SUPPORTING CHESAPEAKE BAY RESTORATION BY MODELING NUTRIENT AND SEDIMENT SOURCES AND TRANSPORT

Applications and Results of SPARROW Models

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Chesapeake Bay Watershed

- Drains the largest estuary in North America
- Stresses led to the Bay and its tidal rivers being listed as “impaired waters” under the Clean Water Act
  - Largely because of low dissolved oxygen levels and other problems related to pollution like excessive nutrients and sediment
  - Imposed TMDL throughout watershed
- Restoration efforts have been ongoing for several decades.
- Challenges:
  - Diverse and changing land uses
  - Variety of contaminant sources
  - Diverse natural conditions relevant to contaminant fate and transport
- Restoration efforts have been designed and supported using numerical models:
  - Chesapeake Bay Program HSPF watershed model
    - TMDL’s implemented and managed
  - USGS SPARROW
    - Help gain a comprehensive understanding of where nutrients and sediment originate
    - How they move throughout the watershed
    - Assist management actions
SPA\textit{tially} \textbf{R}eferenced \textbf{R}egressions \textbf{O}n \textbf{W}atershed \textbf{A}ttributes

- Spatial Statistical Approach that Empirically Relates Contaminant Sources and Transport Factors to Measured Stream Flux
  - Identify the spatial variability and magnitude of contaminant supply
  - Quantify the contributions at various locations
  - Identify the factors affecting transport

- Tool Provides Spatially Detailed Predictions:
  - Map individual contaminant sources in unmonitored locations
  - Statistical importance and quantification of contaminant sources
  - Provides measures of uncertainty

- Spatial Framework
  - Explicit for evaluating geographic distribution of sources and the factors affecting flux
  - Potential Geographic Targeting for intensive study, increased monitoring, or management practice evaluation/implementation (BMP)
SPARROW Spatially Designed

Integrates spatial data over multiple scales to predict origin & fate of contaminants

Network of connected and attributed streams and watersheds

Monitoring Data (Dependent Variable)

Source data

Slope, Physiography, Soil Characteristics, Reservoir Systems

Land to Water Delivery
USGS State Science Center Projects

National and Regional Modeling

1) Contiguous U.S.
2) Upper and Lower Mississippi River Basin
3) USGS NAWQA Major River Basin Studies

Map showing NAQWA study units and revised Sept. 2004.
Northeastern US SPARROW

- Provides broader context of how Chesapeake compares to wider region
- Similar calibration to Chesapeake models:
  - TN and TP
  - Early 2000s
  - 1:100,000 scale
  - Slightly different source and transport specification
- September release
  - Online tool for customized mapping and reporting of SPARROW results and scenario testing

Moore et al., in press
JAWRA
Chesapeake Bay SPARROW Models

- **Previous models:**
  - Late 1980s (TN, TP)
  - Early 1990s (TN, TP)
  - Late 1990s (TN, TP)
  - Early 2000s (sediment)

- **Updated models:**
  - Early 2000s (TN, TP)
  - Finer spatial resolution
  - More calibration stations
  - Updated sources and expanded transport specification

<table>
<thead>
<tr>
<th>Scale</th>
<th>Watersheds</th>
<th>Mean Size (km²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1:500,000</td>
<td>2,734</td>
<td>75</td>
</tr>
<tr>
<td>1:100,000</td>
<td>80,579</td>
<td>2.1</td>
</tr>
</tbody>
</table>
Nitrogen SPARROW

- Sources: On average:
  - 1,090 kg/km$^2$ of N from Urban areas reach the stream
  - 24% of N from fertilizer and fixation reaches streams
  - Only 6% of N in manure reaches streams
  - 27% of N from atmospheric deposition reaches streams

<table>
<thead>
<tr>
<th>Nitrogen Model</th>
<th>Estimate</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sources</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Point sources (kg/yr)</td>
<td>0.774</td>
<td>0.0008</td>
</tr>
<tr>
<td>Urban land (km$^2$)</td>
<td>1090</td>
<td>&lt;0.0001</td>
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<td>Manure (kg/yr)</td>
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<td><strong>Land to Water Transport</strong></td>
<td></td>
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<tr>
<td>Ln(mean evi)</td>
<td>-1.70</td>
<td>0.0039</td>
</tr>
<tr>
<td>Ln(mean soil AWC)</td>
<td>-0.829</td>
<td>0.0016</td>
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<tr>
<td>Ln(GW recharge (mm))</td>
<td>0.707</td>
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<td>Ln (% Piedmont carb)</td>
<td>0.158</td>
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<td></td>
<td></td>
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<td>Small streams (&lt;122 cfs)</td>
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<td>0.0118</td>
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<tr>
<td>Lg Streams, T &gt; 18.5 C</td>
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<td>Impoundments</td>
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RMSE=0.2892, $R^2=0.9784$, yield $R^2=0.8580$  
N = 181
Nitrogen SPARROW

- Fate and transport:
  - Delivery to streams is greater in areas of greater groundwater flow, particularly in the Piedmont carbonate.
  - Delivery to streams is less in areas with reducing conditions or greater plant uptake.
  - In-stream losses are greater in smaller streams.
  - In-stream losses in larger streams are greater in warmer areas.
  - Losses in impoundments are likely due mainly to denitrification.

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RMSE=0.2892, \( R^2=0.9784 \), yield\( R^2=0.8580 \)  
\( N = 181 \)
Spatial Distribution of TN

Estimated annual yield of total nitrogen, in kg/km² (high value in lb/ac)

- 0 - 152 (1.4)
- 152 - 221 (2.0)
- 221 - 297 (2.6)
- 297 - 398 (3.6)
- 398 - 526 (4.7)
- 526 - 683 (6.1)
- 683 - 887 (7.9)
- 887 - 1186 (11)
- 1186 - 1710 (15)
- >1710
Nitrogen Source Shares

- Agriculture is widespread, and a dominant source of N to the Bay and most tributaries.
On average, less than 5% of applied P in fertilizer and manure reaches streams

Urban areas yield 49 kg/km²

Natural mineral sources are significant

Delivery to streams is greater where runoff is more likely and in the Coastal Plain, possibly due to legacy applications or saturation

Significant losses occur in impoundments

### Phosphorus Model

<table>
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<tr>
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<th>Estimate</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Point sources (kg/yr)</td>
<td>0.877</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Urban land (km²)</td>
<td>49</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Fertilizer (kg/yr)</td>
<td>0.0377</td>
<td>0.0014</td>
</tr>
<tr>
<td>Manure (kg/yr)</td>
<td>0.0253</td>
<td>0.0002</td>
</tr>
<tr>
<td>Siliclastic rocks (km²)</td>
<td>8.52</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Crystalline rocks (km²)</td>
<td>6.75</td>
<td>0.0009</td>
</tr>
</tbody>
</table>

### Land to Water Transport

<table>
<thead>
<tr>
<th>Land to Water Transport</th>
<th>Estimate</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil erodibility (k factor)</td>
<td>6.25</td>
<td>0.0002</td>
</tr>
<tr>
<td>Ln(% well drained soils)</td>
<td>-0.100</td>
<td>0.0019</td>
</tr>
<tr>
<td>Ln(precipitation (mm))</td>
<td>2.06</td>
<td>&lt;0.0237</td>
</tr>
<tr>
<td>Coastal Plain (% of area)</td>
<td>1.02</td>
<td>&lt;0.0001</td>
</tr>
</tbody>
</table>

### Aquatic Decay

<table>
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<tr>
<th>Aquatic Decay</th>
<th>Estimate</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impoundments</td>
<td>54.3</td>
<td>0.0174</td>
</tr>
</tbody>
</table>
Spatial Distribution of TP

Estimated annual yield of total phosphorus, in kg/km² (high value in lb/ac)

- 0 - 6 (0.054)
- 6 - 9 (0.060)
- 9 - 12 (0.11)
- 12 - 15 (0.13)
- 15 - 19 (0.17)
- 19 - 25 (0.22)
- 25 - 34 (0.30)
- 34 - 48 (0.43)
- 48 - 77 (0.69)
- > 77
TP from urban (including point sources) and agricultural sources are roughly equivalent.

Natural mineral sources represent about 14 percent of TP sources.
Suspended Sediment SPARROW

- Sediment yields *(export coefficient)* are greatest from areas of urban development *(represented by an increase in impervious surface)* ~4,000 kg/km²
- Agriculture contributes less by unit area, but is widespread and a significant source of sediment to local streams and Chesapeake Bay
- In-stream sources *(bank, bed, or flood plain erosion)* are also significant in small streams above the Fall Line
- Upland sediment transport to streams is enhanced in areas with greater slope, fewer reservoirs, less permeable soils, and in the Piedmont
- Significant losses occur in impoundments and large Coastal Plain streams

<table>
<thead>
<tr>
<th>Sediment Model Variable</th>
<th>Estimate</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sources</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Agriculture Area (km²)</td>
<td>56.96</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Forested Area (km²)</td>
<td>0.98</td>
<td>0.495</td>
</tr>
<tr>
<td>Developed lands (km²)</td>
<td>3,928.41</td>
<td>0.004</td>
</tr>
<tr>
<td>Stream Channel &lt; 35 ft³/sec</td>
<td>.029</td>
<td>0.030</td>
</tr>
<tr>
<td><strong>Land to Water Transport</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Watershed Slope</td>
<td>0.01</td>
<td>0.083</td>
</tr>
<tr>
<td>Soil Permeability</td>
<td>-1.19</td>
<td>0.022</td>
</tr>
<tr>
<td>Piedmont Province</td>
<td>0.96</td>
<td>0.002</td>
</tr>
<tr>
<td>Off Reach Impoundment density</td>
<td>-22.96</td>
<td>0.021</td>
</tr>
<tr>
<td><strong>Aquatic Decay</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Impoundments (m/yr)</td>
<td>234.91</td>
<td>0.034</td>
</tr>
<tr>
<td>CP Streams (120 – 250 ft³/sec) Day⁻¹</td>
<td>2.54</td>
<td>0.007</td>
</tr>
<tr>
<td>CP Streams (&gt; 250 ft³/sec) Day⁻¹</td>
<td>1.92</td>
<td>0.14</td>
</tr>
</tbody>
</table>

RMSE = 0.96

Published in Brakebill et al., 2010, JAWRA, 1:500,000 stream network
Sediment Source Shares

- Incremental (local) sources – how much sediment is generated in each catchment?

<table>
<thead>
<tr>
<th>Source Share (%)</th>
<th>Mean</th>
<th>Median</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agriculture</td>
<td>62</td>
<td>74</td>
</tr>
<tr>
<td>Urban Development</td>
<td>26</td>
<td>14</td>
</tr>
<tr>
<td>Forest</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>Small streams</td>
<td>7</td>
<td>0</td>
</tr>
</tbody>
</table>

* Forest mapped 1 order of magnitude less than other sources
Sediment Source Distribution By Physiography

Application – Quantifying Sediment Supply

 Flux Generated

 Mean incremental flux by physiography and source

- Appalachian Plateau
- Valley and Ridge
- Blue Ridge
- Piedmont
- Coastal Plain

 Delivered

 Mean delivered flux by physiography and source

- Appalachian Plateau
- Valley and Ridge
- Blue Ridge
- Piedmont
- Coastal Plain

 Yield Generated

 Mean incremental yield by physiography and source

- Appalachian Plateau
- Valley and Ridge
- Blue Ridge
- Piedmont
- Coastal Plain

 Delivered

 Mean delivered yield by physiography and source

- Appalachian Plateau
- Valley and Ridge
- Blue Ridge
- Piedmont
- Coastal Plain

Brakebill et al., 2010, JAWRA
Delivery to the Bay
Sediment Source Distribution

- Quantified amounts of each sediment source transported to the Bay
- Can be quantified and mapped at any location on the network

<table>
<thead>
<tr>
<th>Source</th>
<th>Flux (10^6 Mg/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agriculture</td>
<td>51%</td>
</tr>
<tr>
<td>Urban Development</td>
<td>39%</td>
</tr>
<tr>
<td>Forest</td>
<td>08%</td>
</tr>
<tr>
<td>Small Streams</td>
<td>02%</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td></td>
</tr>
</tbody>
</table>

Brakebill et al., 2010, JAWRA
How much local generation reaches Chesapeake Bay

How much is generated locally independent of upstream contributions

**Applications – Geographic targeting**

**Incremental Yield**
- < 12 Mg per km² per year
- 12 - 24
- 24 - 55
- 55 - 129
- > 129 Mg per km² per year

**Delivered Yield**
- < 12 Mg per km² per year
- 12 - 24
- 24 - 55
- 55 - 129
- > 129 Mg per km² per year

Modified from Brakebill et al., 2010, JAWRA
Additional information required?

- Ability to look at each source individually
  - Is sediment yield related to urbanization?
  - Is sediment yield related to agriculture?
- Other sources?
- Other factors?

Upper Monocacy River Basin
Applying the SPARROW model provides the ability to gain a regional understanding of contaminant supply, fate, and transport within the Chesapeake Bay watershed.

- The SPARROW model demonstrates reasonable relations between the response variable (long-term water-quality conditions) and selected exploratory data representing supply, transport, and storage (Model diagnostics).

Model evaluations and predictions are directly applicable to nutrient and sediment management in watersheds of estuaries like Chesapeake Bay:

- Identifying individual source contributions and their relative importance
- Identifying important transport factors and their relative importance
- Quantifying relative amounts of sediment generated and transported to Chesapeake Bay
- Enhanced geographic targeting tool for further study, additional monitoring, or prioritizing management actions for a variety of sources and settings

Seeking out and working with State and Local agencies to better provide information suited for their needs
Information

- **2002 North East Nitrogen and Phosphorus SPARROW models**
  - September, 2011
  - 1:100,000 scale
  - JAWRA
  - Online tool (DSS) for customized mapping and reporting of SPARROW results and scenario testing

- **2002 Chesapeake Bay Nitrogen and Phosphorus SPARROW models**
  - Last quarter, 2011
  - 1:100,000 scale
  - USGS SIR Report (including predictions)
  - Also available in DSS (soon after publication) for customized mapping and reporting of SPARROW results and scenario testing

- **2002 Chesapeake Bay Suspended Sediment model** – Published
  - 1:500,000 scale
  - JAWRA
Thank You

- jwbrakeb@usgs.gov
- 443-498-5557
SPARROW Mass-Balance Model

Nonlinear regression

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

Load leaving the reach = Load generated within upstream reaches and transported to the reach via the stream network + Load originating within the reach’s incremental watershed and delivered to the reach segment

Source
Delivery
Decay/storage
in-stream reservoir
Monitoring

Nonlinear model structure includes topography and water routing; provides separation of land and water processes

Steady-state, mass-balance structure gives improved interpretability of the model coefficients and predictions

Schwarz et al., 2006
Phosphorus

- Denver et al. (2010) suggested crystalline and siliciclastic rocks may represent a natural mineral P source:
  - Alkili-feldpars
  - Fluor-apatite
  - Fe-hydroxides
- Model coefficients generally agree with previous estimates of P yields
- Natural mineral sources dominate TP yields over large areas

<table>
<thead>
<tr>
<th>Rock</th>
<th>Bay Model</th>
<th>Ontario (Dillon and Kirchner, 1975)</th>
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<tbody>
<tr>
<td>Crystalline</td>
<td>6.8</td>
<td>4.8</td>
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<td>Siliciclastic</td>
<td>8.5</td>
<td>10.7</td>
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Estimated Yield (kg/km²/yr)
Nitrogen

- Nitrogen yields from agricultural sources are greatest in the Lancaster, PA area.