Modeling watershed nutrient fluxes & delivery to coastal waters

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US Geological Survey
National Water Quality Assessment Program
Outline

- Some noteworthy watershed modeling tools.
- Overview of SPARROW water quality modeling approach.
- Applications of SPARROW to quantify N & P loads to the Gulf of Mexico from Mississippi & Atchafalaya basins.
- Applications of SPARROW in progress to consider C loads at national scale.

Some watershed modeling approaches

SMHI HBV (& SOILN & ICE-CREAM)
http://www.smhi.se/sgn0106/if/hydrologi/hbv_np.htm

USGS Modular Modeling System (MMS)

USDA Agricultural Policy EXtenderder (APEX)
http://www.brc.tamus.edu/apex/index.html

USDA Soil Water Assessment Tool (SWAT)
http://www.brc.tamus.edu/swat/

CENTURY soil organic model
http://www.nrel.colostate.edu/projects/century5/
**SPAtially Referenced Regression on Watershed Attributes**

**SPARROW water quality model**

Potential applications:
- Reliably predict nutrient concentration, flux, yields in unmonitored streams; should be consistent with monitoring data
- Quantify the major sources in watersheds that contribute nutrients to surface waters
- Quantify the principal hydrological and biogeochemical controls on nutrient transport in watersheds
- Consider nutrient response to future changes in land use & climate
Calibration to mean-annual conditions at stream monitoring sites

e.g., The standardized mean nutrient load at each station is the load that would have occurred in 1992 if mean annual flow conditions from 1975-2000 had prevailed.
USGS National Streamflow Information Program

176 currently threatened stream gages
http://water.usgs.gov/osw/lost_streamgages.html

Lobby for Long-Term!

SPARROW model components

Alexander et al. 2002
SPARROW model predictions

- Represents terrestrial & aquatic processes; accounts for non-conservative transport in watersheds.
- Predictions of Loads, concentrations, stream & reservoir losses, source shares, uncertainties.
- Reflect long-term, net nutrient supply and loss processes.

SPARROW model components

Spatial referencing is accomplished by linking all data to a geographically defined stream-reach data set.

Sources

Terrestrial Landscape
- Temperature
- Permeability
- Slope/Concavity
- Stream Density
- Wetlands
- Precipitation
- Irrigation
- Tile Drains

Aquatic Landscape
- Flow
- Velocity
- Reservoir retention
SPARROW mathematical form
reach-scale mass balance; relate watershed data to monitored loads

\[ LOAD_i = \sum_{j \in J(i)} \sum_{w=1}^{W} S_{w,j} \beta_j \exp(-\alpha Z_{j,w}) \prod_{m=1}^{M} \exp(-\delta_j T_{j,m}) \prod_{l=1}^{L} \frac{1}{1+K q_{i,l}} \exp(\varepsilon_i) \]

- The optimal set of rate coefficients are estimated, balancing the nutrient mass of the source inputs, stream loads, and storage/loss on land and in water.
- All calibrated parameters are simultaneously determined to best fit the data.

SPARROW model components
aggregated reach-by-reach

Load leaving the reach = Load generated within upstream reaches and transported along the reach via the stream network + Load originating within the reach's incremental watershed and delivered to the end of reach segment
SPARROW predictions
example from the Mississippi River Basin

Differences in Phosphorus and Nitrogen Delivery to the Gulf of Mexico from the Mississippi River Basin

Alexander et al. 2008

SPARROW nutrient model calibration
observed versus predicted riverine yields of N & P

18 model coefficients:
- 10 sources
- 6 landscape transport
- continuous stream and reservoir decay

15 model coefficients:
- 8 sources
- 5 landscape transport
- continuous stream and reservoir decay

Alexander et al. 2008
**Statistically significant source & transport features**

**NUTRIENT SOURCES**
- Urban and population-related sources
- Atmospheric N deposition
- Cultivated crops:
  - County farm fertilizer sales and expenditures; crop acreage
  - NLCD agricultural land use
  - State application rates (corn, soybeans, cotton, wheat, other crops)
  - Corn/soybean rotations
  - N$_2$ fixation – cultivated lands
  - Recoverable manure applied
- Non-recoverable animal manure on pasture/rangelands (unconfined wastes excreted; confined losses)
- Natural background and residual sources (lands in forest, barren, shrub)

**LAND-TO-WATER DELIVERY**
- Climate (precipitation, temperature)
- Soils (permeability)
- Topography/subsurface (slope, specific catchment area)
- Artificial drainage (tiles, ditches)

**AQUATIC ATTENUATION**
- Streams
  First-order decay ~ f(water travel time, flow
  and depth)
- Reservoirs
  First-order decay ~ f(areal hydraulic load—
  ratio of
  outflow to surface area)

Alexander et al. 2008

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**Sources of nutrients delivered to Gulf of Mexico**

Statistically-significant source shares explaining the variation of loads among reaches. N & P delivery are affected by different sources and land uses.

Alexander et al. 2008

*Non-recoverable animal manure*
Aquatic nutrient removal

modeled estimates of aquatic N & P loss rates are consistent with measurements reported in the literature.

streams & rivers

reservoirs

In-stream nutrient removal: % of nutrient loads in stream reaches that are delivered downstream to Gulf of Mexico

Nitrogen

Phosphorus

Remove 4 kg = 1/0.25
Remove 1.1 kg = 1/0.9

Nutrients to the Gulf of Mexico

Alexander et al. 2008
Nutrients to the Gulf of Mexico

Delivered nutrient masses: nutrient load from the reach network delivered downstream to Gulf of Mexico

Nitrogen

Phosphorus

Agricultural sources in the watershed contribute more than 70% of the N & P delivered to the Gulf of Mexico

Important differences in land uses that contribute N & P

Disproportionate loads from individual geographic areas (9-31 states contribute more than 75% of the N & P, but comprise only 1/3 of the drainage area)

Important hydrological controls on nutrient delivery (non-conservative transport of N & P in streams & reservoirs)

Alexander et al. 2008
SPARROW development
example for national carbon models

- What changes are occurring, and why? Trends in C concentrations (& fluxes) in rivers suggest changes in terrestrial C reserves.
- How much C is stored in aquatic systems anyway, and how much is transported to coastal waters?
- How will changes in basic terrestrial ecosystem processes affect riverine C transport?

Boyer et al., in prep.

SPARROW development
example for national carbon models

269 stations used for initial calibration of OC models

Boyer et al., in prep.
Initial DOC model calibration

\[ R^2 = 81\%; \ RMSE = 88\%; \ n = 269 \]

Soil characteristics are statistically-important source terms

Boyer et al., in prep.
Hydrological metrics are statistically-important land-to-water-delivery terms

Precipitation & drainage density both are significant with higher exports from wetter areas.

Boyer et al., in prep.

Initial predictions of DOC yields

DRAFT!

Boyer et al., in prep.
Current efforts to improve predictability

**Calibration data:** Increase number of stations included.

[Map of the United States with stations marked]

Boyer et al., in prep.

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Current efforts to improve predictability

**OC sources:** net primary productivity, Soil C:N ratio, soil nitrogen, other soil elements

[Map of the United States showing soil nitrogen distribution]

Boyer et al., in prep.
Current efforts to improve predictability

**OC sources or land-to-water-delivery:** wetlands

Winter et al. 1998

Current efforts to improve predictability

**Aquatic Transport:** Attenuation of sediments in reservoirs, geochemical reactions in streambed

Relationships to streambed geochemical environment control water column DOC concentrations

McKnight et al. 2002
Contemporary estimates of C transported in rivers from Mississippi Basin to GOM

<table>
<thead>
<tr>
<th></th>
<th>Raymond et al. 2008</th>
<th>Bianchi et al. 2004</th>
<th>Trefry et al. 1994</th>
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</thead>
<tbody>
<tr>
<td>Tg DOC</td>
<td>3.1</td>
<td>3.1</td>
<td>2.0</td>
</tr>
<tr>
<td>Tg DOC+POC</td>
<td>3.9</td>
<td>3.9</td>
<td>5.8</td>
</tr>
<tr>
<td>Tg DIC</td>
<td>17</td>
<td>17</td>
<td>17</td>
</tr>
<tr>
<td>Tg POC</td>
<td>0.8</td>
<td>0.8</td>
<td>3.8</td>
</tr>
<tr>
<td>Tg POC</td>
<td>0.8</td>
<td>0.8</td>
<td>3.8</td>
</tr>
</tbody>
</table>

Note – these are draft estimates from a quick read of these papers, to put Mississippi fluxes into context.

All together, now

US Carbon Budget: Sinks of carbon for 1990 in the Contiguous USA, in Pg C yr⁻¹ (from Pacala et al. 2001)

<table>
<thead>
<tr>
<th>Category</th>
<th>Low</th>
<th>High</th>
<th>Land area 1990-90 (10⁶ ha)</th>
<th>Miehling et al. 1994</th>
<th>Napa and Heal 1992</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forest trees</td>
<td>0.11</td>
<td>1.1</td>
<td>247-247</td>
<td>0.06</td>
<td>0.11</td>
</tr>
<tr>
<td>Other forest</td>
<td>0.03</td>
<td>0.15</td>
<td>247-247</td>
<td>0.01</td>
<td>0.18</td>
</tr>
<tr>
<td>Organic matter</td>
<td>0.00</td>
<td>0.04</td>
<td>185-188</td>
<td>0.14</td>
<td>–</td>
</tr>
<tr>
<td>Cropland soils</td>
<td>0.12</td>
<td>0.13</td>
<td>334-336</td>
<td>0.12</td>
<td>–</td>
</tr>
<tr>
<td>Nonforest, noncropland</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wood products</td>
<td>0.03</td>
<td>0.07</td>
<td>–</td>
<td>0.03</td>
<td>0.09</td>
</tr>
<tr>
<td>Reservoirs</td>
<td>0.01</td>
<td>0.04</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Coal/silvum</td>
<td>0.04</td>
<td>0.09</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Exports minus imports of food/wood</td>
<td>0.03</td>
<td>0.04</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Food in United States but not exported by rivers</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average US sink without Mpi</td>
<td>0.25</td>
<td>0.58</td>
<td>766</td>
<td>0.15-0.23</td>
<td>0.31</td>
</tr>
</tbody>
</table>

Note: These are draft estimates from a quick read of these papers, to put Mississippi fluxes into context.
At the end of the day

- Transfers of C via land-to-water are orders of magnitude lower than transfers from land-to-atmosphere.
- Small shifts in the C balance of the terrestrial landscape will result in disproportionately-large changes in aquatic C export.
- Important implications for water quality & ecosystems.

Boyter et al., in prep.

SPARROW MODEL
Home page: http://water.usgs.gov/nawqa/sparrow
Documentation (theory, application, user manual): http://pubs.usgs.gov/tm/2006/tm663/
Software: http://water.usgs.gov/nawqa/sparrow/sparrow-mod.html

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