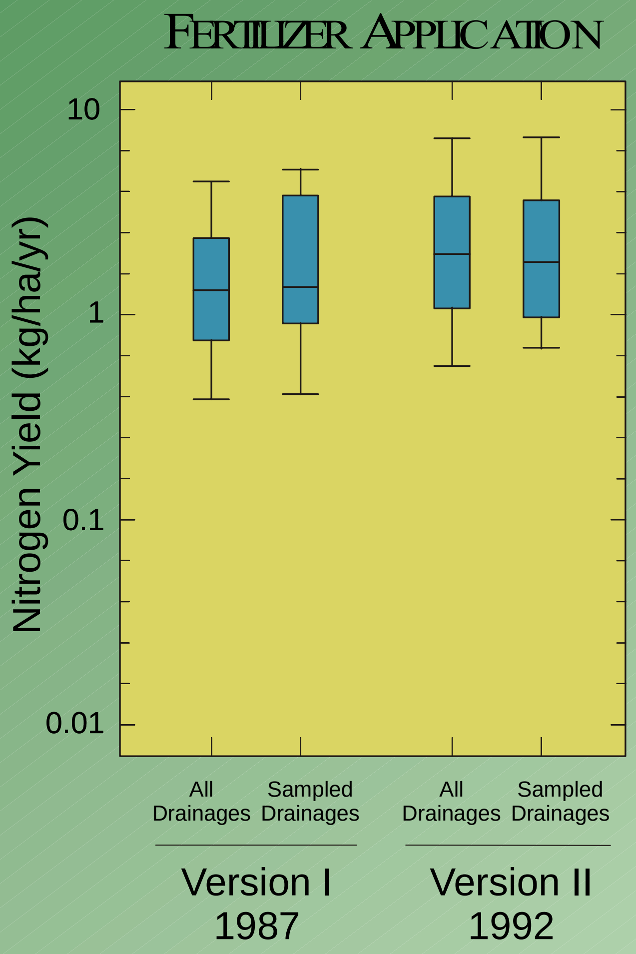
INCREMENTAL YIELD

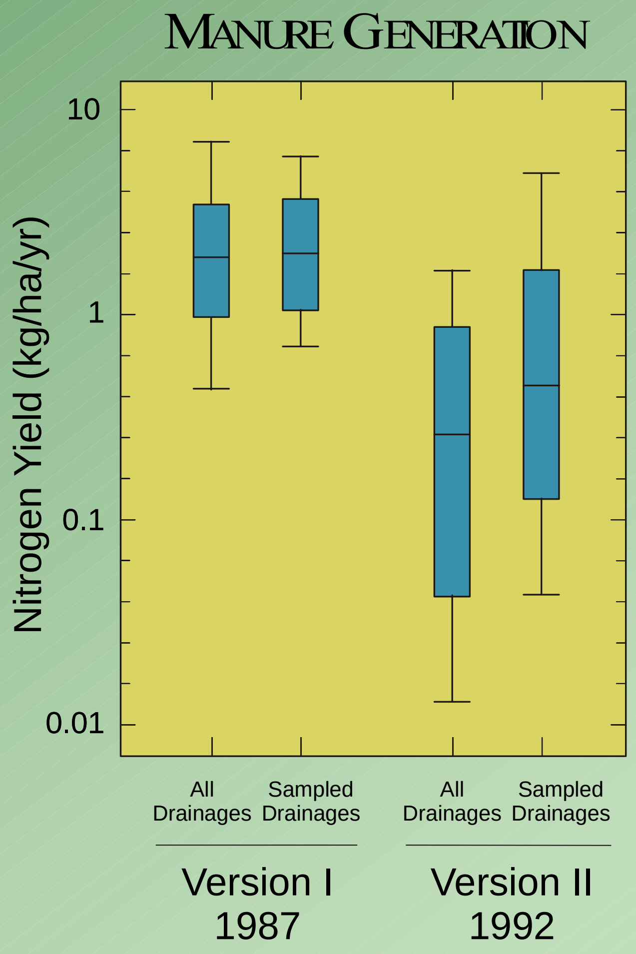


DELIVERED YIELD



MONITORING NETWORK REPRESENTATIVENESS





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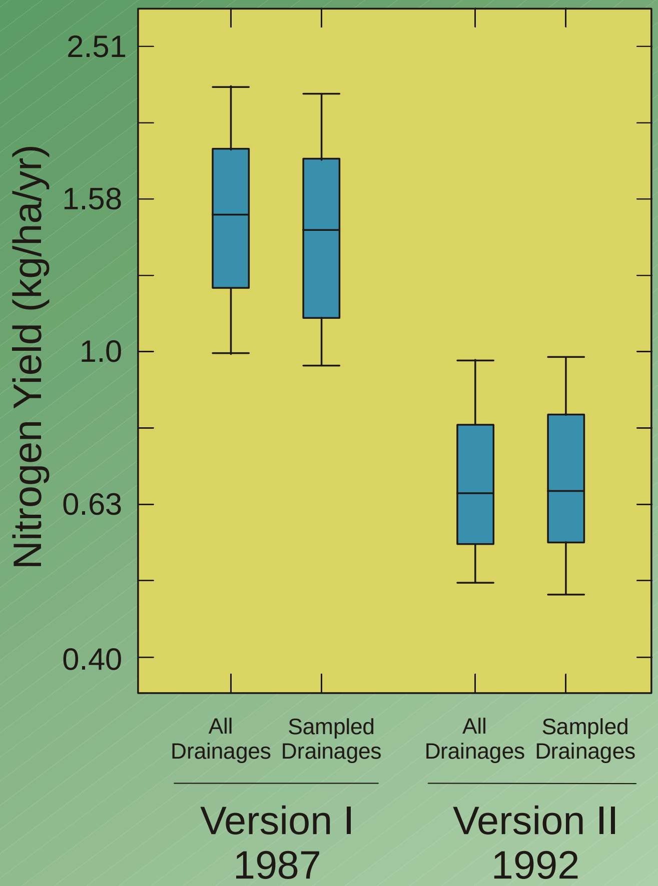
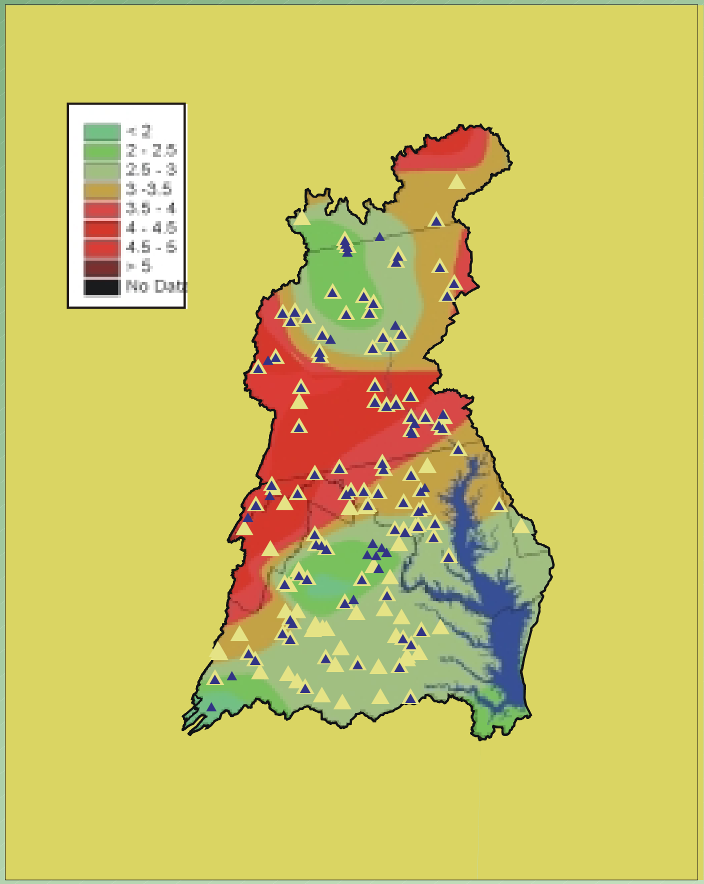
MONITORING NETWORK REPRESENTATIVENESS

ATMOSPHERIC DEPOSITION

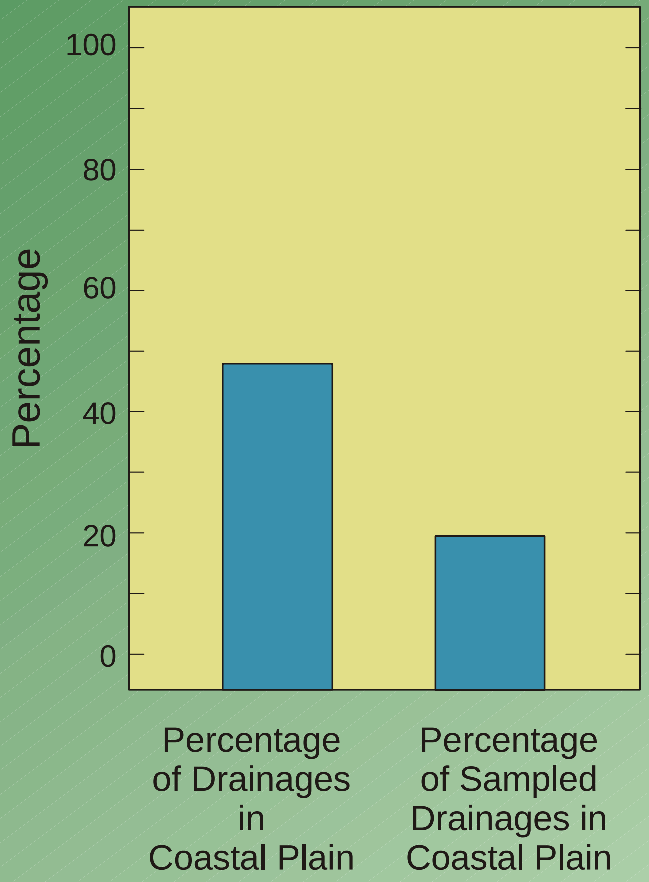


NADP / STREAM LOAD SITES

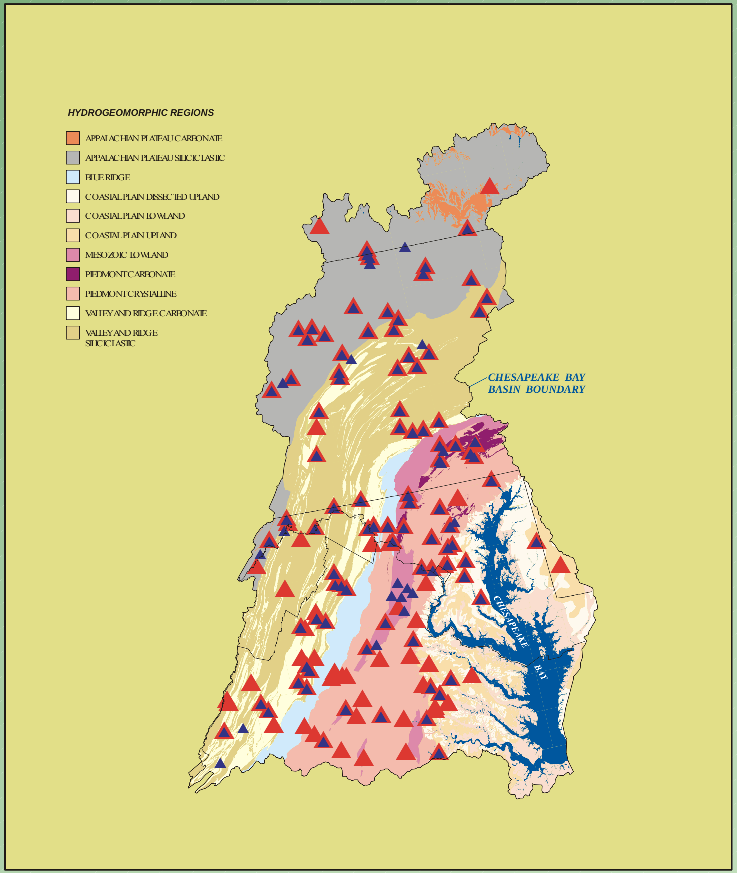


MONITORING NETWORK REPRESENTATIVENESS

COASTAL PLAIN PERCENTAGE



HGMR / STREAM LOAD SITES



Preliminary Recommendations for Non-Tidal Monitoring Network

* Add Sites to the Coastal Plain Part of the Watershed

* Add Sites at Drainage Boundaries of Management Strategy Design Units

* Increase the Amount of Storm Sampling

SPARROW Management Applications

- TMDL
- Studying change over time
- Targeting of nutrient controls
- Natural background
- Atmospheric deposition
- Drinking Water Quality
- Network design
- Marginal Effects of Changing Inputs

Application of SPARROW in Simulation Mode

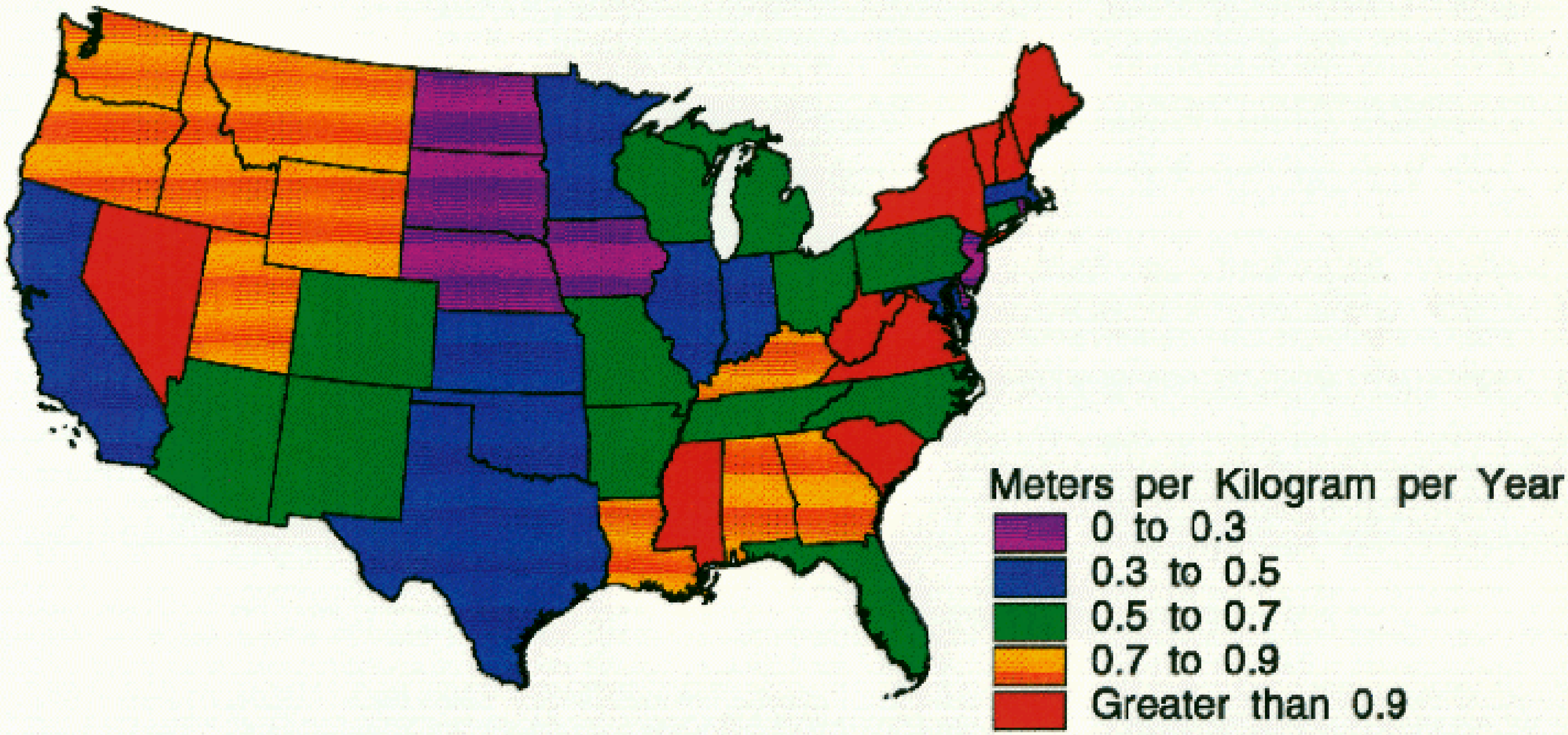
Marginal Effects of Changing Inputs

(e.g. Meters of stream channel brought into compliance with a w.q. standard per kilogram of TP reduction)

- Run model with a small incremental reduction in loads from specified sources
- Track reaches in which concentration falls below 0.1 mg/l
- Summarize results over desired region (and map reaches that change status)
- Results not easily anticipated
- Note: results will differ with a larger reduction

Marginal Benefits of Phosphorus Control:

Meters of U.S. Streams Brought into Compliance per Kilogram per Year of Phosphorus Source Reduction by Individual States



SPARROW Model Applications: Other issues

- Model uncertainty in predictions
- Web access to SPARROW applications

Evaluation of Uncertainty in SPARROW

Three Sources of Uncertainty

- Parameter uncertainty due to finite sample size
  - Goes to zero as sample size goes to infinity
- Model uncertainty due to unaccounted factors affecting water quality
  - Goes to zero only by including additional explanatory factors
- Measurement error
  - Exists in both the dependent variables and the predictors
  - Cannot be removed by introducing either more observations or more variables
  - Measurement error in predictors causes biased coefficient estimates, but not necessarily biased predictions
  - The use of estimated loads as the dependent variable creates complications in deriving prediction intervals

Measures of Uncertainty

- Standard Error of Prediction

$$\text{StandardError}\,\hat{y} = \sqrt{E\left(y - \hat{y}\right)^2}$$

- Confidence Intervals

$$\Pr\left(\underline{\hat{\theta}}_k \le \theta_k \le \bar{\hat{\theta}}_k\right) = \alpha$$

Problems with Standard Uncertainty Measures in the SPARROW Model

- Parameters are estimated using non-linear least squares
  - Estimates of coefficient error are valid only asymptotically (that is, for large sample sizes)
- Errors in model may not be normally distributed
- Predictions are generally not linear functions of the parameters or model errors
  - Analytic derivation of uncertainty measures is intractable
  - Predictions may be biased

Uncertainty in Parameters vs. Uncertainty in Predictions

- Uncertainty in Parameters

Objective function:

$$S = \sum_{i=1}^{N} \left(y_i - f_i(\theta) \right)^2$$

Covariance Matrix:

$$V(\hat{\theta}) = s^2 \left(\sum_{i=1}^{N} f_{i,\theta} \, f'_{i,\theta} \right)^{-1}$$

Bootstrap Variance

- The bootstrap method computes B estimates of θ, call them $\hat{\theta}_b$, $b = 1, \ldots, B$, by minimizing:

$$S^b = \sum_{i=1}^{N} w_i^b \left(y_i - f_i(\theta)\right)^2$$

where w_i^b are integer random weights that sum to N.

Bootstrap Variance

$$V\left(\hat{\theta}_k\right)^* = \frac{1}{B}\sum_{b=1}^{B}\left(\hat{\theta}_{k,b} - \hat{\theta}_k^*\right)^2$$

where, $\hat{\theta}_k^* = \frac{1}{B}\sum_{b=1}^{B}\hat{\theta}_{k,b}$

Parametric Confidence Intervals

$$\underline{\hat{\theta}}_k = \hat{\theta}_k - \sqrt{V\left(\hat{\theta}_k\right)}\Phi^{-1}\left((1+\alpha)/2\right), \text{ and}$$

$$\overline{\hat{\theta}}_k = \hat{\theta}_k - \sqrt{V\left(\hat{\theta}_k\right)}\Phi^{-1}\left((1-\alpha)/2\right)$$

where Φ^{-1} is the inverse standard normal distribution

This confidence interval is second order accurate.

Bootstrap Confidence Intervals

$$\underline{\hat{\theta}}_k^* = \hat{\theta}_k - H^{*-1}\left((1+\alpha)/2\right), \text{ and}$$

$$\overline{\hat{\theta}}_k^* = \hat{\theta}_k - H^{*-1}\left((1-\alpha)/2\right)$$

where $H^{*-1}(p)$ is the p^{th} quantile of the empirical distribution of $\hat{\theta}_{k,b} - \hat{\theta}$

This confidence interval is also second order accurate.

Uncertainty in Predictions

- Parametric Prediction

$$c = g(\theta, \varepsilon)$$

If $P_\varepsilon(z)$ and θ were known, the prediction of c would be

$$\bar{c} = \int g(\theta, z)\, dP_\varepsilon(z)$$

Parametric Prediction – Stage 1

Use coefficient estimates and estimated errors

$$\hat{c} = \frac{1}{N}\sum_{i=1}^{N} g\left(\hat{\theta}, \hat{\varepsilon}_i\right)$$

Because of non-linearity of g, this estimate is biased.
Assume proportional bias:

$$\beta = \frac{E\left[\hat{c}\right]}{\bar{c}}$$

Bootstrap Method for the Correction of Proportional Bias

Bootstrap resampled iteration *b* prediction $\hat{c}_b = \frac{1}{N}\sum_{i=1}^{N} g\left(\hat{\theta}_b, \hat{\varepsilon}_i\right)$

and mean $\overline{\hat{c}_b} = \frac{1}{B}\sum_{b=1}^{B} \hat{c}_b$

Bootstrap estimated bias $\beta^* = \frac{\overline{\hat{c}_b}}{\hat{c}}$

Bias corrected estimate of *c* $\hat{c}_{BC} = \frac{\hat{c}}{\beta^*} = \frac{\hat{c}^2}{\overline{\hat{c}_b}} > 0$

Variance Estimate

$$\hat{V}\left[c-\hat{c}_{BC}\right]=\frac{1}{N}\sum_{i=1}^{N}g\left(\hat{\theta},\hat{\varepsilon}_i\right)^2-\hat{c}^2+\frac{\frac{1}{B}\sum_{b=1}^{B}\left(\hat{c}_b-\overline{\hat{c}_b}\right)^2}{\beta^*}$$

Bootstrap Prediction Interval

$$\text{Lowerbound} = \hat{c}\exp\left(-H^{-1}_{\tilde{\hat{c}}_b^* - \tilde{\hat{c}}^*}\left(\left(1+\alpha\right)/2\right)\right)$$

$$\text{Upperbound} = \hat{c}\exp\left(-H^{-1}_{\tilde{\hat{c}}_b^* - \tilde{\hat{c}}^*}\left(\left(1-\alpha\right)/2\right)\right)$$

where $\hat{c}^* = g\left(\hat{\theta}, \hat{\varepsilon}^*\right), \hat{\varepsilon}^*$ is a randomly-selected residual from among the *N* residuals obtained in the original full model calibration, and $H_{\tilde{\hat{c}}_b^* - \tilde{\hat{c}}^*}\left(x\right)$ is the empirical distribution of $\ln\left(\hat{c}_b^*\right) - \ln\left(\hat{c}^*\right)$

This prediction interval is first order accurate and strictly positive.

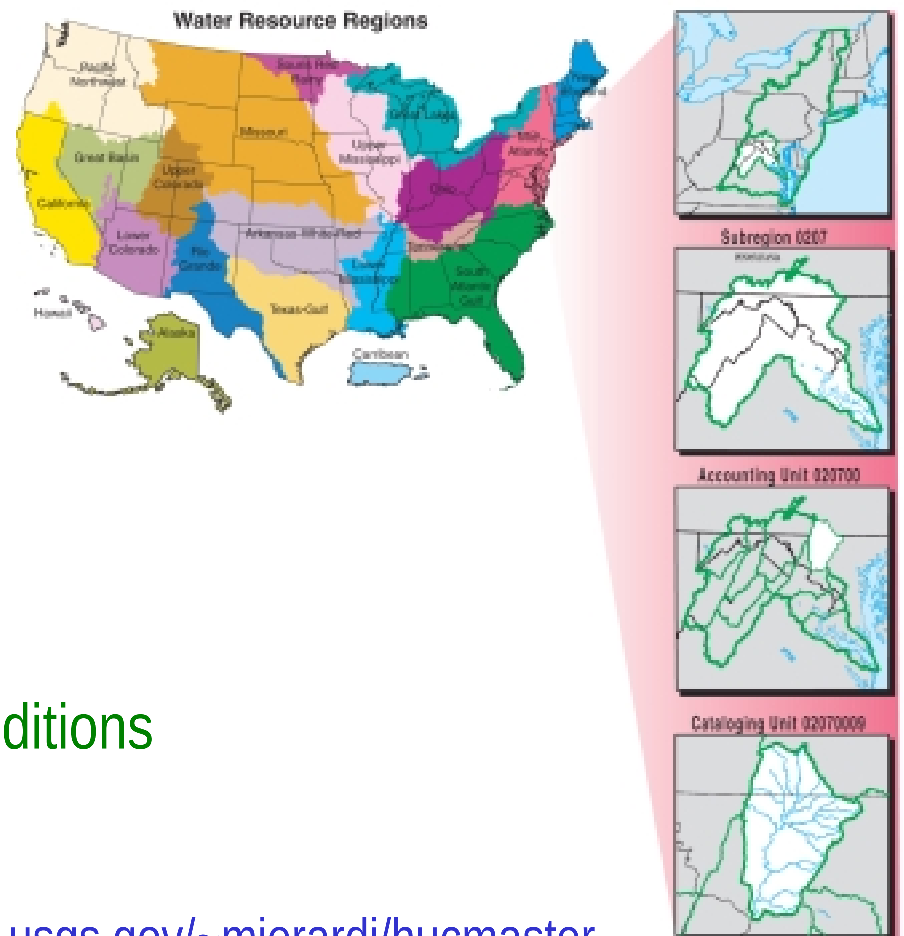
SPARROW Model Applications: Other issues

- Model uncertainty in predictions
- Web access to SPARROW applications

SPARROW WEB

Watershed Data and Model Predictions for 62,000 Stream Reaches

Example of Nested Hydrologic Units in the Mid Atlantic Region 02



- Mean-annual streamflow, water velocity, drainage area
- NLCD land use (1992)
- Population, waste disposal type (1990 Census)
- Mean-annual nutrient conditions (yield, concentration, sources, prediction uncertainties)
- Natural background nutrient conditions
- Public release: 2003

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Internal URL: http://hqsun2.er.usgs.gov/~mierardi/hucmaster