Spatial Estimates of Phosphorus Transport in the Chesapeake Bay Watershed

An Application of the SPARROW model

by Scott W. Ator and Ana María García
Topics

- Summary of research questions, objectives, and approach
- Preliminary results for TP
- Ideas for further investigations…
Research Questions

- **Mass Budget:**
  - What is the relative importance of uplands vs. stream corridors to the removal or retention of N and P between application areas and the bay?
  - How much N and P are removed or retained in upland landscapes, annually?
  - How much of a net change in N or P storage in the landscape might this represent?

- **Understanding Upland Processing:**
  - In what areas of the upland landscape are N or P processed/retained/transmitted differently? Why?
Over the long-term, contaminant transport from source, \( n \), within a catchment, \( i \), can be represented by a budget:

- **Inputs** = **Outputs** +/- Any net change in storage

- Inputs might include natural or human applications (such as fertilizer)

- Outputs might include removal, such as through denitrification or stream flow.

- Change in storage could include sequestration in or removal from soils or biomass.
Conceptual Model – Budget Approach

- **Mass Balance:**
  - $S_{ni} = UPL_{ni} + TAQL_{ni} + D_{ni}$
  - $S_{ni} = (UPH_{ni} + UPOni) + TAQL_{ni} + D_{ni}$

- $S_{ni}$ = mass of contaminant applied from source $n$ to catchment $i$
- Mass of contaminant from source $n$ applied to catchment $i$ that:
  - $UPL_{ni}$ = is lost within uplands in catchment $i$
  - $UPH_{ni}$ = is lost to crop harvest in uplands in catchment $i$
  - $UPOni$ = is lost to processes other than crop harvest in uplands in catchment $i$
  - $TAQL_{ni}$ = is lost within the stream corridor within or downstream of catchment $i$
  - $D_{ni}$ = is delivered to downstream tidal (i.e. terminal) waters
Conceptual Model – Budget Approach

Mass Balance:
- \( S_{ni} = UPL_{ni} + TAQL_{ni} + D_{ni} \)
- \( S_{ni} = (UPH_{ni} + UPOni) + TAQL_{ni} + D_{ni} \)

- All terms are in units of mass/time (i.e. kg/year)
- All terms are specific to each individual source, \( n \)
- Because they are specific to each catchment, \( i \), they can be viewed individually or summed over subareas (like subwatersheds or hydrogeologic settings), which can be useful given the relative uncertainty in predictions for individual catchments
Conceptual Model – Budget Approach

- **Mass Balance:**
  - \[ S_{ni} = UPL_{ni} + TAQL_{ni} + D_{ni} \]
  - \[ S_{ni} = (UPH_{ni} + UPO_{ni}) + TAQL_{ni} + D_{ni} \]

  **Input to SPARROW (for intensive sources – see Schwarz et al, 2006, p. 44)**

  **Can be computed with an independent estimate of one or the other**

  **Can be computed from SPARROW output**

  **Estimated by SPARROW**

The budget equation can be solved for each catchment with routine output from the steady-state SPARROW model. This does not require additional model calibration or predictions.
Background – SPARROW Coefficients

- **Source coefficients**
  - Intensive or extensive
  - Estimate mean proportion or yield delivered to streams

- **Land-to-water coefficients**
  - Allow for spatial variability in delivery to streams
  - Positive or negative

- **Stream decay coefficients**

RMSE=0.4741, $R^2=0.9510$, yield $R^2=0.7300$

<table>
<thead>
<tr>
<th>Phosphorus Model</th>
<th>Estimate</th>
<th>p</th>
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<tbody>
<tr>
<td><strong>Sources</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Point sources (kg/yr)</td>
<td>0.877</td>
<td>&lt;0.0001</td>
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<tr>
<td>Urban land (km$^2$)</td>
<td>49</td>
<td>&lt;0.0001</td>
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<tr>
<td>Fertilizer (kg/yr)</td>
<td>0.0377</td>
<td>0.0014</td>
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<tr>
<td>Manure (kg/yr)</td>
<td>0.0253</td>
<td>0.0002</td>
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<tr>
<td>Siliclastic rocks (km$^2$)</td>
<td>8.52</td>
<td>&lt;0.0001</td>
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<tr>
<td>Crystalline rocks (km$^2$)</td>
<td>6.75</td>
<td>0.0009</td>
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<tr>
<td><strong>Land to Water Transport</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soil erodibility (k factor)</td>
<td>6.25</td>
<td>0.0002</td>
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<tr>
<td>Ln(% well drained soils)</td>
<td>-0.100</td>
<td>0.0019</td>
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<tr>
<td>Ln(precipitation (mm))</td>
<td>2.06</td>
<td>&lt;0.0237</td>
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<tr>
<td>Coastal Plain (area)</td>
<td>1.02</td>
<td>&lt;0.0001</td>
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<tr>
<td><strong>Aquatic Decay</strong></td>
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<tr>
<td>Impoundments</td>
<td>54.3</td>
<td>0.0174</td>
</tr>
</tbody>
</table>

Ator et al., 2011
Computing Upland Loss ($UPL_{ni}$)

- $UPL_{ni} = S_{ni} (1 - LDR_{ni})$
- $LDR_{ni} =$ Landscape delivery ratio, or the proportion of contaminant from source $n$ in catchment $i$ that reaches the local stream (Hoos and McMahon, 2009):

$$LDR_{ni} = \alpha_n \cdot DVF_i$$
$$= \alpha_n \exp(\sum_m (\omega_{mn}Z_{mi}O_m))$$

$\alpha_n =$ model-estimated coefficient for source $n$. This is also the mean $LDR_{ni}$.

$DVF_i =$ delivery variation factor or “delivery factor” (Schwarz et al, 2006), or “relative upland erosion vulnerability” (Ator et al., 2010)

$m =$ individual land-to-water term in the model

$\omega_{mn} =$ interaction between source $n$ and land-to-water term, $m$ ($0,1$)

$Z_{mi} =$ mean-adjusted value of term $m$ in catchment $i$

$O_m =$ model-estimated coefficient for land-to-water term $m$
Some Preliminary Results...

- **Question**: In what areas of the upland landscape is P processed or transmitted differently? Why?

- **Approach**: Look at the $DVF_i = \exp(\sum_m (\omega_{mn}Z_{mi}O_m))$
  - A continuous function of land-to-water terms demonstrated by the model to be significant to transport from uplands to stream corridors
  - Allows for spatial variability of land-to-water transport among catchments in SPARROW models
Delivery Variation Factor (DVF$_i$)

- Is independent of source*, a function only of land-to-water specification

- TP terms
  - Soil erodibility (+)
  - Soil drainage (-)
  - Coastal plain area (+)
  - Precipitation (+)

*DVFi = exp(Σ$_m$(ω$_{mn}$Z$_{mi}$O$_m$)), for sources interacting with same land-to-water terms
Relative Losses

- Proportion of TP from that is lost in uplands
- This is really just a function of DVFi, as:
  - UPLni = Sni (1 − LDRni)
  - UPLni / Sni = 1 - LDRni
  - UPLni / Sni = 1 − αn DVFi
Explaining DVF$_i$ - Phosphorus

Type A Soils (-)

Coastal Plain (+)

Precip (+)

Soil K-factor (+)
Delivery Variation Factor (DVF$_i$)

* area-weighted DVF$_i$
Some Preliminary Results...

- **Question**: How much annual net N and P losses (retention?) occur during transport from upland source areas to tidal waters
  - In uplands
  - In stream corridors

- **Approach**: Look at the mass balances of inputs and outputs over different areas of interest:
  - Major watersheds
  - Hydrogeologic settings
  - Land-use settings
Mass Balance of TP

INPUTS

- Tidal Waters
- Other upland
- Streams
- Fertilizer

OUTPUTS

- Harvest
- Manure

Annual Mass (kg/year)
Mass Balance of TP

INPUTS
- Susquehanna WS
- Potomac WS
- James WS
- Rappahannock WS
- Appomattox WS
- Pamunkey WS
- Mattaponi WS
- Patuxent WS
- Choptank WS
- Remainder, ES
- Remainder, WS

OUTPUTS

Annual Mass (kg/km²/year)

Tidal Waters
Streams
Fertilizer
Harvest
Other upland
Manure
Summary

- Review of DVFi allows for us to visualize and explain why and how different areas of the watershed process or transmit N and P from uplands to streams differently.
- We can also quantify relative upland processing retention in different areas.
One Limitation

- Math only works for intensive sources in the SPARROW models. For TN/TP, this includes fertilizer/fixation, manure, atmospheric (86% of non-point TN flux to bay, 63% of non-point TP flux to bay).

- For extensive sources, \( \alpha_n \) when "combined" with the land-to-water delivery factor is the "mean quantity of contaminant mass per unit area that is delivered to streams" (Schwarz et al., 2006, p. 45).
  
  \[ \alpha_n \text{ DVF}_i = \frac{(S_{ni} - UPL_{ni})}{A_n} \]

- So we could compute \((S_{ni} - UPL_{ni})\), but we don’t know either of those terms, individually.
Status

- The method seems to work very well with the CBTN_v4 model. We are preparing a paper for JAWRA presenting the approach and demonstrating it for the case of TN in the Chesapeake Bay watershed.
- We can then try different calibrations of the Bay TN and TP models to provide the most useful output for understanding fate and transport.
Delivery Variation Factor (DVF_i)

* area-weighted DVF_i
Delivery Variation Factor (DVF_i)