Advances in hypoxic extent estimation through geostatistical modeling

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Eutrophic and Hypoxic Coastal Areas of North America and the Caribbean

Source: DRI
<table>
<thead>
<tr>
<th></th>
<th>Lake Erie (Central basin)</th>
<th>Chesapeake Bay (Mainstem)</th>
<th>The northern Gulf of Mexico</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface area (km²)</td>
<td>16,138</td>
<td>9,690</td>
<td>62,500</td>
</tr>
<tr>
<td># of measurement stations</td>
<td>9-10</td>
<td>40</td>
<td>60-100</td>
</tr>
<tr>
<td># of stations per 2,000 km² area</td>
<td>1</td>
<td>8</td>
<td>2-3</td>
</tr>
</tbody>
</table>
Sampling locations

August/September

Late July

Legend
- project stations
- 10-80 m. isobaths

Study Area

Mississippi River

Atchafalaya River

TX LA MS AL FL

K J I F E D C B AA A B DD

0 25 50 Kilometers

Late July
Motivation – better understand hypoxia

• Geostatistical application in hypoxia
  – Estimate hypoxic extent and its uncertainty.
  – Provide interannual variability of hypoxia.

• Ancillary information
  – Help reduce estimation uncertainty.

• Sampling network
  – Sampling density affects estimation and its uncertainty.
Geostatistical algorithms of estimating the hypoxic extent (e.g., Lake Erie)

In situ DO data

Geostatistical model selection

Significant variables

Universal Kriging (UK) & Conditional realizations

Auxiliary variables
- Latitude
- Longitude
- Bathymetry
- Sea surface temperature, Chlorophyll (Remote sensing data)

Probability distribution of hypoxic extent
Geostatistical model formulation

\[ z = X\beta + \eta + \epsilon \]

- **Response Variable**
- **Deterministic Component (trends with space and other covariates)**
- **Spatially Correlated Stochasticity**
- **Uncorrelated Stochasticity**

Graph showing the relationship between response, \( z \), and space, \( x \), with a trend line and data points.
Application of Model to the Gulf: deterministic component

\[ z = X\beta + \eta + \epsilon \]

- Significant Variables (X)

Depth

Easting

Northing

Overall BWDO trend
Application of Model to Shelfwide Cruises: stochastic components

\[ z = X\beta + \eta + \epsilon \]

\[ \gamma (mg^2 L^{-2}) \]

\[ \begin{align*}
0 & \quad 50 \quad 100 \quad 150 \quad 200 \\
\sigma_{\epsilon}^2 & \quad \sigma_{\eta}^2 \quad 3l_h
\end{align*} \]

\[ 2: \text{sill} \]

\[ 2: \text{nugget} \]

\[ 3l_h: \text{range} \]
Spatial structure parameters

The northern Gulf of Mexico

Erie (C)

Chesapeake (M)

100 km
Example results for BWDO/hypoxic area: BWDO spatial distribution
Example results for BWDO/hypoxic area:
Probability of hypoxia
In addition to provide hypoxic extent, based on these results, we could …

• Quantify the effect of human activities and nature forces
  – Chesapeake Bay (Zhou et al. 2014, *L&O*)
  – Lake Erie (Zhou et al. manuscript)

• Separate the effect of human activities from nature forces
  – the northern Gulf of Mexico (Obenour et al. 2012, *ES&T*)

• Provide nutrient reduction suggestions
  – the northern Gulf of Mexico (Obenour et al. 2012, *ES&T*)
  – Chesapeake Bay (Zhou et al. 2014, *L&O*)
Candidate variables (various month combinations)

1. Previous year nutrient loads (western + central basin) [2]
2. Present year nutrient loads (western basin, central basin, western + central basin) [52]
3. River discharge (western basin, central basin, western + central basin) [132]
4. Wind directions (cardinal / intercardinal directions) [260]
5. Wind speed, wind stress [23]
6. Precipitation [28]
7. Lake Surface temperature [21]
8. Ice cover [3]

Significant variables

Soluble Reactive Phosphorous (May-July, western + central basin)
In(discharge) (April-June, western + central basin)
NW wind duration (June)
Wind stress (July)

BIC: ≤1 variable per group

Zhou et al. (in review)
BIC selection results

<table>
<thead>
<tr>
<th>In$(D_t)$</th>
<th>Apr-Jun</th>
<th>Apr-Jun</th>
<th>Apr-Jun</th>
<th>Apr-Jun</th>
<th>Apr-Jun</th>
<th>Apr-Jun</th>
<th>Apr-Jul</th>
<th>Apr-Jul</th>
</tr>
</thead>
<tbody>
<tr>
<td>WD$_t$</td>
<td>-</td>
<td>NW Jun</td>
<td>-</td>
<td>NW Jun</td>
<td>NW Jun</td>
<td>NW Jun</td>
<td>SW Jul</td>
<td>SW Jul</td>
</tr>
<tr>
<td>SRP$_t$</td>
<td>-</td>
<td>-</td>
<td>May-Jul</td>
<td>May-Jul</td>
<td>May-Jul</td>
<td>May-Jul</td>
<td>Feb-May</td>
<td>Feb-May</td>
</tr>
<tr>
<td>WS$_t^2$</td>
<td>-</td>
<td>-</td>
<td>Jul</td>
<td>Jul</td>
<td>Jul</td>
<td>Jul</td>
<td>Jun</td>
<td>Jun</td>
</tr>
<tr>
<td>P$_t$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Aug</td>
<td>Aug</td>
<td>May-Jul</td>
<td>Jan-Dec</td>
</tr>
<tr>
<td>SRP$_{-1,t}$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>May-Jul</td>
<td>Jan-Dec</td>
<td>Jan-Dec</td>
</tr>
<tr>
<td>IC$_t$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Apr</td>
<td>Apr</td>
</tr>
<tr>
<td>LST$_t$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Jul-Aug</td>
</tr>
</tbody>
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More hypoxia  Less hypoxia

Zhou et al. (in review)
A four-variable model is found to explain 82% of the interannual variability in the seasonally-averaged hypoxic extents.
Summary of findings

• Conditional realizations yield more robust extent estimates and uncertainties.
• Covariate information reduces uncertainty and provides more realistic representations of DO.
• Both human activities and nature forces affect interannual variability of hypoxia.
Acknowledgments

• Data providers: U.S. EPA, Environment Canada, NOAA, NASA, USGS, Chesapeake Bay Program

• Funders: NSF, EPA, NOAA, Rackham Graduate School

• Thank you!