Overview of SPARROW Modeling

R.A. Smith, R.B. Alexander, G.E. Schwarz, J.V. Nolan

U.S. Geological Survey
National Water Quality Assessment Program
Reston, Virginia USA

USGS science for a changing world

http://water.usgs.gov/nawqa/sparrow

Outline of Topics

- What is SPARROW? How is it unique?
- How is it structured and evaluated?
- How can it be used?
- What is the role for SPARROW in future national and regional modeling?
- How is the model evaluated for accuracy?
- Who is currently involved in SPARROW modeling?
- What are the problems and limitations?

USGS
science for a changing world

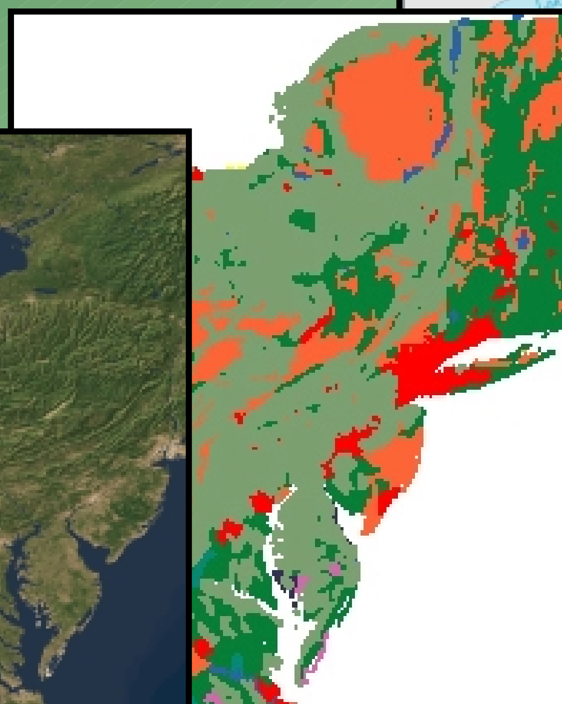
What is SPARROW?

- **SPA**tially-**R**eferenced **R**egression **O**n **W**atershed Attributes
- Water-quality model linked to a network of monitoring stations
- Statistically calibrated
- Equations expressed in terms of watershed flow paths (network of stream reaches) and attributes

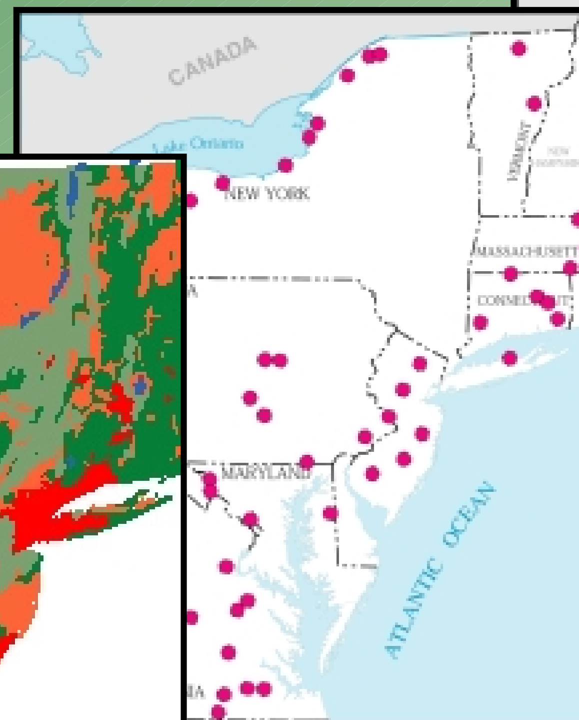
Uses watershed data and simple mechanistic features to statistically estimate origin & fate of contaminants

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

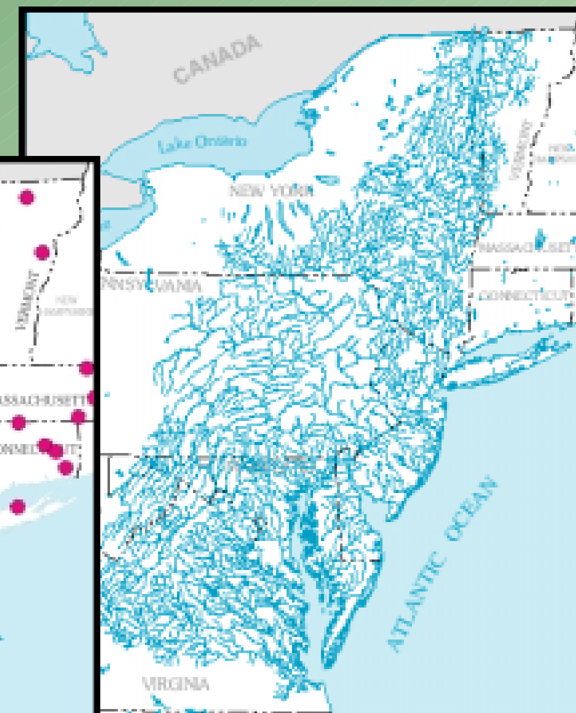
Landscape Features



Land Use & Sources



Monitoring Data

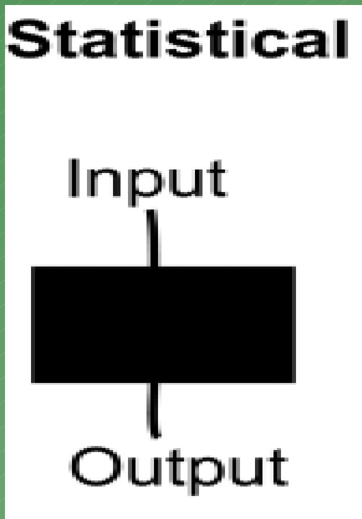


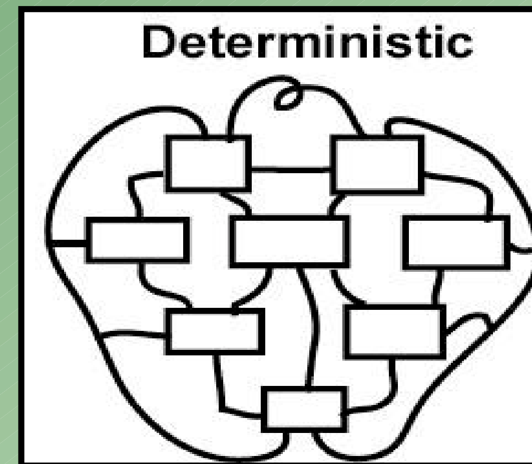
Drainage & Impoundments

Smith et al. Water Resour. Res., 1997
http://water.usgs.gov/nawqa/sparrow

USGS
science for a changing world

What is the relation of SPARROW to other watershed models?





<u>Statistical ("Black box") Models</u>

- Simple mathematical structure
- Easy to build
- Known error bounds (<u>in range of data</u>)

- Little process description
- Difficult to interpret results

<u>Deterministic Models</u>

- Complex math structure
- Large time/resources to build
- Error bounds not well known

- Detailed description of processes
- Provides insight into behavior of system (<u>if accurate</u>)

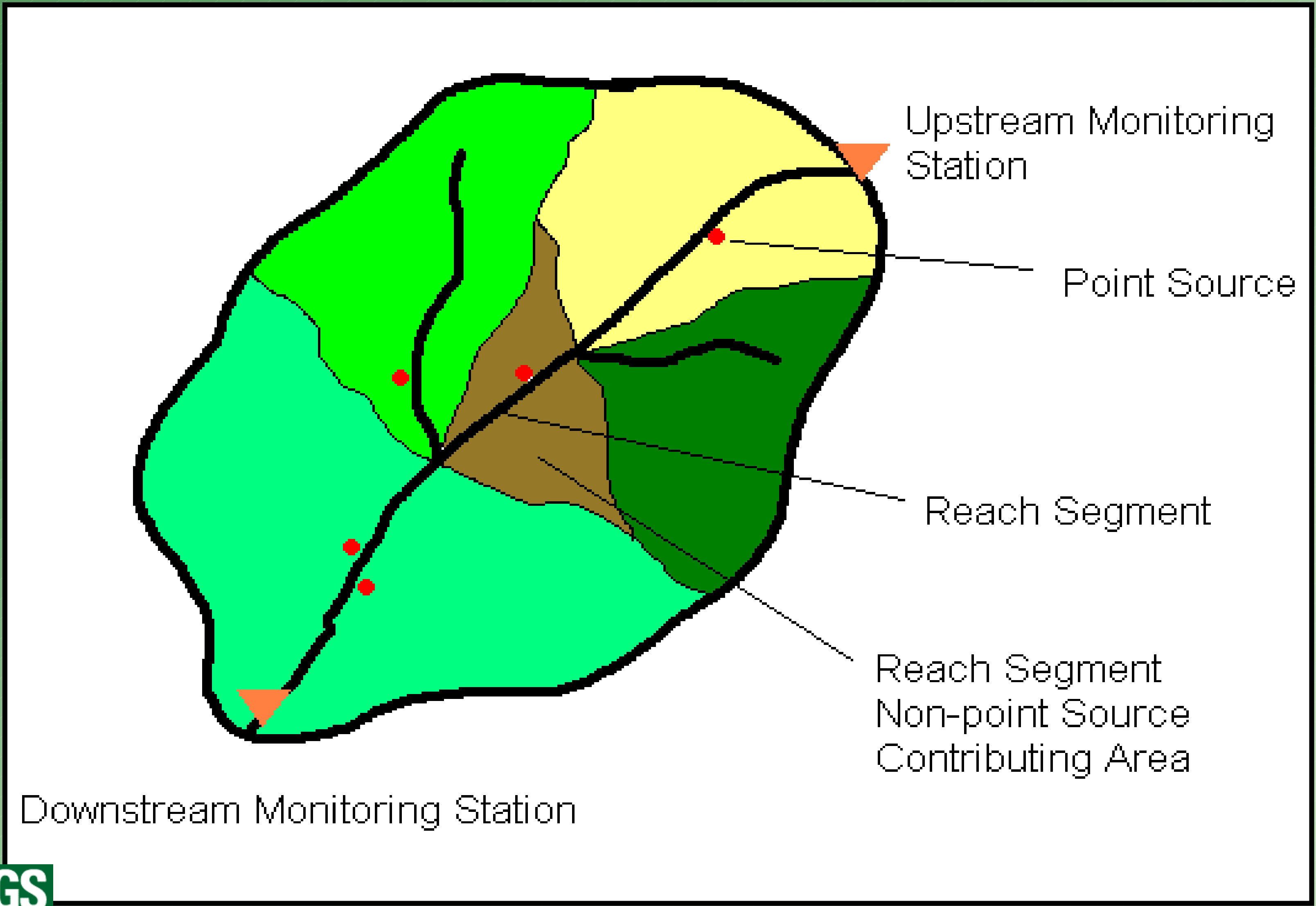
USGS
science for a changing world

How is SPARROW structured?

- Equations describe the average rate of movement of material through watersheds:
  - from sources on land to stream channels,
  - then downstream through stream channels.
- Characteristics of the sources, land, and stream channels are variables in the model.
- Measurements of material flux past monitoring sites are regressed on these variables.

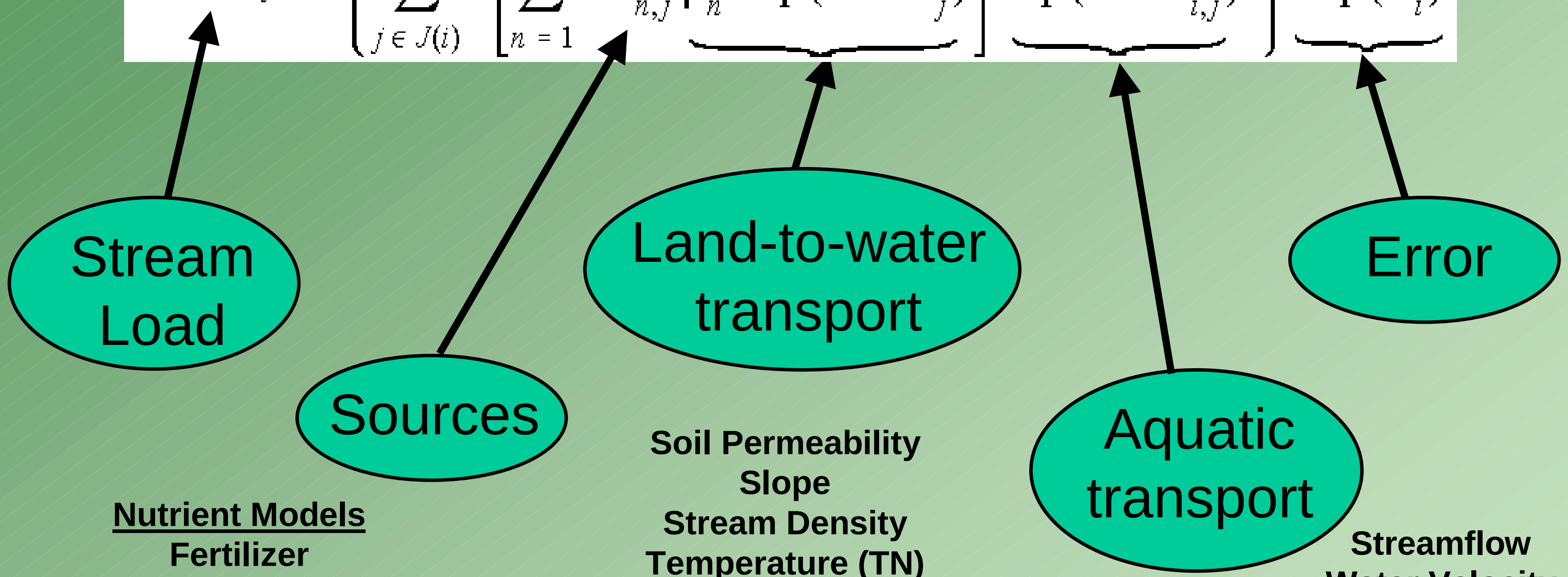
USGS
science for a changing world

How is SPARROW structured?



SPARROW
Estimated Equation

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



Soil Permeability
Slope
Stream Density
Temperature (TN)

<u>**Nutrient Models**</u>
Fertilizer
Animal Wastes
Atmosphere (TN)
Industrial & Municipal Wastes
Nonagricultural Diffuse Sources
Land Use

Streamflow
Water Velocity
Channel Length
Reservoir Hydraulics

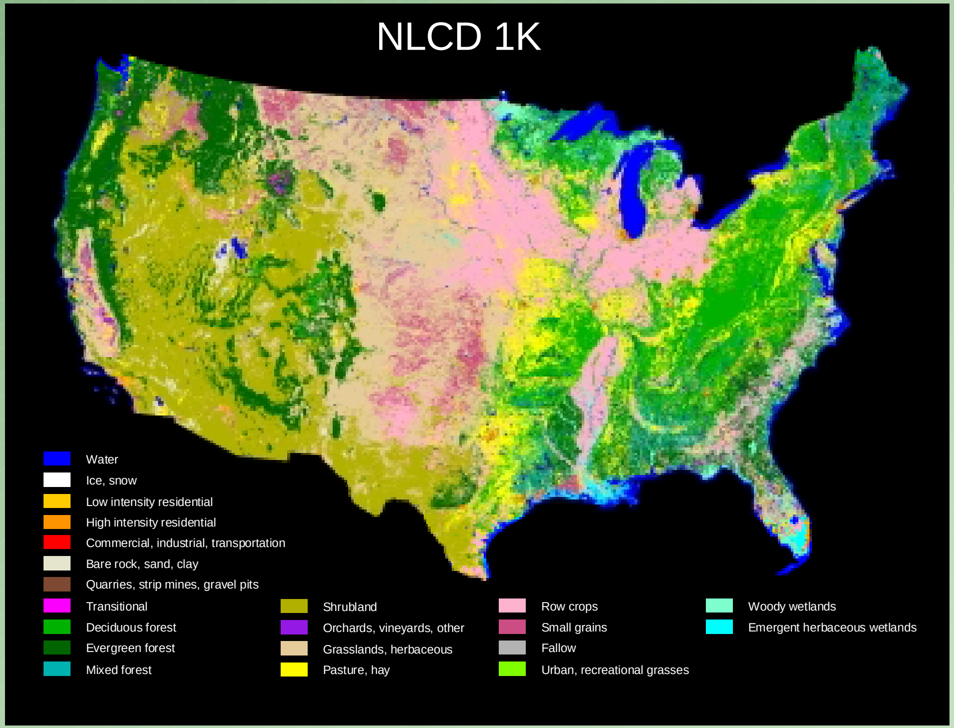
USGS science for a changing world

New SPARROW Infrastructure

HYDRO 1-km Watershed Boundaries

Nolan et al. 2002
(http://water.usgs.gov/lookup/getspatial?erf1-2)

1992 NLCD 30-m Land Use



How may SPARROW be used?

- Describe conditions
- Identify sources
- Simulate alternative conditions
- Analyze uncertainty (design monitoring)
- Conduct basic research

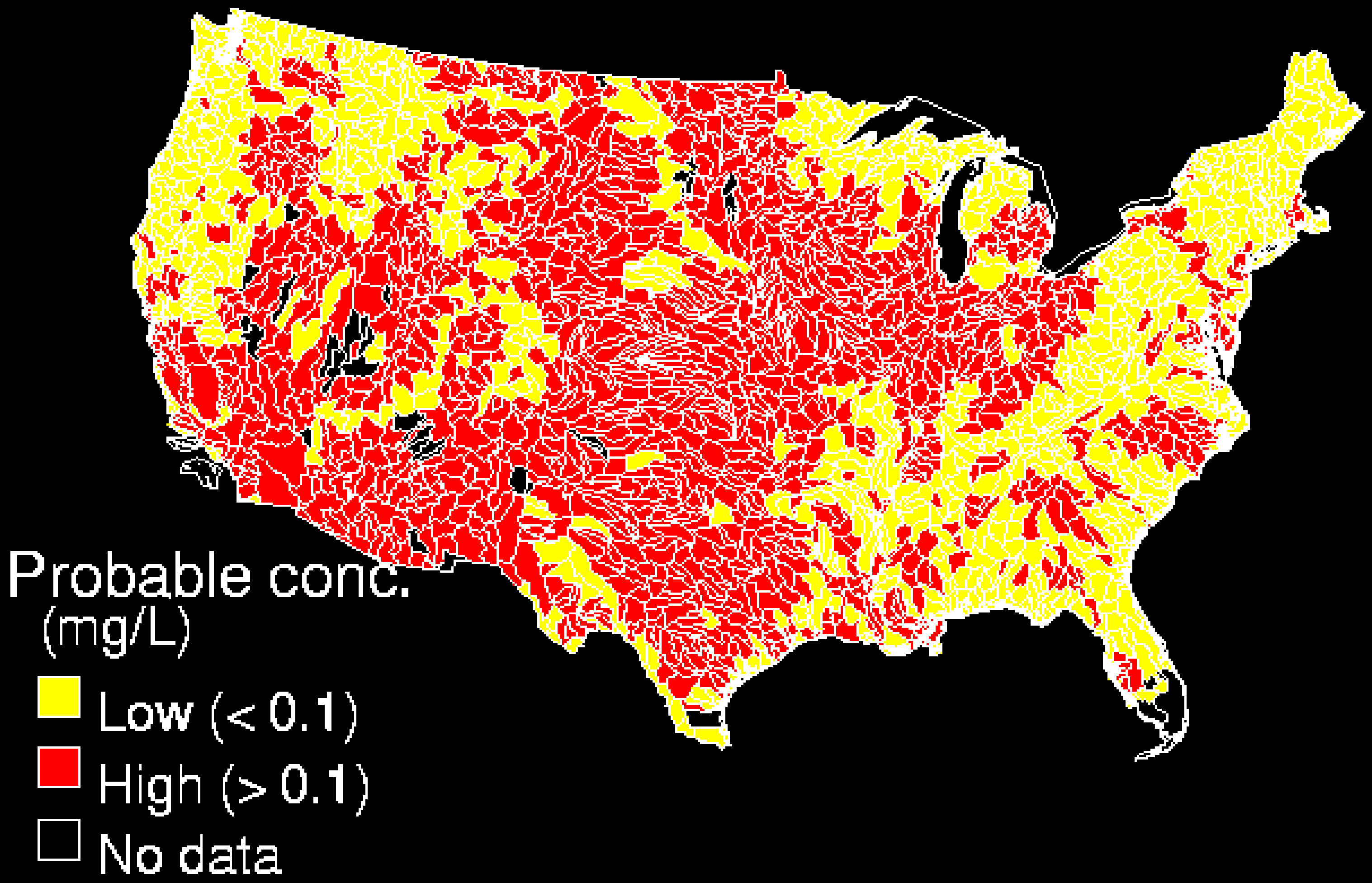
How may SPARROW be used?

1. Describe National and Regional Conditions

- Addresses two major limitations of monitoring:
  - Cost (sparse sampling)
  - Geographic sampling bias
- May be integrated into National and regional assessment programs
- Will provide reach-level info. on WWW
- Other basin information will be included

USGS science for a changing world

CLASSIFICATION OF PREDICTED TP CONCENTRATION IN HUCs



From Smith et al. 1997

USGS
science for a changing world

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

USGS science for a changing world

How may SPARROW be used?

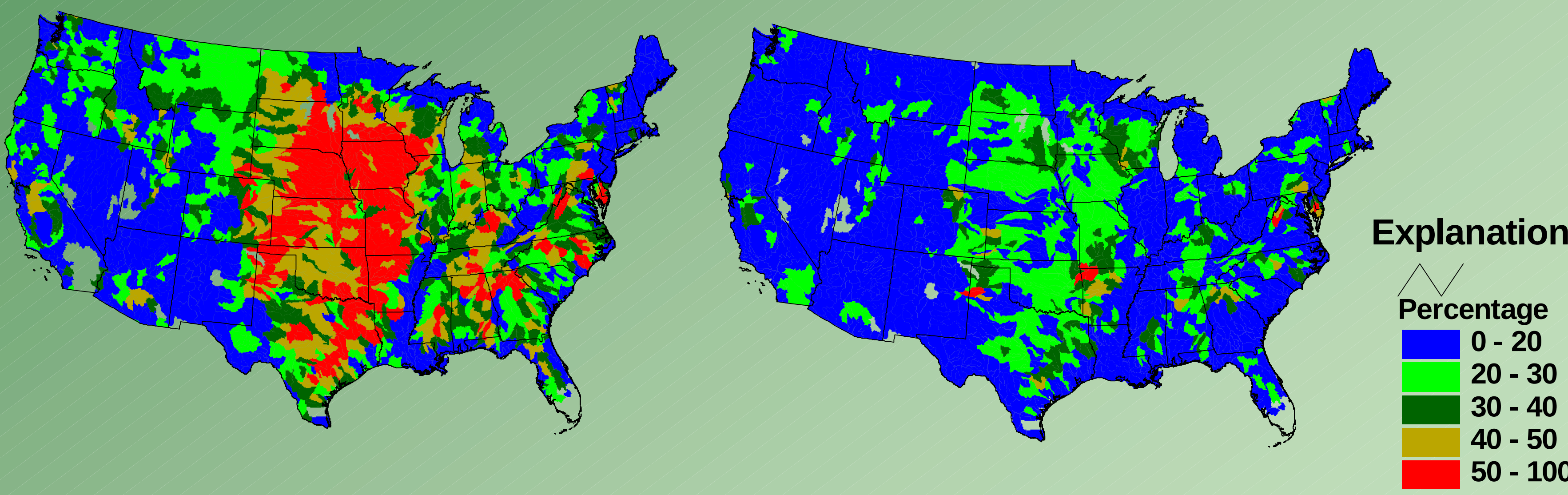
2. Identify Pollution Sources

- Model links conditions in each stream reach to individual sources in each upstream reach.
- Potential tool for TMDL development
- Especially valuable in large (interstate) basins

SPARROW Predictions

Nutrients from Animal Agriculture in Streams

Total Phosphorus **Total Nitrogen**



From Smith and Alexander, 2000

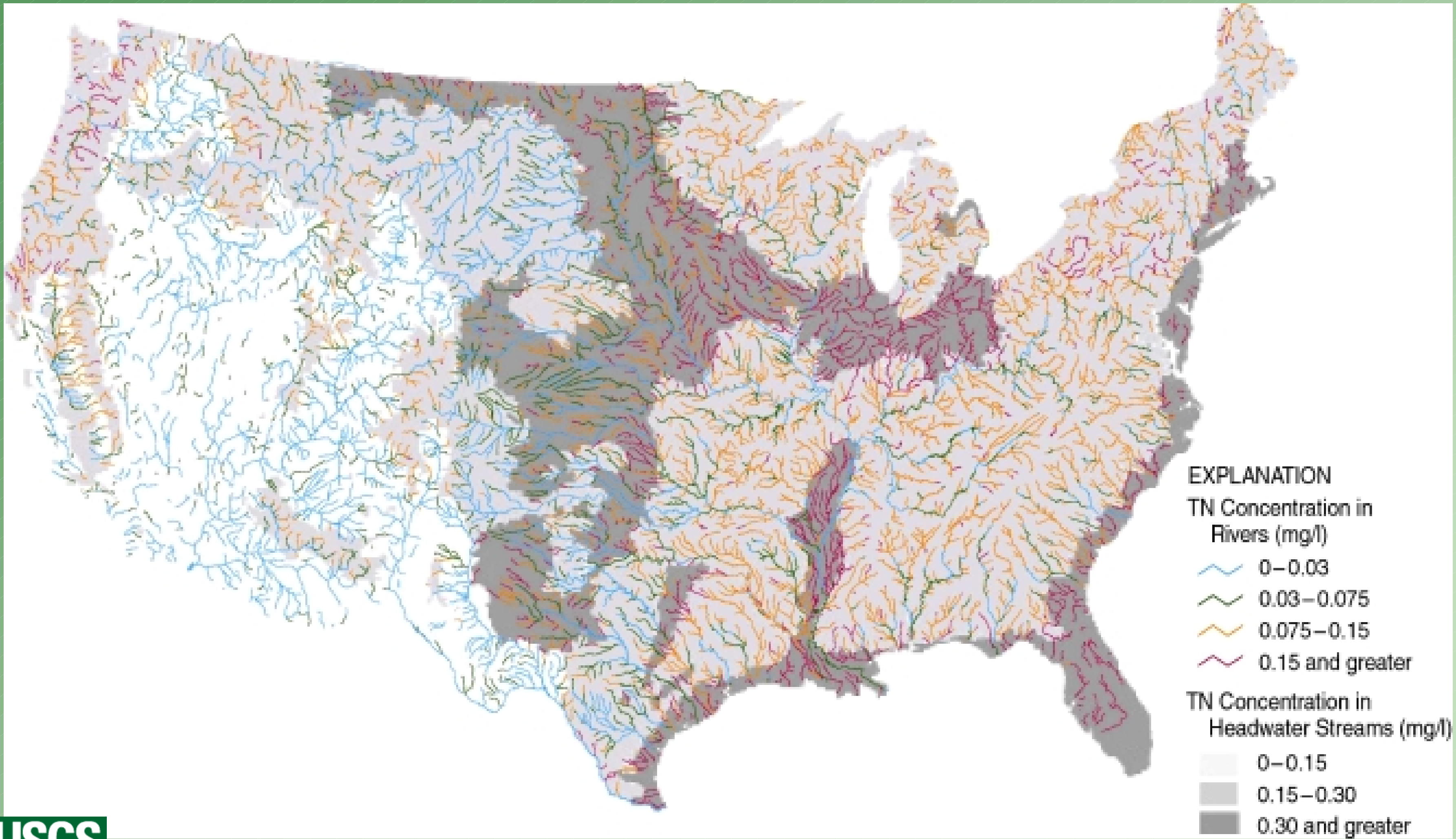
How may SPARROW be used?

3. Simulate Alternative Conditions

- Evaluate pollution control programs
- A potential tool for research in large basins

USGS
science for a changing world

Estimated Background TN Concentrations in RF1 Streams and Rivers



USGS
science for a changing world

How may SPARROW be used?

4. Analyze Uncertainty

- A statistical tool in ecological risk assessment
- Design monitoring to reduce uncertainty

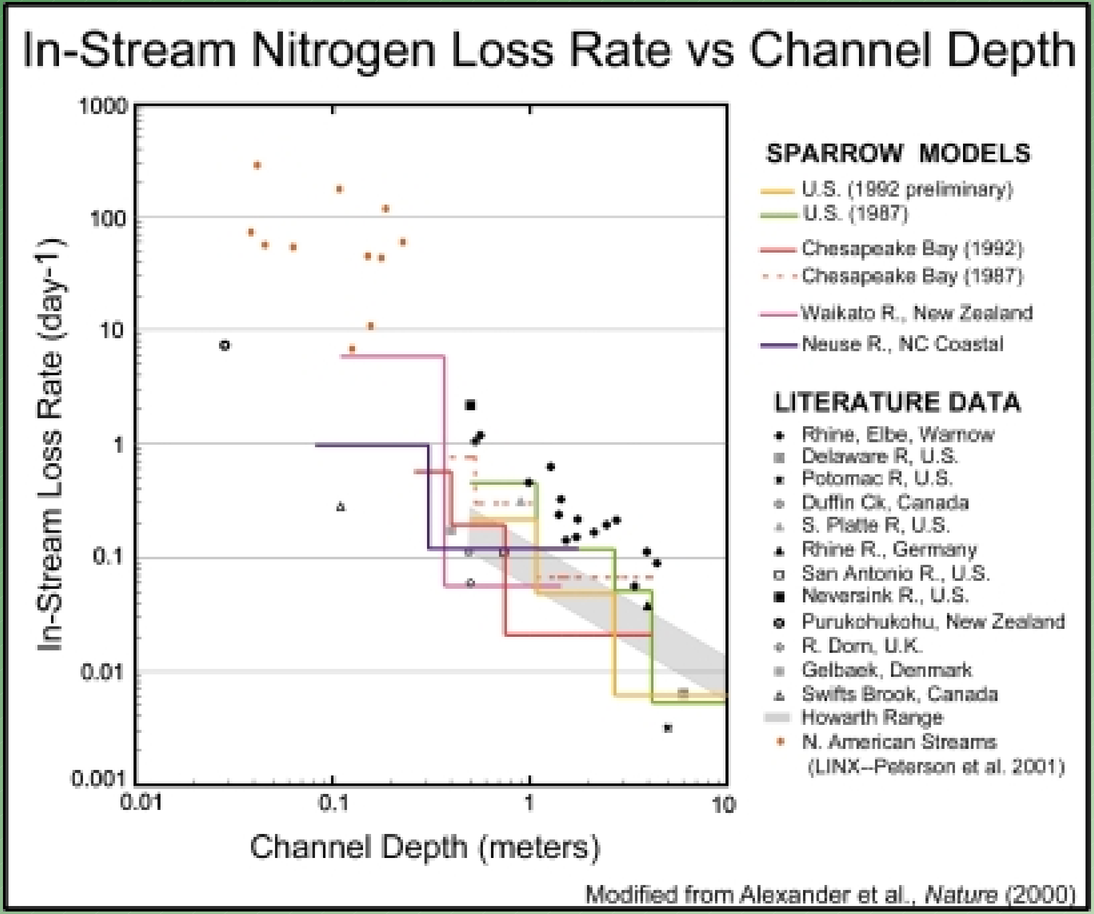
How may SPARROW be used?

5. Conduct Basic Research

- Test hypotheses over large geographic areas
  - Test generality
  - Take advantage of wide range in dependent and independent variables
- National and regional models could be made available to the research community for testing hypotheses

USGS science for a changing world

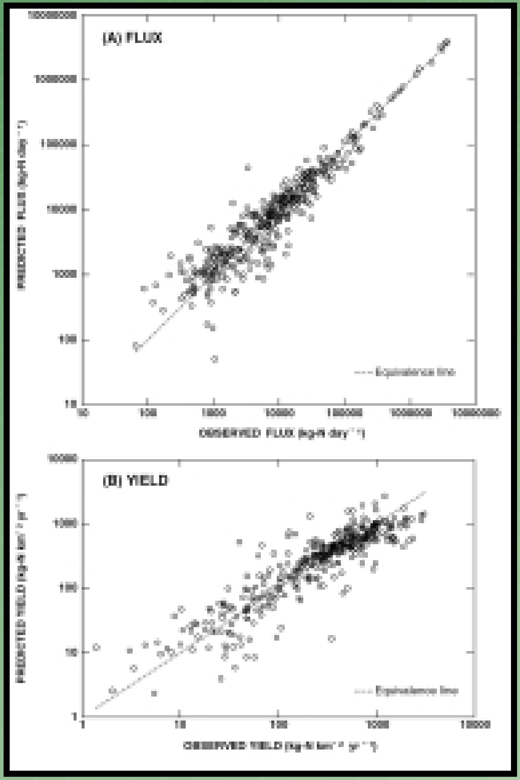
In-Stream Routing of Nitrogen



- In-stream routing of contaminants performed as a function of 1st-order decay & water TOT or channel length estimated for a range of stream sizes

Evaluation and Verification of SPARROW Models

Observed vs Predicted N at Monitoring Stations



- **Statistical measures of model fit**

  --Model explains ~88-96% of spatial variability in flux

  --Typical prediction errors: +/- 35% to +/- 75%

  --Coefficient confidence intervals

- **Comparisons of model coefficients with literature rates**

  --Physical interpretability of the model

  --Catchment yields by land use, per capita waste loads, point-source coef., in-stream decay, reservoir settling rates

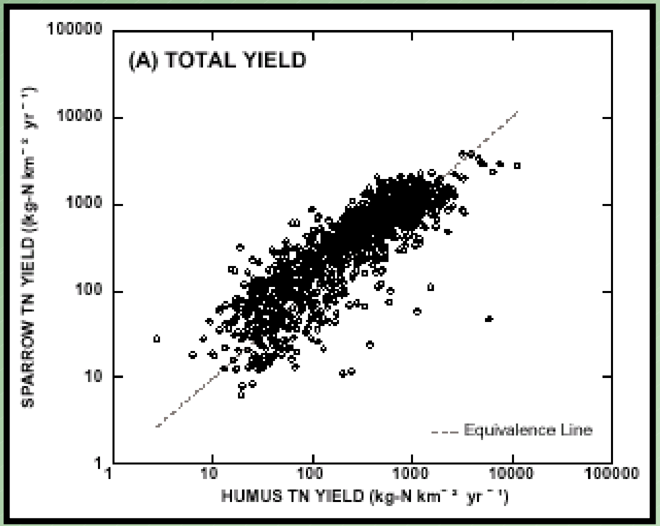
- **Independent stream monitoring data**

Evaluation and Verification of SPARROW Models

- **Inter-model comparisons**

  U.S. and Regional SPARROWs, SWAT, HSPF, Regression methods, N budgets, RivR-N [Valigura et al. 2001 AGU volume; SCOPE N project: Seitzinger et al. 2002 and Alexander et al. 2002]

SPARROW vs. HUMUS (SWAT)
U.S. Hydrologic Cataloging Units

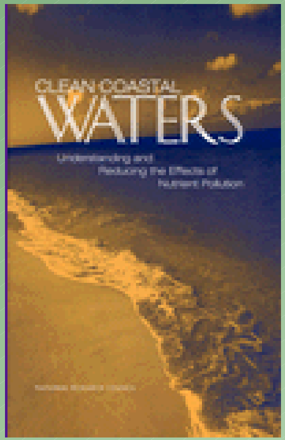


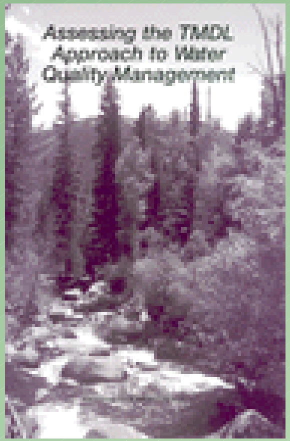
- **Spatial analyses of prediction errors** (tests of mis-specification of large watershed models; *SCOPE N project: Alexander et al. 2002)*

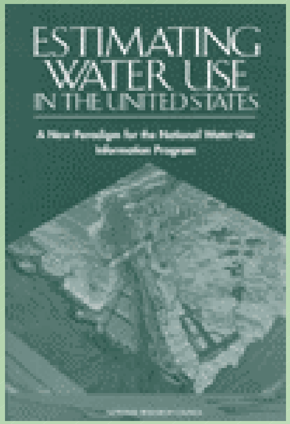
USGS
science for a changing world

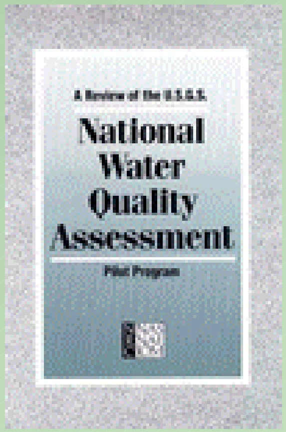
Evaluation and Verification of SPARROW Models

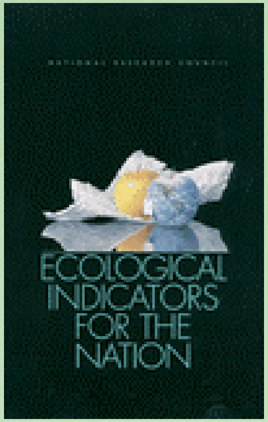
- **National Research Council Reports**
  - Clean Coastal Waters: Understanding and Reducing the Effects of Nutrient Pollution, 2001
  - Ecological Indicators for the Nation, 2001
  - Assessing the TMDL Approach to Water Quality Management, 2001
  - Review of the USGS National Water-Quality Assessment Program, 2002
  - Estimating Water Use in the United States: A New Paradigm for the National Water-Use Information Program, 2002











USGS
science for a changing world

Who is Currently Involved in SPARROW Modeling?

Drainage Basin	***Staff***	***Institution***
• National model	4	USGS/Reston
• Chesapeake Bay	2	MD District
• New England	3	NH/VT District
• Neuse R.	2	NC Dist; Duke U
• Delaware R.	3	NJ District
• Waikato R., NZ	3	NIWA, USGS
• Upper MS (prop.)	4?	USGS (WRD, NMD, BRD, Region ?)

USGS science for a changing world

Applications of the National Model

R.A. Smith, R.B. Alexander, G.E. Schwarz, J.V. Nolan

U.S. Geological Survey
National Water Quality Assessment Program
Reston, Virginia USA

USGS science for a changing world

http://water.usgs.gov/nawqa/sparrow

Past and Current National SPARROW Applications

Programmatic

- USEPA nutrient criteria
- Agriculture and nutrients
  - Livestock waste management (nutrients, fecal bacteria)
  - Evaluating effects of extensive changes in agriculture
  - Prioritizing lands for enrollment in Conservation Reserve Program
- Nitrogen delivery to coastal waters
  - NOAA Eutrophication Assessment
  - N sources to major U.S. estuaries (atmospheric deposition)
  - Mississippi River Basin sources and Gulf hypoxia
  - Evaluations of efficiency of nutrient controls (World Resources Institute)
  - Economically efficient management of nutrients
- Contaminants in surface water drinking water supplies (atrazine)

USGS science for a changing world

Past and Current National SPARROW Applications

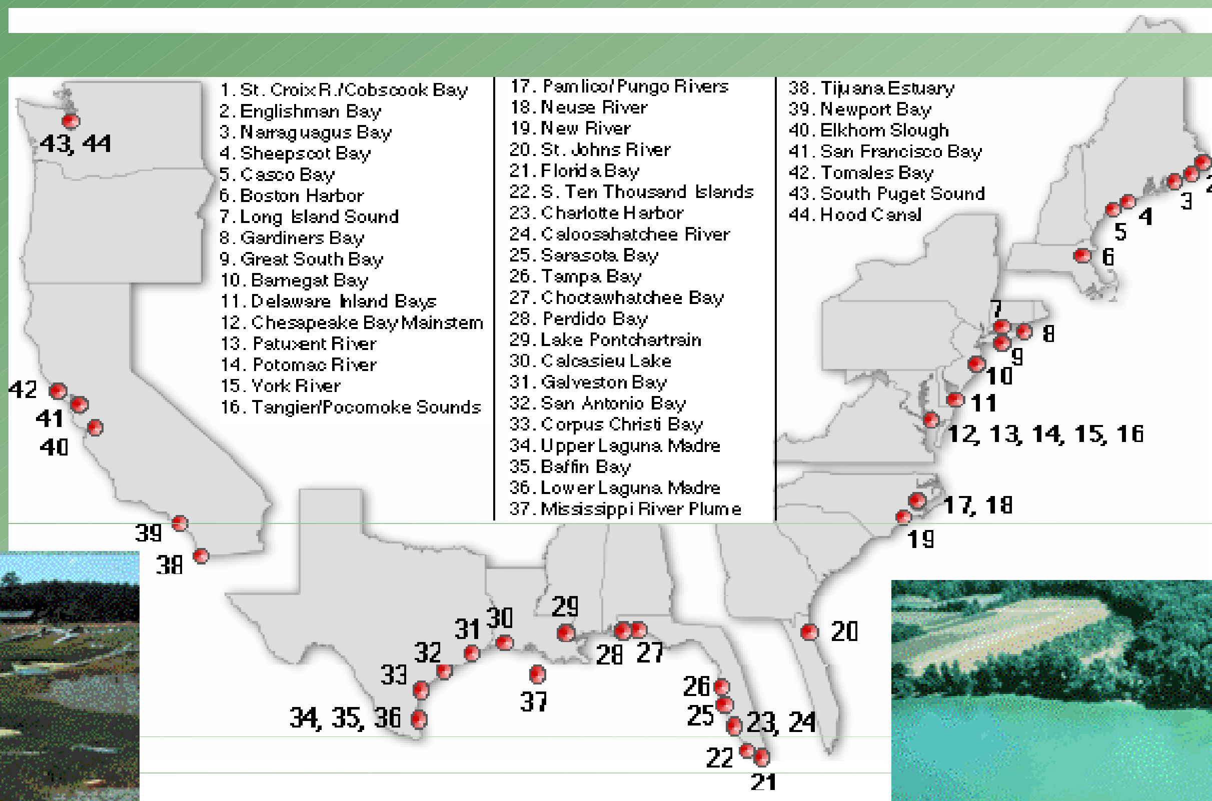
Research

- Nutrient and contaminant processing in streams and reservoirs—mass-balance methods and scaling variables
- SCOPE Nitrogen Project
  - N processing over regional spatial scales (N.E. U.S.)
  - Inter-model comparisons:
    - Riverine export – accuracy evaluation
    - In-stream N loss
- Background nutrients

Estuaries of the United States

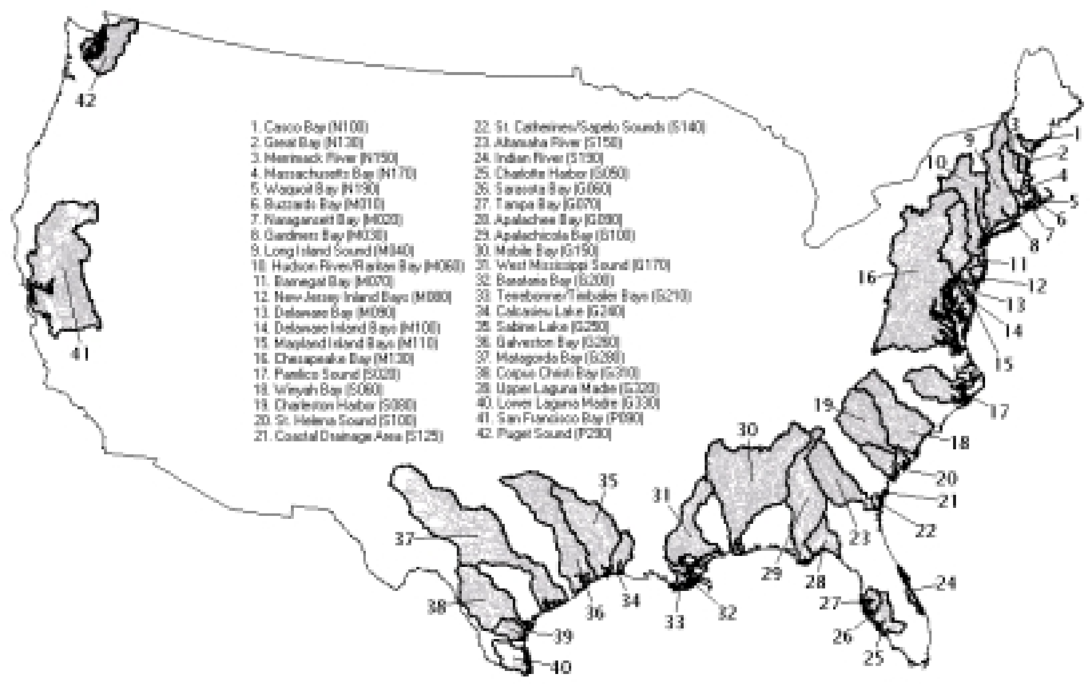
WQ Indicators Denote Highly Stressed Trophic Conditions

NOAA National Eutrophication Assessment, 1999



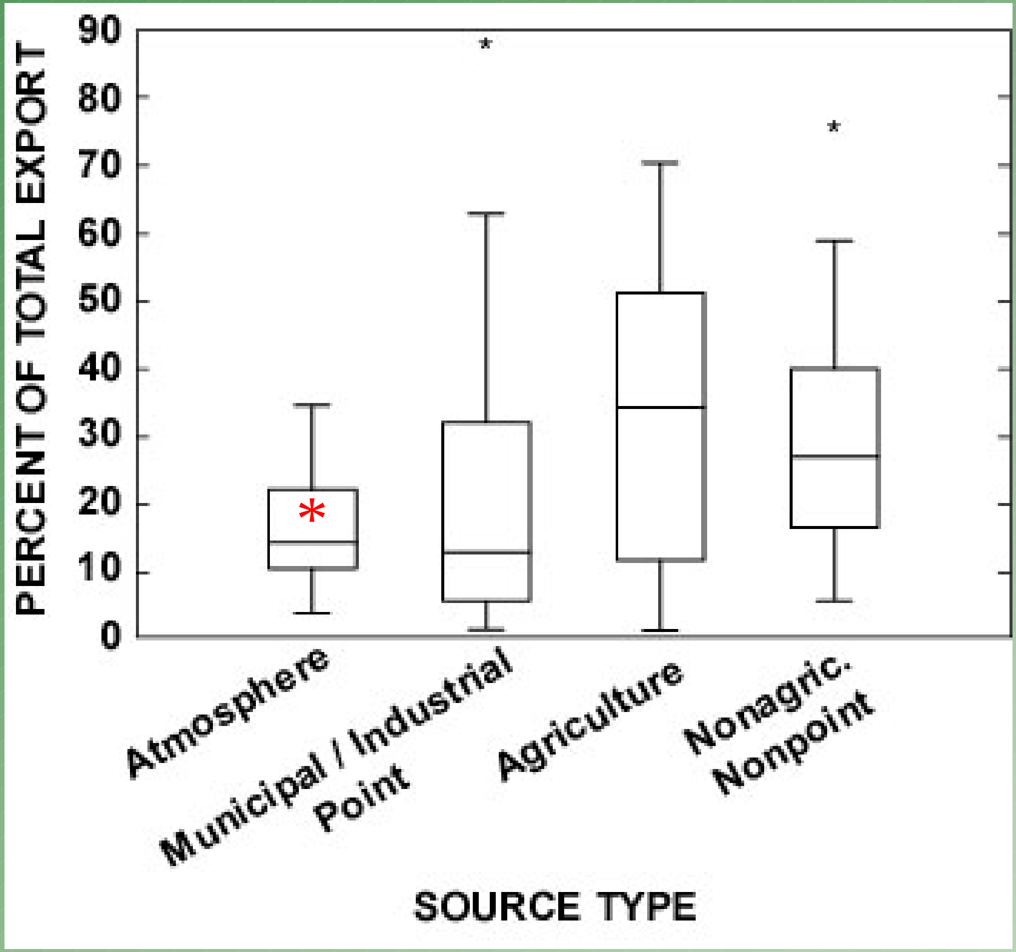
Modified from Bricker et al. 1999

Major Estuarine Watersheds of the Conterminous United States



- A NOAA-EPA sponsored study involving collaboration of > 30 freshwater and marine researchers
- First comprehensive national study of N sources in coastal watersheds
- Study complement a recent NOAA assessment of coastal eutrophication problems (Bricker et al. 1999)

SPARROW Estimates of Nitrogen Sources in Streams Entering 40 Major U.S. Estuaries

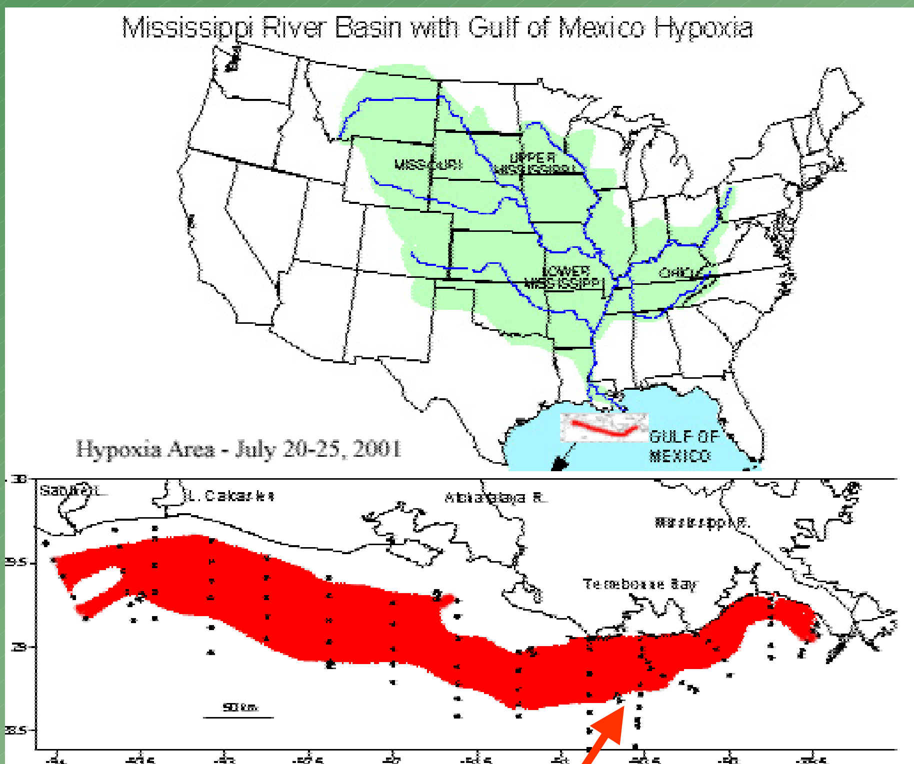


- Largest N contributions from fertilizer and livestock wastes
- Atmospheric and point sources highest along North Atlantic and Gulf coasts
- Direct atmospheric deposition to estuarine water surface a major source of nitrogen

Alexander et al., AGU Coastal & Estuarine Studies 57, 2001, Valigura et al. (eds.)

* Mississippi R. Basin (Alexander et al., *Nature*, 2000)

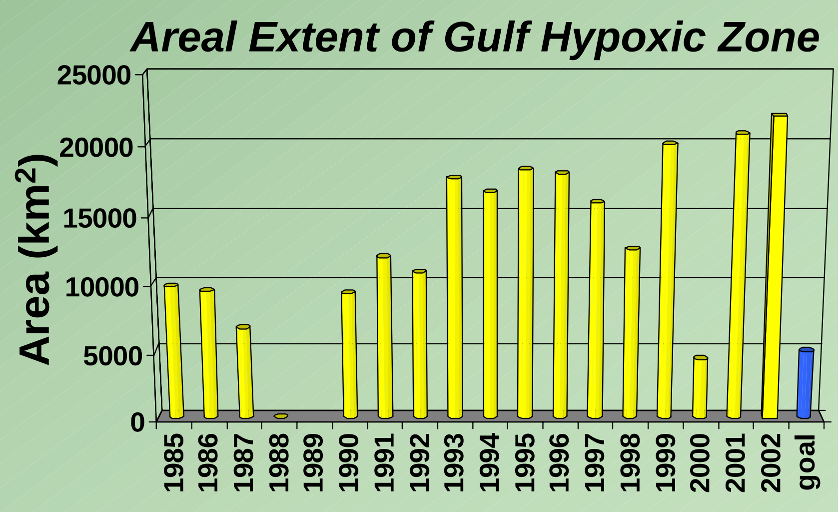
Elevated nutrient loads in coastal streams have caused estuarine trophic conditions to decline



Dissolved oxygen <2 mg/L

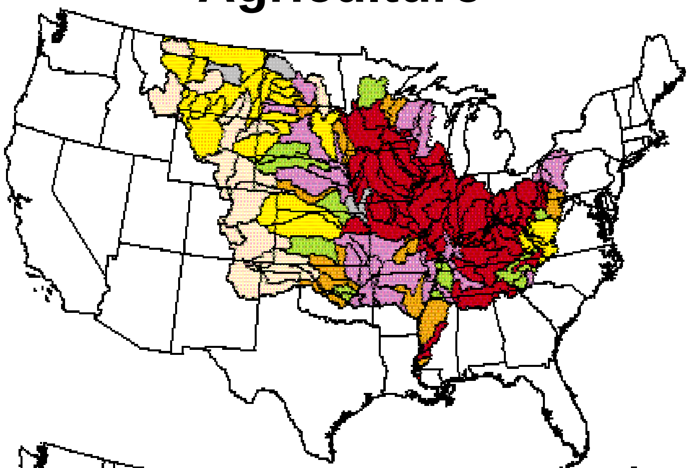
modified from Rabalais et al. 2002

- 44 of 138 U.S. estuaries display eutrophic conditions related to high nutrient loads
- A 30% nitrogen reduction goal recently adopted for the Mississippi River Basin; more stringent goal for 2015

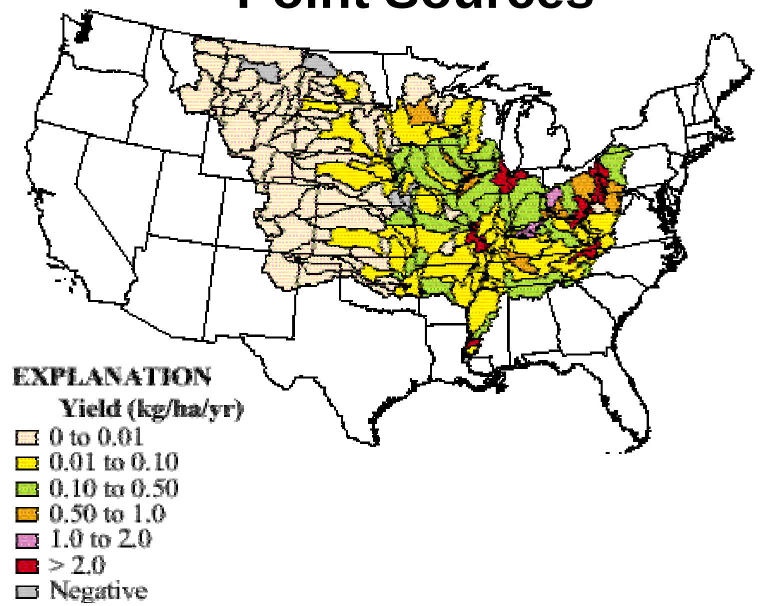


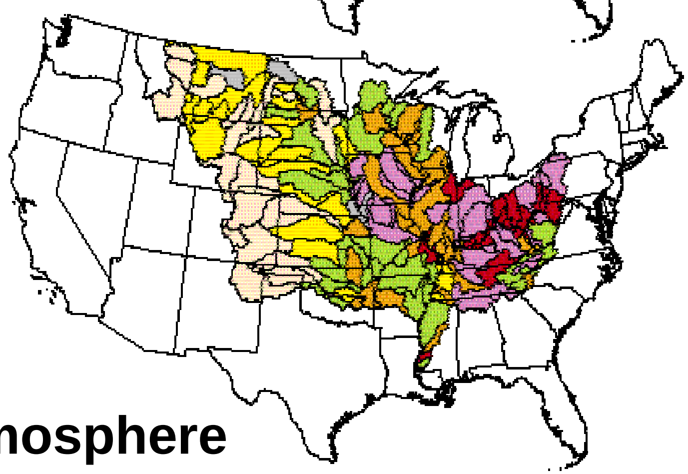
Total Nitrogen Yield Delivered to Gulf of Mexico

Agriculture



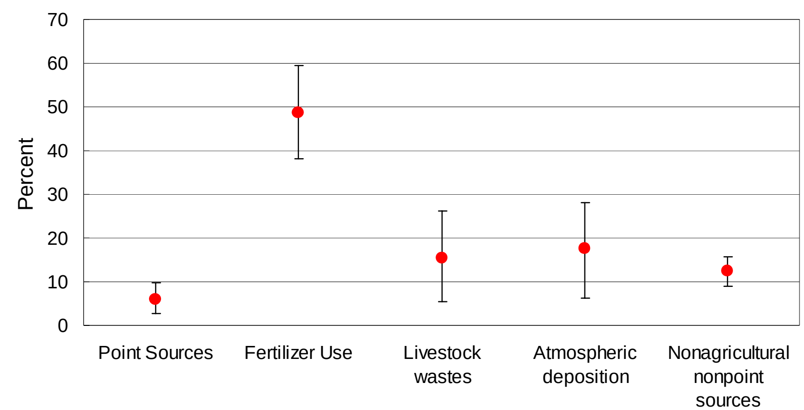
Point Sources





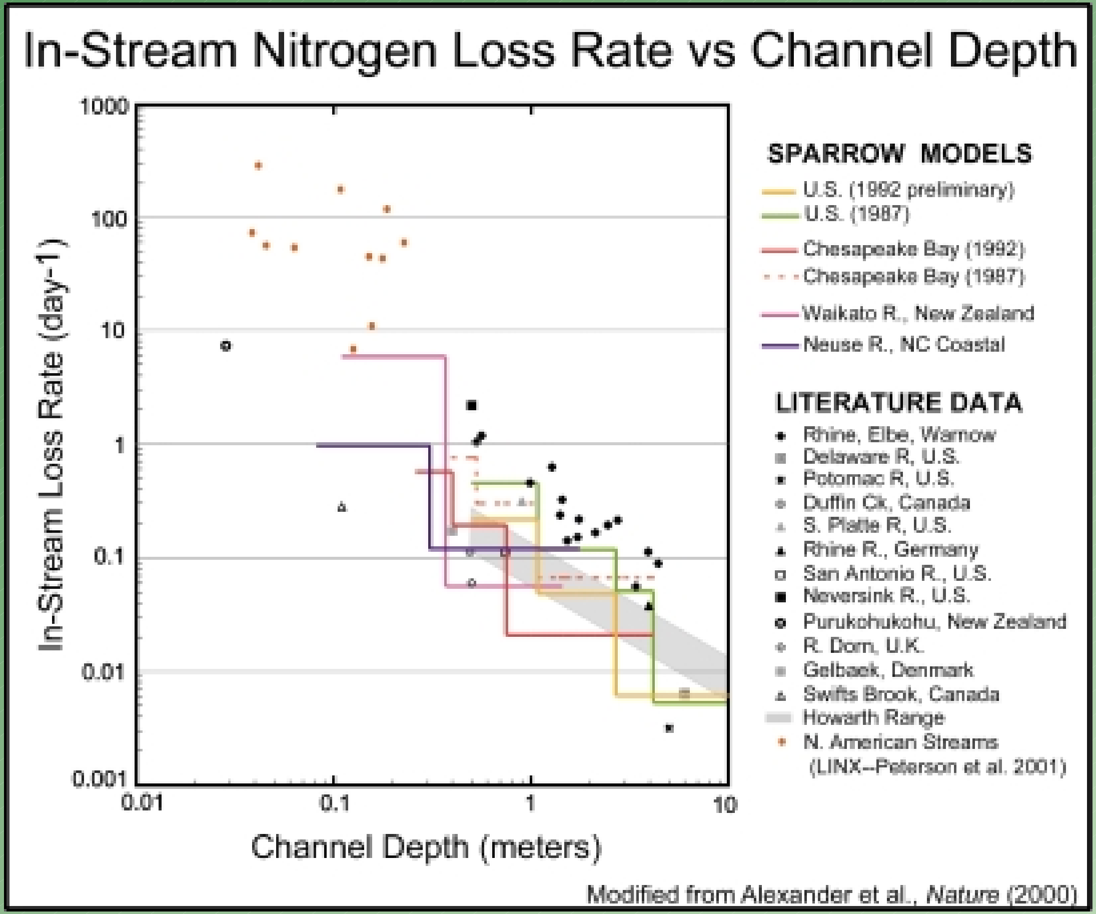
Atmosphere

Nitrogen Flux from the Mississippi River to the Gulf of Mexico: Share from Major Sources (with 90 percent confidence intervals)



Alexander et al. Nature, 2000

National and Regional SPARROW Models



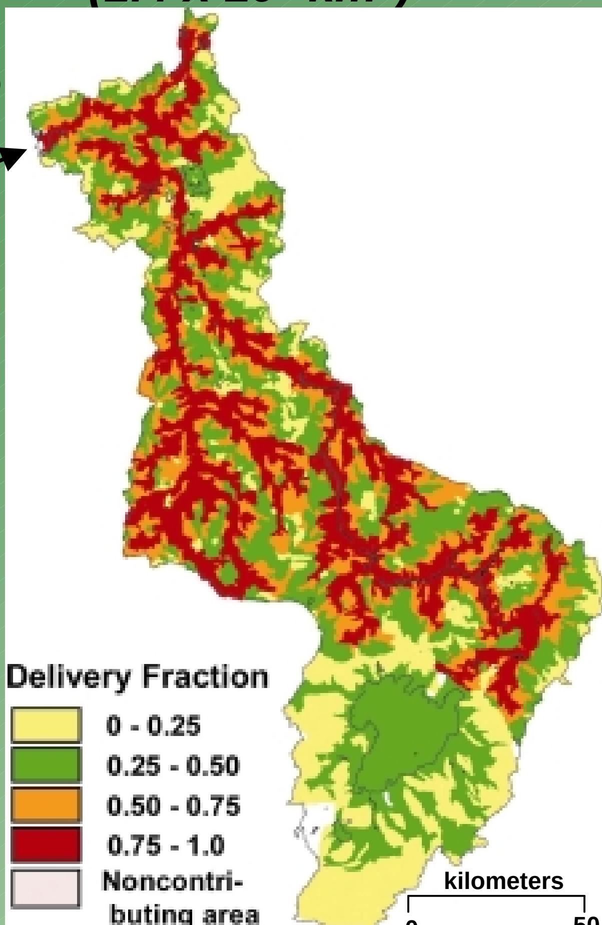
- Channel size (depth) is an important scaling property controlling N transport over range of stream sizes
- Illustrates use of model to test hypotheses—inverse relation theoretically expected; i.e., less water contact with stream bottom in large channels (e.g., Stream Solute Workshop, 1992; LINX)

Fraction of In-Stream Nitrogen Delivered to Watershed Outlet

Waikato R. Basin, N.Z.

(1.4 x 10^4 km^2)

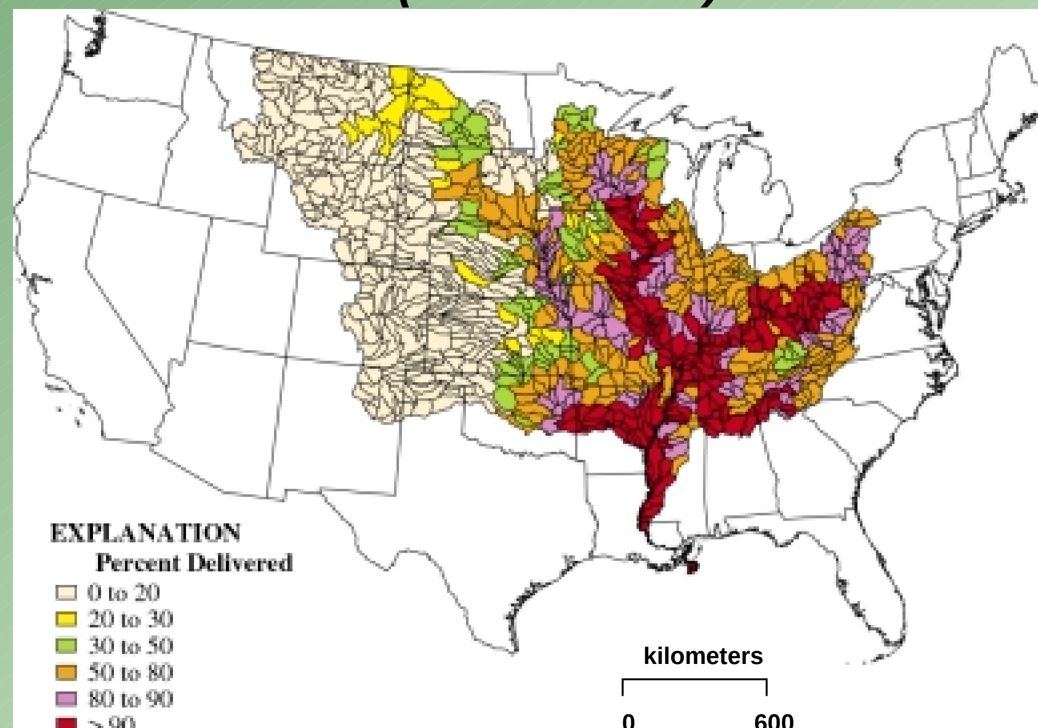
Outlet to Tasman Sea



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

Mississippi R. Basin

(2.9 x 10^6 km^2)



Alexander et al. *Nature*, 2000

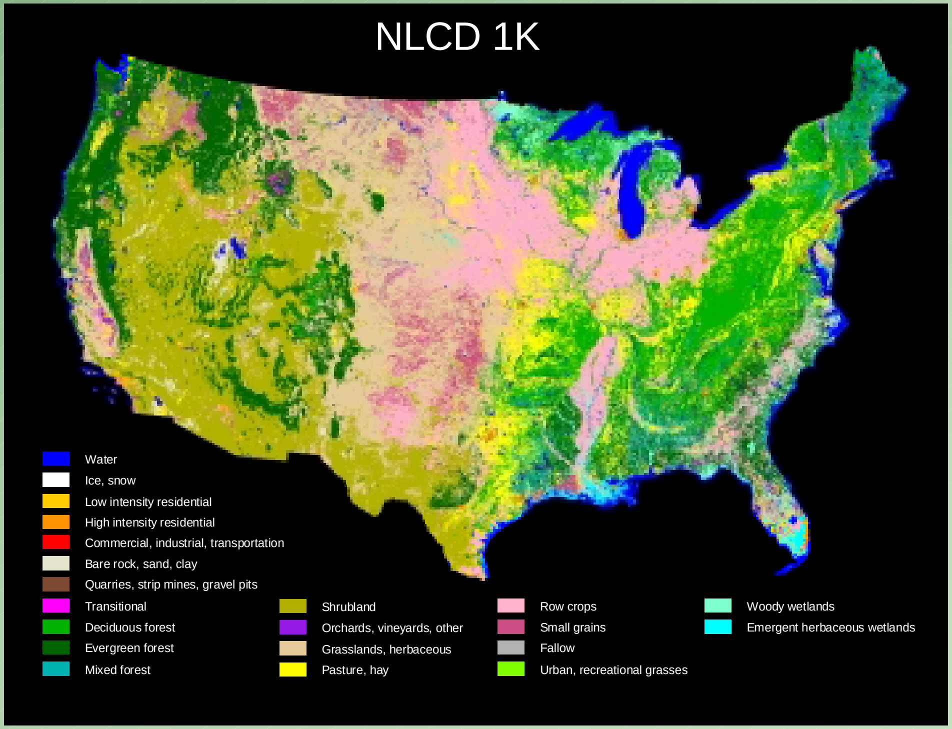
USGS
science for a changing world

New SPARROW Infrastructure

HYDRO 1-km Watershed Boundaries

Nolan et al. 2002
(http://water.usgs.gov/lookup/getspatial?erf1-2)

1992 NLCD 30-m Land Use



SPARROW Total Phosphorus Models
New Infrastructure

Land-use based model:

Row crops, pasture, urban, forest, shrub/grass

Intensive-source model:

Fertilizer, livestock wastes, sewered population, urban, forest, shrub/grass

Both model types of interest for research and policy analysis

USGS
science for a changing world

TP Land-Use Model

Sources	*kg ha^{-1} yr^{-1}*
Row crops	0.33
Row crops-MS Basin	1.23
Pasture	1.20
Urban	3.63
Forest	0.19
Shrub/grass	0.06

Land-to-Water Transport:

Soil permeability	(- coef.)
Drainage density	(+ coef.)

In-stream loss (day^{-1})

0.01, 0.07, 0.195

Reservoir loss (m yr^{-1}) 14.3

R-squared 0.87

Reach-accuracy +/- 74%

TP Intensive-Use Model

Sources:	*kg ha^{-1} yr^{-1}*
Sewered pop.	0.2 kg person^{-1}
Fertilizer use	3.5% of inputs
Livestock wastes	4.3% of inputs
Urban	2.21
Forest	0.21
Shrub/grass	0.05

Land-to-Water Transport:

Soil permeability	(- coef.)
Drainage density	(+ coef.)

In-stream loss (day^{-1})

0.04, 0.13, 0.24

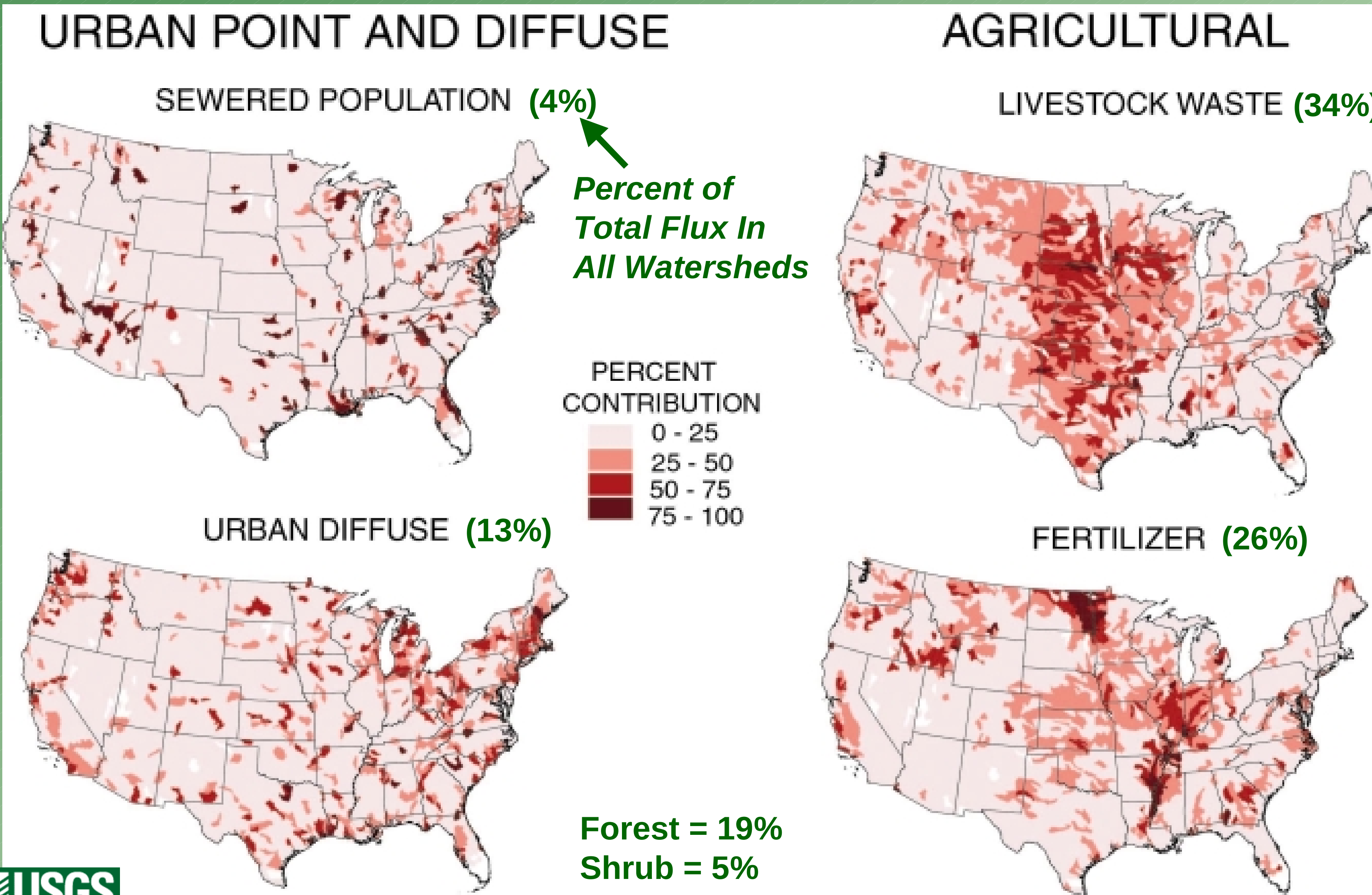
Reservoir loss (m yr^{-1}) 12.1

R-squared 0.86

Reach-accuracy +/- 75%

USGS science for a changing world

SPARROW TP Intensive-Source Model



Conclusions from Studies of Nitrogen and Phosphorus

- SPARROW identifies major point and diffuse nutrient sources and storage/loss in soils, streams, reservoirs
- Nonlinear interactions of sources and processes evident (flux from small catchments not additive)
- Nutrient loss in surface waters:
  - Physical / hydrologic properties affecting water contact time with benthic sediment important (e.g., channel size, reservoir flushing rate)
  - Smaller losses in deeper channels and more rapidly flushed lakes/reservoirs
  - Under these conditions, nutrients transported over 100s to 1000s kilometers in stream networks
  - Preferential delivery of nutrients from areas in vicinity of large rivers

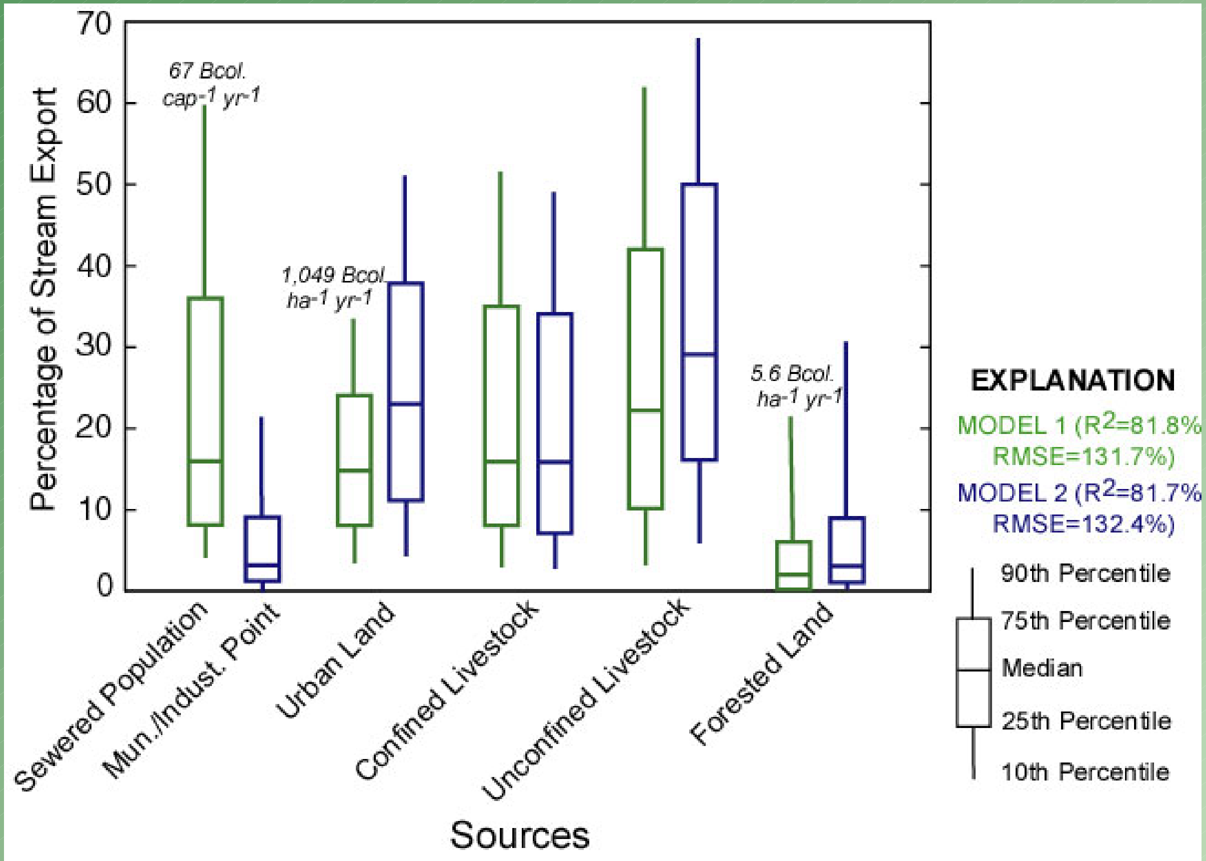
USGS science for a changing world

Effects of Animal Feeding Operations on Water Quality

Research Question:

Is there a statistically significant difference in the effects of confined and unconfined feeding operations on fecal bacteria concentrations in streams?

Sources of Fecal Coliform Bacteria in Streams



- Predominant source depends on basin
- Livestock are major source in many basins
- Confined livestock contribute nearly as much as unconfined
- In-stream decay rates 0.08 to 1.00 per day

USGS science for a changing world

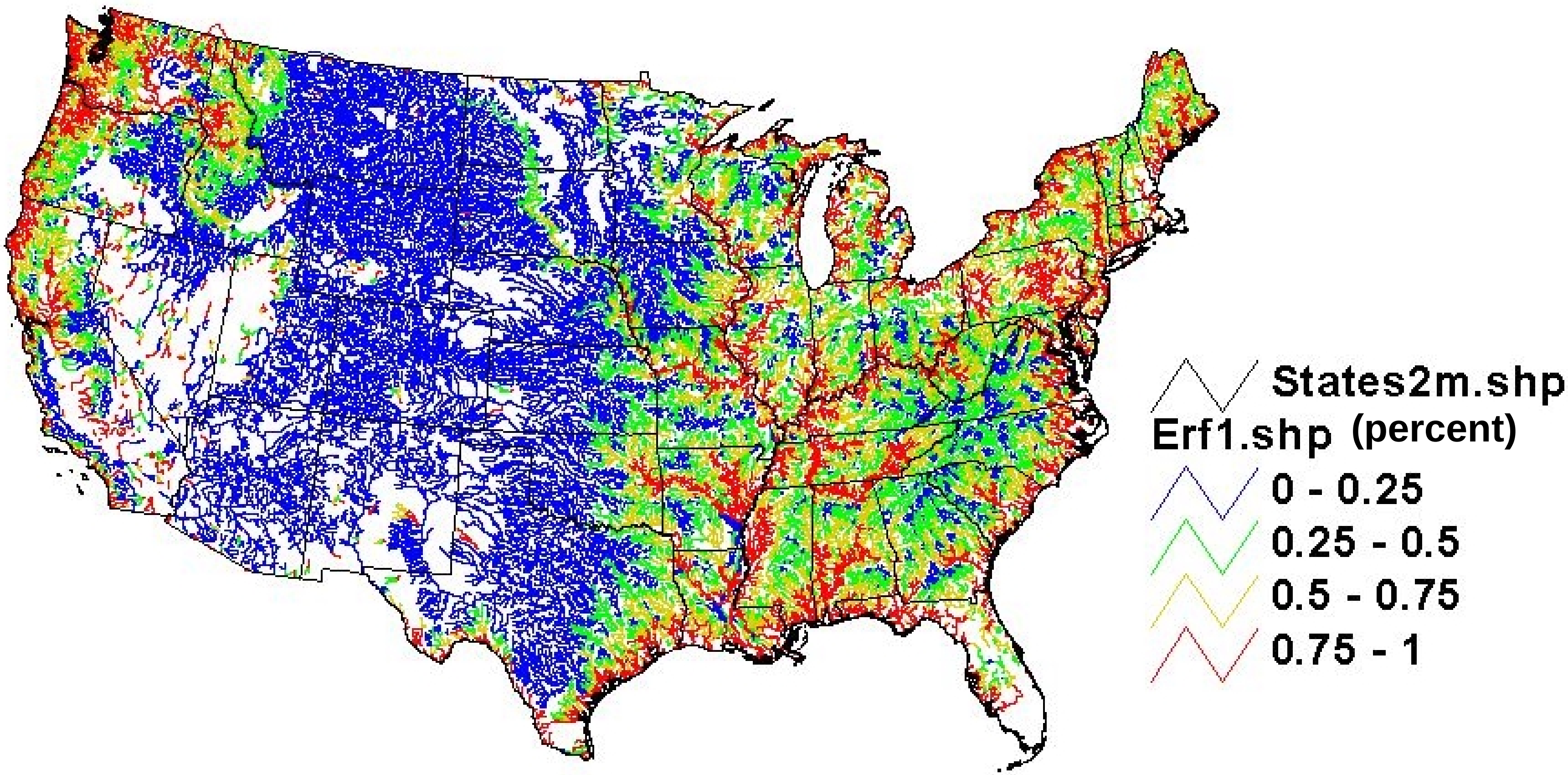
Economically Efficient Targeting of Pollution Controls

If the nation wanted to reduce the flux of nitrogen to coastal waters by a given percentage, we could:

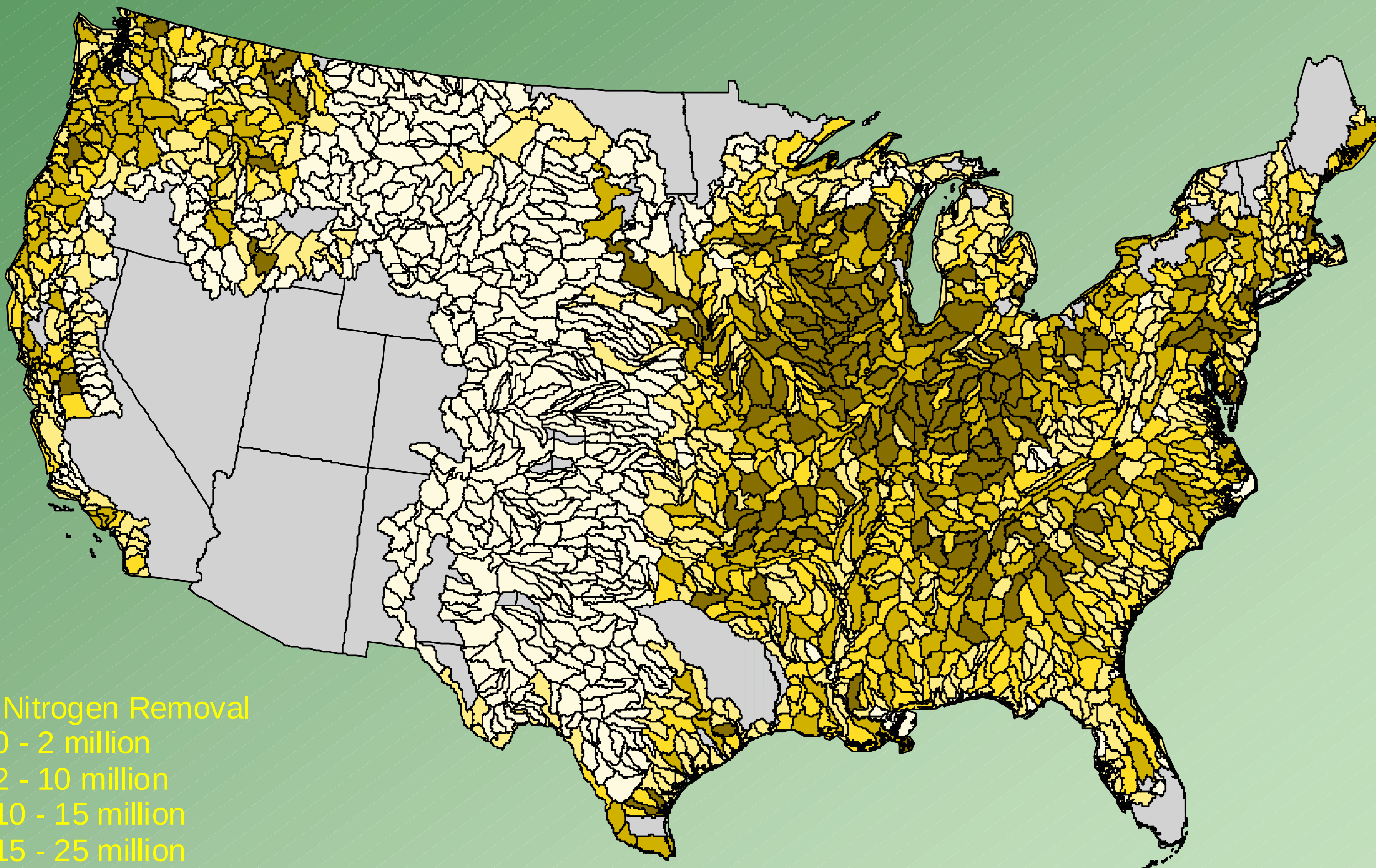
1) reduce all sources by that percentage, or

2) reduce some sources more than others depending on where they are located relative to large rivers

Percentage of N Export Delivered to the Coast



Cost of Optimal Nitrogen Removal in Hydrologic Units to Obtain a 40 Percent Reduction at Estuaries

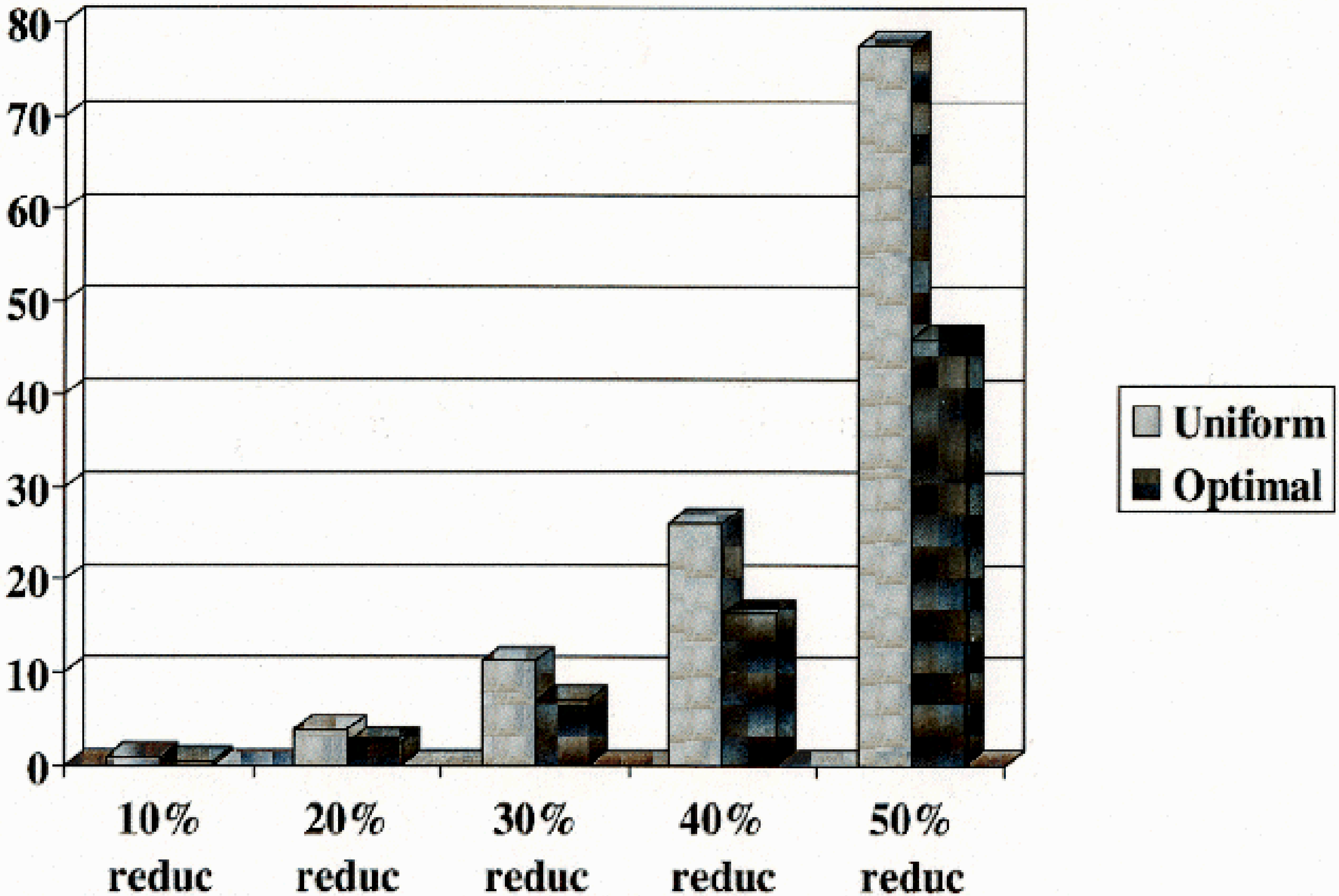


Percent Nitrogen Removal

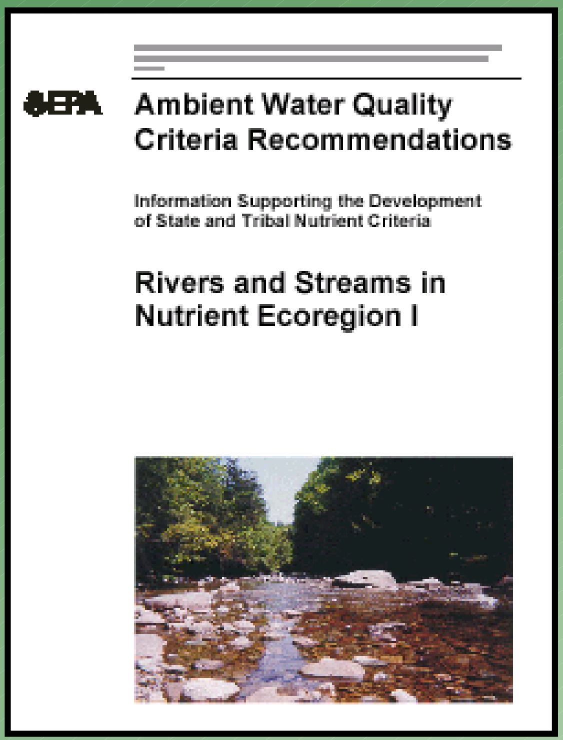
- $ 0 - 2 million
- $ 2 - 10 million
- $ 10 - 15 million
- $ 15 - 25 million
- $ 25 million or greater
- Non-contributing area

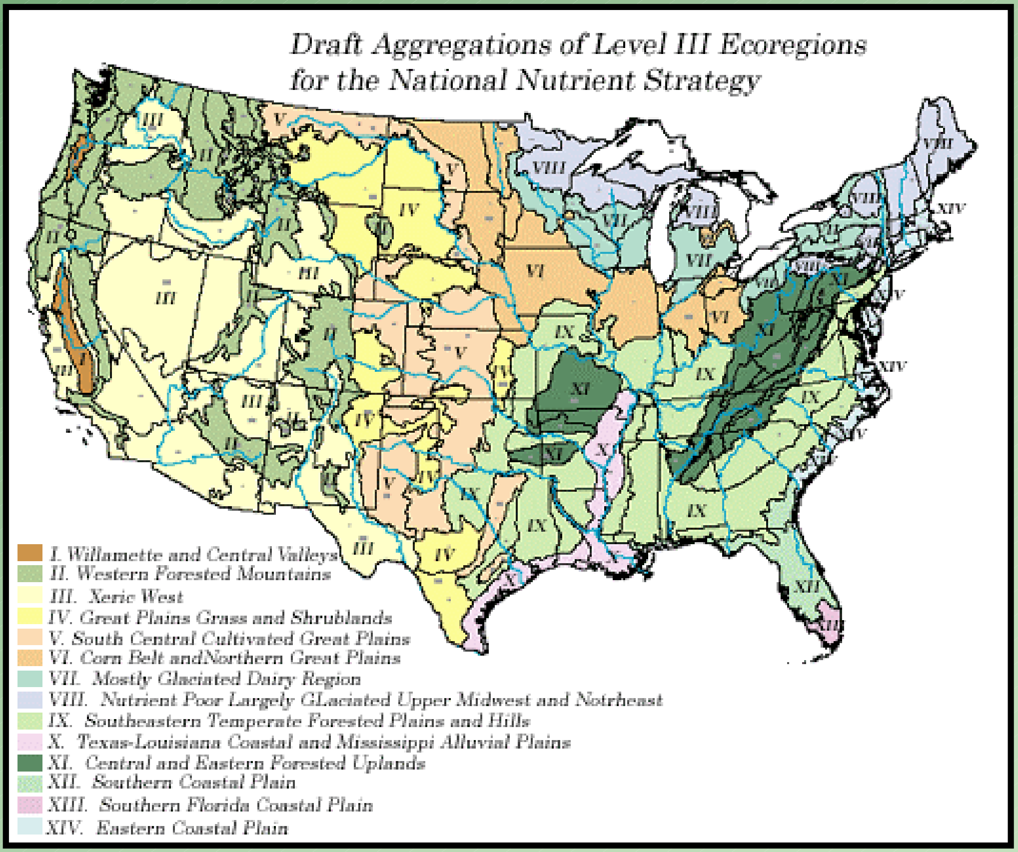
Cost of Nitrogen Control ($B/yr)

National Totals



Estimation of Background Nutrient Concentrations
(with application to criteria development)


EPA
Ambient Water Quality Criteria Recommendations
Information Supporting the Development of State and Tribal Nutrient Criteria
Rivers and Streams in Nutrient Ecoregion I



USGS
science for a changing world

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 watershed size

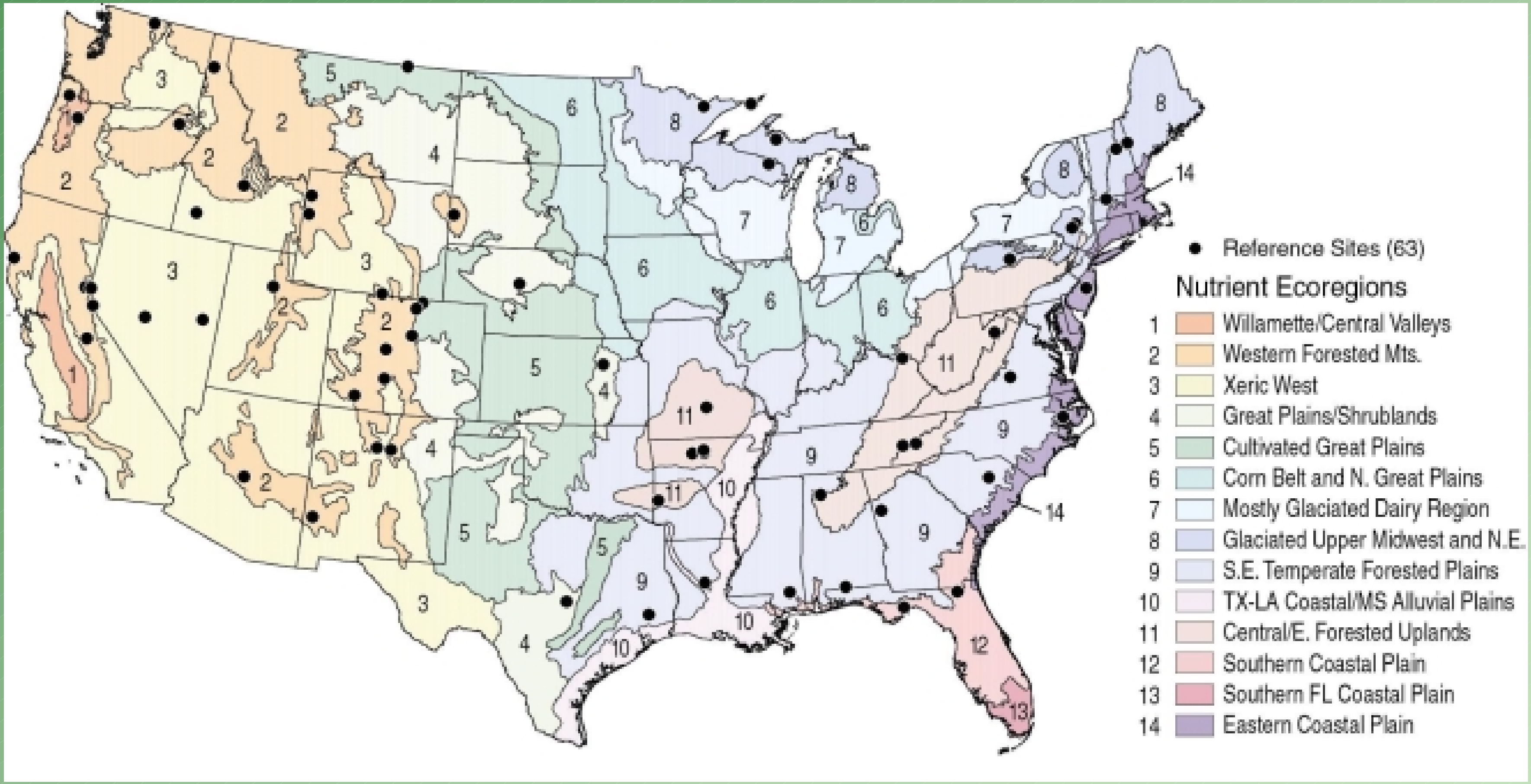
USGS
science for a changing world

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.

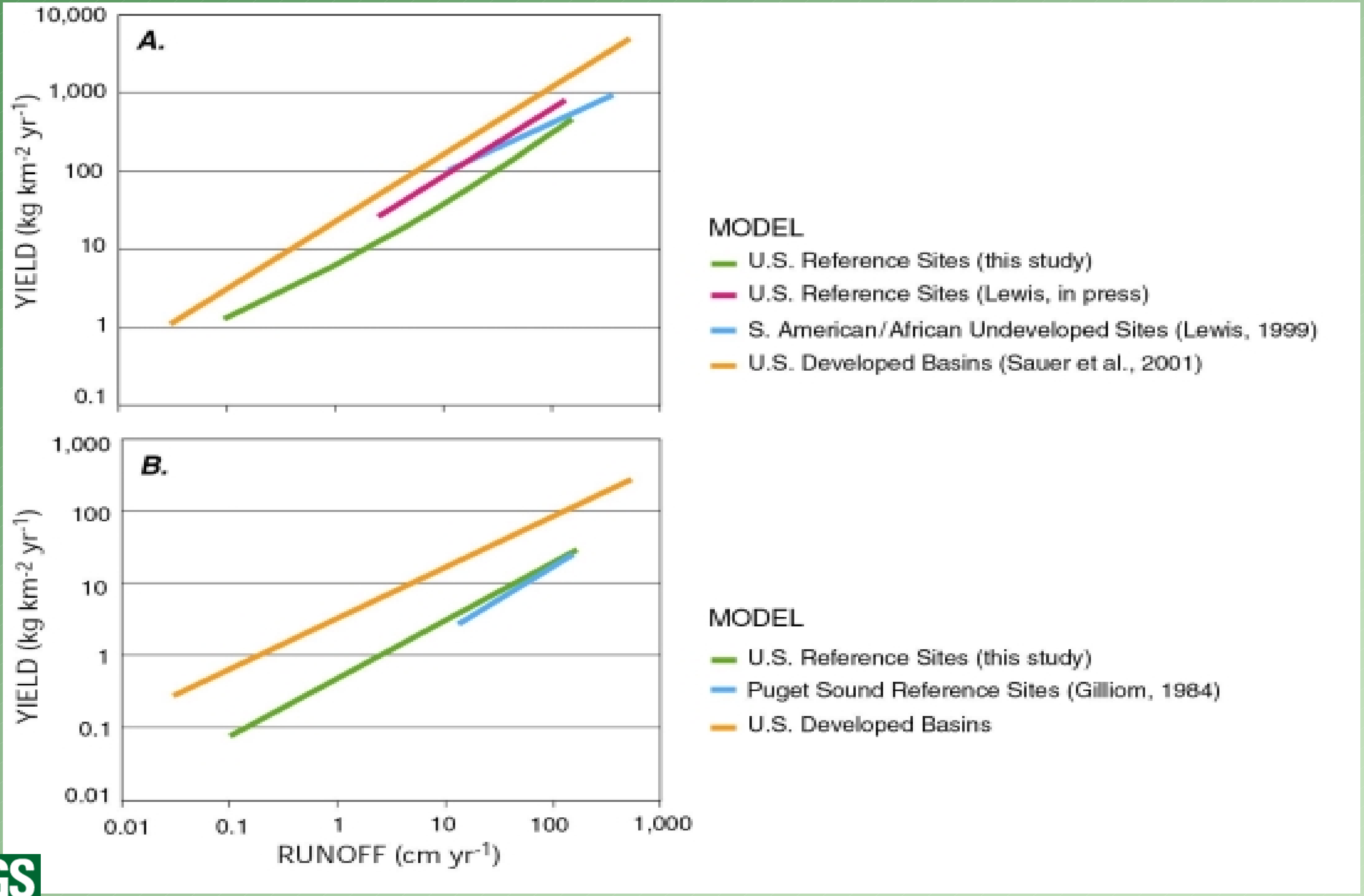
USGS
science for a changing world

US EPA Nutrient Ecoregions & USGS Reference Sites



Comparison with Other Models

(A. = TN; B. = TP)



USGS
science for a changing world

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).

Approach (cont.)

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

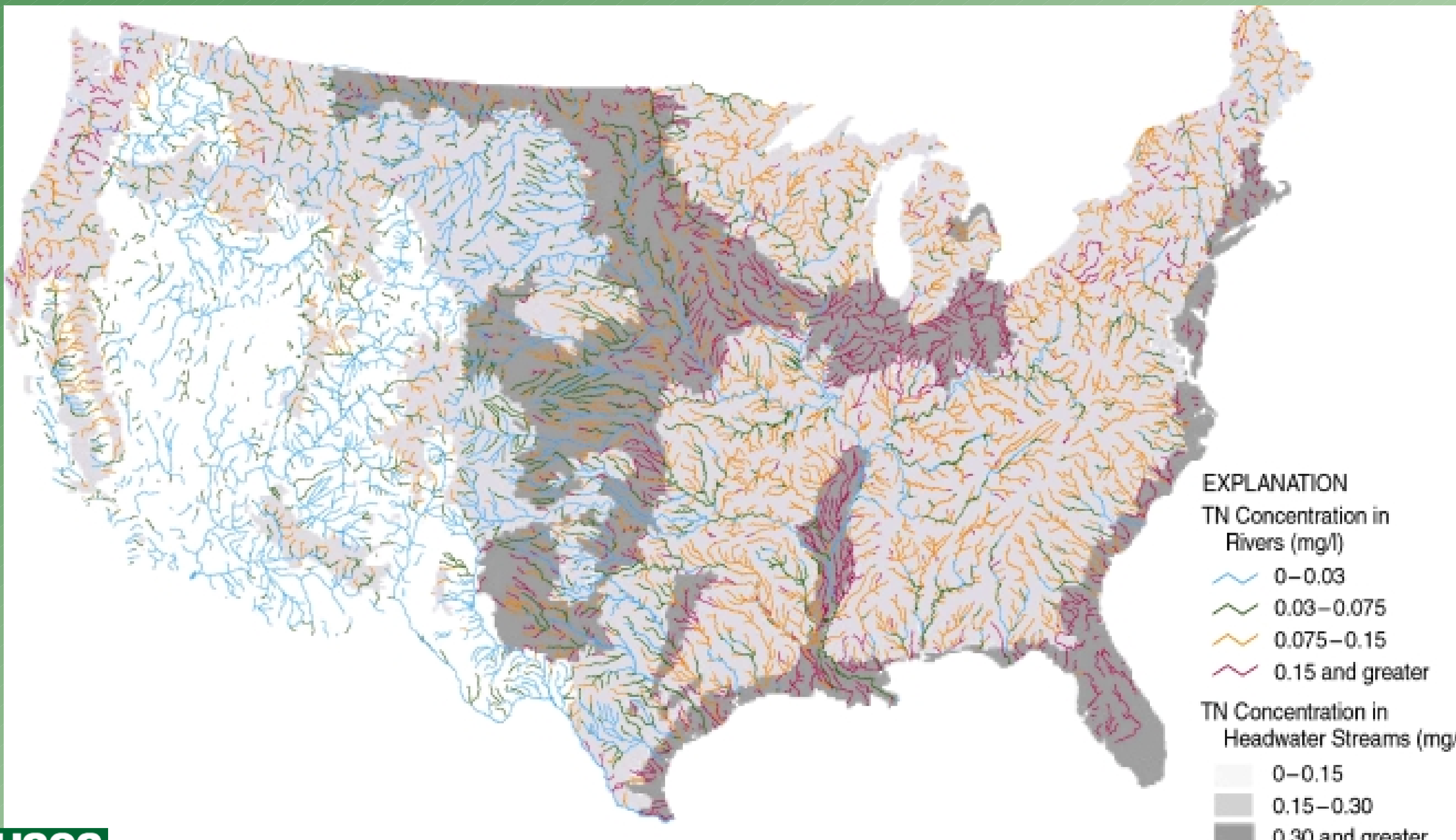
SPARROW Transport Equation

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

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



USGS
science for a changing world

Estimated Background TP Concentrations in RF1 Streams and Rivers

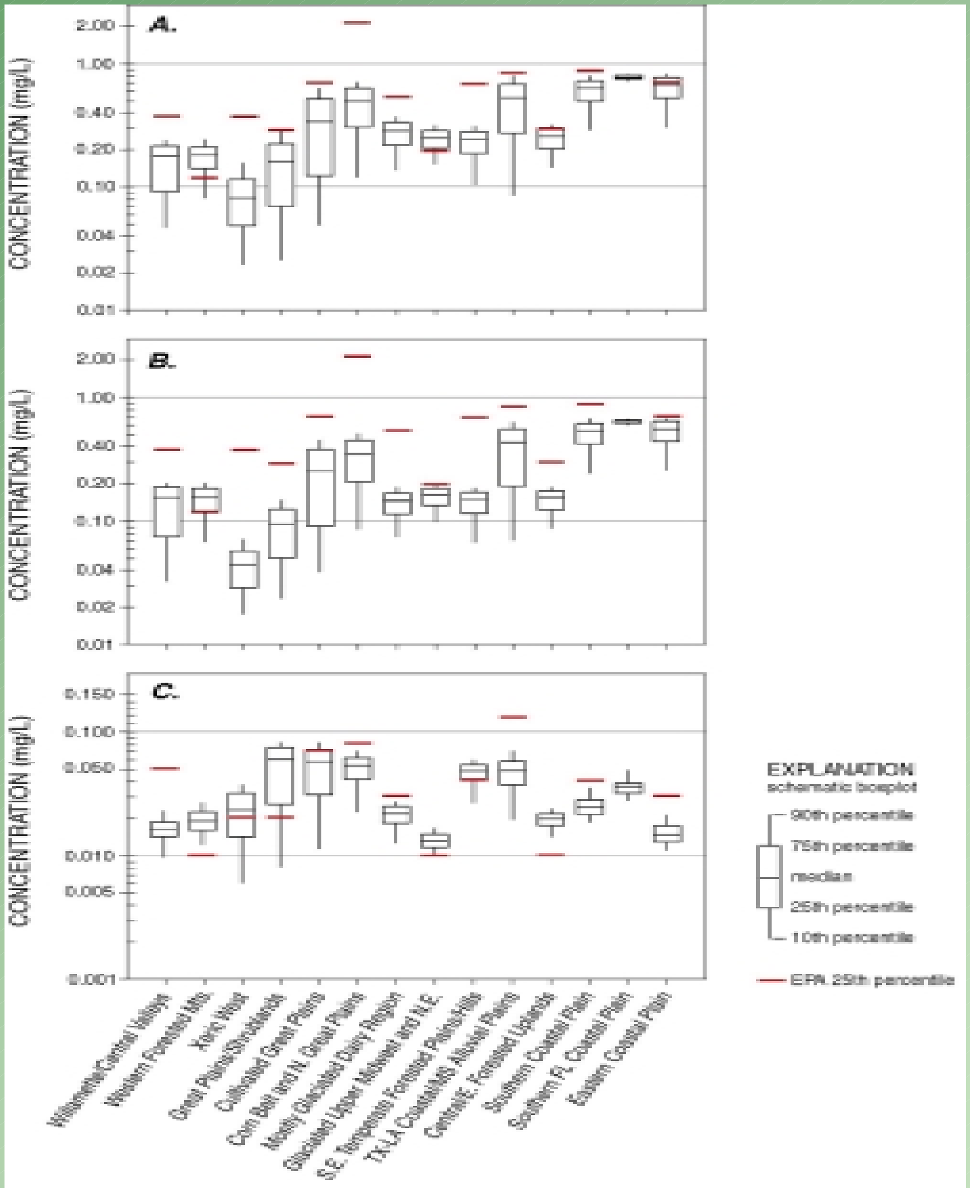
USGS
science for a changing world

Background Nutrient Concentrations in RF1 Streams and Rivers

TN Concentration

Deposition-adjusted TN Concentration

TP Concentration



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.

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).

USGS
science for a changing world

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.

USGS
science for a changing world

SPARROW Surface Water Quality Modeling

http://water.usgs.gov/nawqa/sparrow

USGS
science for a changing world