Overview of SPARROW Modeling

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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?
What is SPARROW?

- **SPAtially-Referenced Regression On Watershed 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
SPARROW (SPAtially Referenced Regression on Watershed Attributes)

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

Land Use & Sources

Drainage & Impoundments

Landscape Features

Monitoring Data

http://water.usgs.gov/nawqa/sparrow
What is the relation of SPARROW to other watershed models?

**Statistical ("Black box") Models**
- Simple mathematical structure
- Easy to build
- Known error bounds (in range of data)
- Little process description
- Difficult to interpret results

**Deterministic Models**
- Complex math structure
- Large time/resources to build
- Error bounds not well known
- Detailed description of processes
- Provides insight into behavior of system (if accurate)
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.
How is SPARROW structured?

- Upstream Monitoring Station
- Point Source
- Reach Segment
- Reach Segment
- Non-point Source
- Contributing Area
- Downstream Monitoring Station
SPARROW
Estimated Equation

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

- **Stream Load**
- **Sources**
- **Land-to-water transport**
- **Aquatic transport**
- **Error**

Nutrient Models:
- Fertilizer
- Animal Wastes
- Atmosphere (TN)
- Industrial & Municipal Wastes
- Nonagricultural Diffuse Sources
- Land Use

Soil Permeability
Slope
Stream Density
Temperature (TN)
Streamflow
Water Velocity
Channel Length
Reservoir Hydraulics
New SPARROW Infrastructure

HYDRO 1-km Watershed Boundaries

1992 NLCD 30-m Land Use

Nolan et al. 2002
(http://water.usgs.gov/lookup/getspatial?erf1-2)
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
CLASSIFICATION OF PREDICTED TP CONCENTRATION IN HUCs

Probable conc. (mg/L)
- Low (< 0.1)
- High (> 0.1)
- No data

From Smith et al. 1997
<table>
<thead>
<tr>
<th>Region</th>
<th>No. HUCs</th>
<th>Proportion</th>
<th>Lower 90% CI</th>
<th>Upper 90% CI</th>
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<tbody>
<tr>
<td>U.S.</td>
<td>2048</td>
<td>0.39</td>
<td>0.37</td>
<td>0.42</td>
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<tr>
<td>New England</td>
<td>52</td>
<td>0.84</td>
<td>0.75</td>
<td>0.90</td>
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<tr>
<td>Mid. Atlantic</td>
<td>88</td>
<td>0.60</td>
<td>0.53</td>
<td>0.67</td>
</tr>
<tr>
<td>Upper Miss.</td>
<td>131</td>
<td>0.19</td>
<td>0.15</td>
<td>0.23</td>
</tr>
</tbody>
</table>
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
Estimated Background TN Concentrations in RF1 Streams and Rivers
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
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

- **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]

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

SPARROW vs. HUMUS (SWAT)
U.S. Hydrologic Cataloging Units
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
**Who is Currently Involved in SPARROW Modeling?**

<table>
<thead>
<tr>
<th>Drainage Basin</th>
<th>Staff</th>
<th>Institution</th>
</tr>
</thead>
<tbody>
<tr>
<td>National model</td>
<td>4</td>
<td>USGS/Reston</td>
</tr>
<tr>
<td>Chesapeake Bay</td>
<td>2</td>
<td>MD District</td>
</tr>
<tr>
<td>New England</td>
<td>3</td>
<td>NH/VT District</td>
</tr>
<tr>
<td>Neuse R.</td>
<td>2</td>
<td>NC Dist; Duke U</td>
</tr>
<tr>
<td>Delaware R.</td>
<td>3</td>
<td>NJ District</td>
</tr>
<tr>
<td>Waikato R., NZ</td>
<td>3</td>
<td>NIWA, USGS</td>
</tr>
<tr>
<td>Upper MS (prop.)</td>
<td>4?</td>
<td>USGS (WRD, NMD, BRD, Region ?)</td>
</tr>
</tbody>
</table>
Applications of the National Model

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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)
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.)

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

- 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

**Areal Extent of Gulf Hypoxic Zone**

Dissolved oxygen <2 mg/L

*modified from Rabalais et al. 2002*
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)

Mississippi R. Basin
(2.9 x 10^6 km^2)

Alexander et al. Water Resour Res, in press

New SPARROW Infrastructure

HYDRO 1-km Watershed Boundaries

1992 NLCD 30-m Land Use

Nolan et al. 2002
(http://water.usgs.gov/lookup/getspatial?erf1-2)
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
### TP Land-Use Model

<table>
<thead>
<tr>
<th>Sources</th>
<th>kg ha(^{-1}) yr(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Row crops</td>
<td>0.33</td>
</tr>
<tr>
<td>Row crops-MS Basin</td>
<td>1.23</td>
</tr>
<tr>
<td>Pasture</td>
<td>1.20</td>
</tr>
<tr>
<td>Urban</td>
<td>3.63</td>
</tr>
<tr>
<td>Forest</td>
<td>0.19</td>
</tr>
<tr>
<td>Shrub/grass</td>
<td>0.06</td>
</tr>
</tbody>
</table>

**Land-to-Water Transport:**
- Soil permeability: (- coeff.)
- Drainage density: (+ coeff.)

**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%

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### TP Intensive-Use Model

<table>
<thead>
<tr>
<th>Sources</th>
<th>kg ha(^{-1}) yr(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sewered pop.</td>
<td>0.2 kg person (^{-1})</td>
</tr>
<tr>
<td>Fertilizer use</td>
<td>3.5% of inputs</td>
</tr>
<tr>
<td>Livestock wastes</td>
<td>4.3% of inputs</td>
</tr>
<tr>
<td>Urban</td>
<td>2.21</td>
</tr>
<tr>
<td>Forest</td>
<td>0.21</td>
</tr>
<tr>
<td>Shrub/grass</td>
<td>0.05</td>
</tr>
</tbody>
</table>

**Land-to-Water Transport:**
- Soil permeability: (- coeff.)
- Drainage density: (+ coeff.)

**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%
SPARROW TP Intensive-Source Model

Percent of Total Flux In All Watersheds

URBAN POINT AND DIFFUSE

SEWERED POPULATION (4%)

AGRICULTURAL

LIVESTOCK WASTE (34%)

URBAN DIFFUSE (13%)

FERTILIZER (26%)

Forest = 19%
Shrub = 5%
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
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
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

States2m.shp
Erf1.shp (percent)

- 0 - 0.25
- 0.25 - 0.5
- 0.5 - 0.75
- 0.75 - 1
Cost of Optimal Nitrogen Removal in Hydrologic Units to Obtain a 40 Percent Reduction at Estuaries

<table>
<thead>
<tr>
<th>Percent Nitrogen Removal</th>
<th>Cost Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0 - 2 million</td>
<td></td>
</tr>
<tr>
<td>$2 - 10 million</td>
<td></td>
</tr>
<tr>
<td>$10 - 15 million</td>
<td></td>
</tr>
<tr>
<td>$15 - 25 million</td>
<td></td>
</tr>
<tr>
<td>$25 million or greater</td>
<td></td>
</tr>
</tbody>
</table>

Non-contributing area
Cost of Nitrogen Control ($B/yr)

National Totals

- Uniform
- Optimal

10% reduc
20% reduc
30% reduc
40% reduc
50% reduc
Estimation of Background Nutrient Concentrations
(with application to criteria development)
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
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

Nutrient Ecoregions:
1. Willamette/Central Valleys
2. Western Forested Mts.
3. Xeric West
4. Great Plains/Shrublands
5. Cultivated Great Plains
6. Corn Belt and N. Great Plains
7. Mostly Glaciated Dairy Region
8. Glaciated Upper Midwest and N.E.
9. S.E. Temperate Forested Plains
10. TX-LA Coastal/MS Alluvial Plains
11. Central/E. Forested Uplands
12. Southern Coastal Plain
13. Southern FL Coastal Plain
14. Eastern Coastal Plain

Reference Sites (63)
Comparison with Other Models

(A. = TN; B. = TP)
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).
3. Use previously calibrated SPARROW models to predict the effects of transport in larger streams and rivers on background nutrient concentrations.
SPARROW Transport Equation

\[ L_i = \sum_{j \in J(i)} Y_j A_j [\exp(-k' T_{i,j})] \]
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
Estimated Background TP Concentrations in RF1 Streams and Rivers
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).
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 Surface Water Quality Modeling

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