A Bayesian Hierarchical Spatio-Temporal Ratio-Estimator Approach to Model Phosphorus Loading in Six Ohio Watersheds: the Importance of Accounting for Inter-Annual and Inter-Basin Variabilities

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Nutrient loading and the problem of load estimation

- Accurately estimating riverine nutrient loads is a critical step towards mitigating and managing eutrophication-based water quality impairments

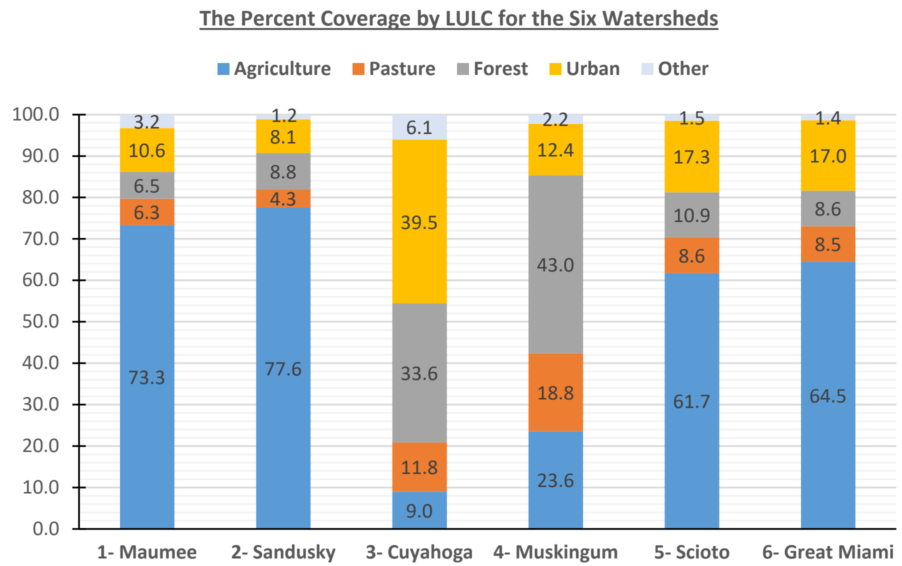
- Load estimation is hindered by the sporadic and infrequent monitoring of nutrient concentrations
  - Flow is continuously measured but concentrations are sparsely measured

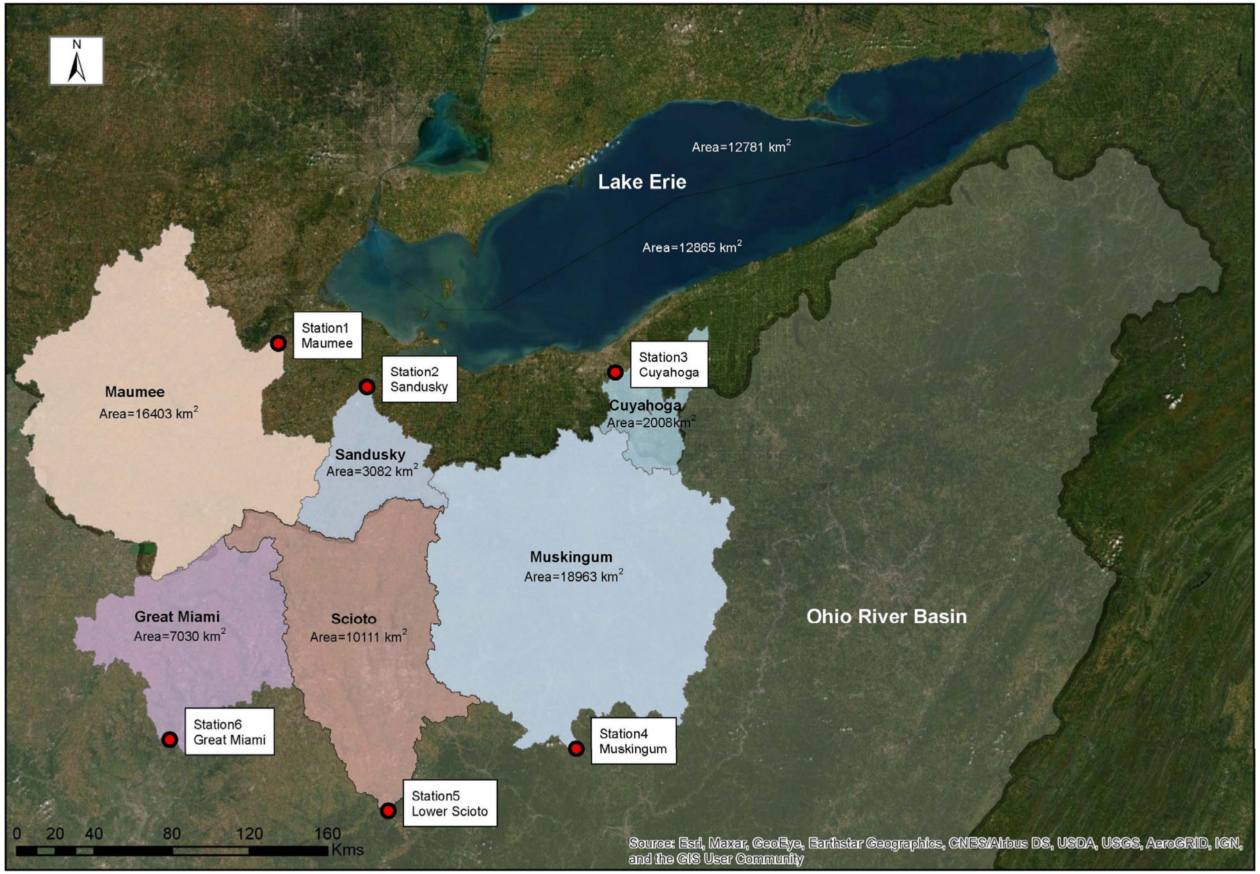
- Several modelling approaches proposed to estimate pollutant loads
  - Most suffer from biases and/or from their limited abilities to transparently quantify uncertainties

Study area

- Six watersheds pouring into the Lake Erie and Ohio River basin
  - Water quality and flow data continuously collected between 2005 and 2020 ➔ opportunity to calculate the actual "true loads"
  - Varying landuse-landcover coverage

Station Number	Station Name	Drainage
1	Maumee	Lake Erie
2	Sandusky	Lake Erie
3	Cuyahoga	Lake Erie
4	Muskingum	Ohio River
5	Lower Scioto	Ohio River
6	Great Miami	Ohio River





Model development

- Developed a **Spatio-temporal Bayesian hierarchical ratio-estimator** model to predict the annual total phosphorus loads between 2005 and 2020 for the six intensively monitored watersheds
  - Ability to compare between the "True Loads" and the "Predicted Loads"
    - Can we accurately predict the "True load" if we had 6 or even 4 measurements of concentration per month?
  - Hierarchy allows for:
    - Pooling the data from multiple watersheds
    - Accounting for the impacts of LULC on inter-station variability in phosphorus load estimates (Space)
    - Accounting for the impacts of annual climatic variability on inter-annual variability in phosphorus load estimates (Time)
  - Model expands on the work done by Cha et al, 2010 on Saginaw River

$$L_{ijk} = \beta_{jk} * Q_{ijk} + \varepsilon_{ijk} * (Q_{ijk})^{1/2}$$
$$\varepsilon_{ijk} \sim N_o(0, \sigma^2)$$
$$\beta_{jk} = \bar{\beta} + \Delta_{S_k} + \Delta_{Y_{jk}}$$
$$\Delta_{S_k} = Space_k * \delta_S$$
$$\Delta_{Y_{jk}} = Temporaljk * \delta_Y$$

Where: ***i*** is the day of the year, ***j*** is the year, and ***k*** is the station/watershed

Q is the daily measured flow; $\bar{\beta}$ is the spatio-temporally-averaged effective concentration; $\Delta_{S_k} and\ \Delta_{Y_{jk}}$ are the spatial and temporal changes in the effective concentrations

$Space_k$ is a spatial predictor at the watershed level; $Temporal_{jk}$ is the temporal predictor at watershed k for year j

δ_S is the slope on the higher-level spatial predictor and δ_Y is the slope on the higher-level temporal predictor

Model comparison

Model predictions will be compared with load predictions calculated by:

1. <u>Four Averaging Approaches:</u>
   Load estimation method using different averaging techniques of concentration and/or flow data

Method 1

$$L_1 = \left(\sum_{i=1}^{n} \frac{C_i}{n}\right) \times \left(\sum_{i=1}^{n} \frac{Q_i}{n}\right)$$

~ average concentration multiplied by average flow when concentration was measured.

Method 2

$$L_2 = K_2 \left(\sum_{i=1}^{n} \frac{C_i \times Q_i}{n}\right)$$

~ average load when concentration was measured.

Method 3

$$L_3 = K_3 \overline{Q_r} \left(\sum_{i=1}^{n} \frac{C_i}{n}\right)$$

~ $\bar{Q}$r is the mean flow for the period of interest from a continuous flow record

Method 4

$$L_4 = \frac{K_4 \sum_{i=1}^{n} (C_i \times Q_i)}{\sum_{i=1}^{n} Q_i} \overline{Q_r}$$

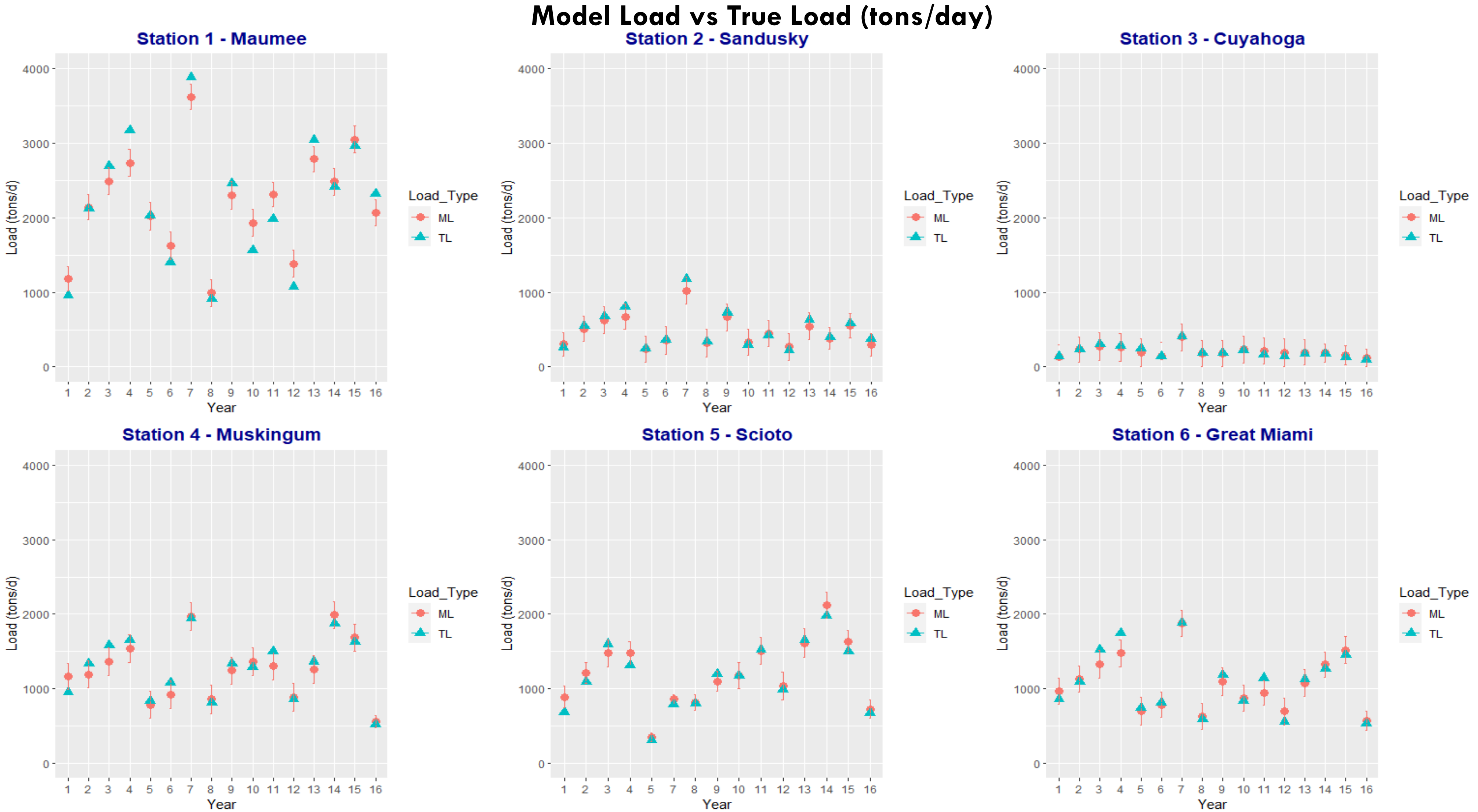
~ $\bar{Q}$r is the mean flow for the period of interest from a continuous flow record.

2. <u>Bayesian Complete Pooling Approach:</u>
   One ratio-estimator model for the whole dataset ➔ ignores variation across watersheds and years

3. <u>Bayesian No-pooling Approach:</u>
   One model for each station-year combination ➔ no sharing of information across different stations and years

Results

How good are the model predictions vs the "True Loads"?

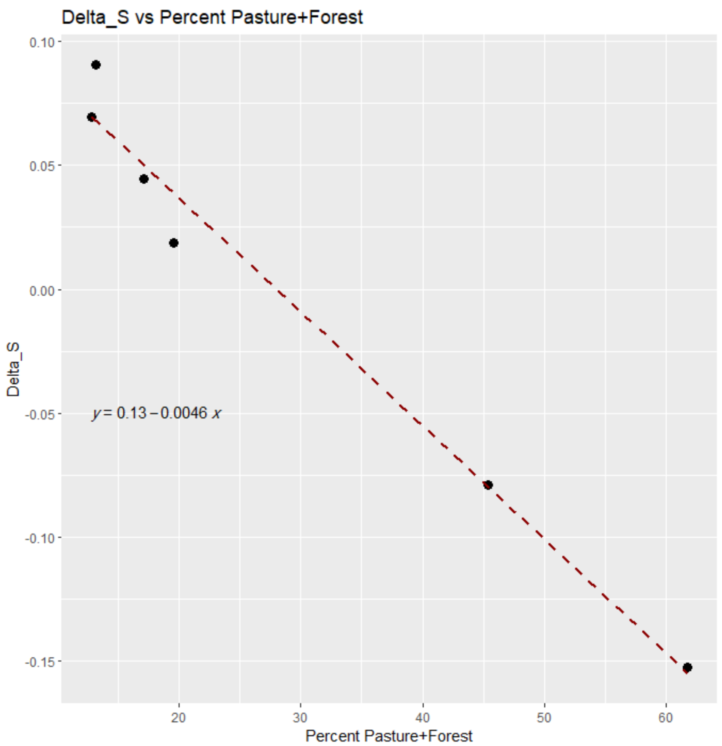


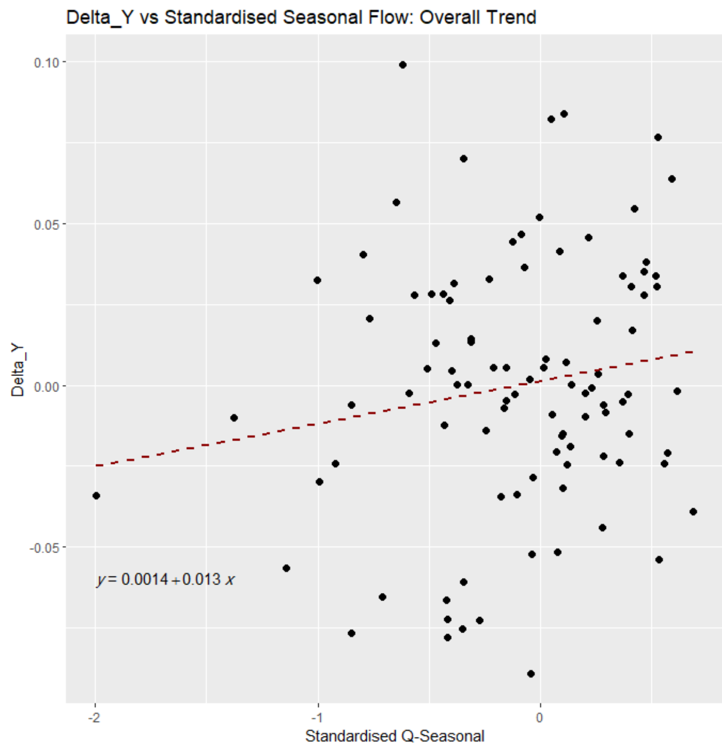
Was the Spatio-temporal Hierarchy necessary?

- The proposed hierarchical model structure strongly supports accounting for "watershed- level" spatial variability; moderately supports accounting for the interannual variability in flow (growing season flows)

Higher % of natural areas (pasture + forest) ➔ lower effective TP concentration for watershed

Higher seasonal flows ➔ higher the effective TP concentration for watershed
Importance of non-point sources





How good are the predictions vs other models?

- Hierarchical Bayesian model outperformed the averaging and the completely pooled and non-pooled models

	Our Model	% Difference Between True and Predicted Loads Across All Watersheds					
		Averaging Methods				Complete Pooling	No- Pooling
		Method1	Method2	Method3	Method4		
Average	1.7%	-11.5%	14.8%	-9.3%	17.4%	71.9%	-79.7%
Maximum	36.8%	214.9%	272.5%	188.8%	181.2%	550.6%	-65.9%
Minimum	-21.6%	-67.9%	-41.4%	-60.4%	-16.3%	-89.4%	-84.7%
Median	0.6%	-16.3%	6.6%	-15. 8%	7.2%	44.0%	-80.1%

- Assuming that Bayesian model had a spatial hierarchy was equally good
  - Median difference in loads across the watersheds was 0.8% instead of 0.6%
  - Total loads vary between -18% and 52% from the true load
- Assuming that Bayesian model had a temporal hierarchy was significantly worse
  - Median difference in loads across the watersheds was 1.78% instead of 0.6%
  - Total loads ranged between -20% and 39% from the true load

Model Validation

Model performance using data from two "NEW" stations: Portage River and Chikasaw River

Portage River:

The load estimates from the proposed model

- Between -6% and 37% from the true loads
- Median difference of 6.5%

%Pasture+%Forest = 17.5%

Average Annual Seasonal Flow = 161,195,879 cmd

	Our Model	Complete Pooling
Average	**12.55%**	-19.24%
Maximum	**37.74%**	2.06%
Minimum	**-6.36%**	-36.95%
Median	**6.44%**	-24.32%

Chikasaw River:

The load estimates from the final proposed model

- Vary between -57% and 25% from the true loads
- Median difference of -27%

%Pasture+%Forest =11.7%

Average Annual Seasonal Flow = 6,348,875 cmd

	Our Model	Complete Pooling
Average	**-27.25%**	-46.44%
Maximum	**25.01%**	9.44%
Minimum	**-57.24%**	-70.46%
Median	**-27.25%**	-48.89%

Conclusions

- Final model predictions of total annual load were on average 1.7% different from the true load
- The model proved to be robust and was validated by calculating the total loads for two additional stations along Portage River and Chikasaw River
  - Predicted total loads for the two new stations were around 6.5% and -27% different that the true load respectively
- Model performance remained adequate even when sampling was reduced to 3 samples per month
  - Total estimated annual loads were 3.94% different from the true loads
- The integration of higher-level spatial predictors successfully captured inter-station variabilities in phosphorus loading
  - Model shows that non-point sources are significant predictors of total phosphorus:
    - The flow-weighted effective nutrient concentration decreased with natural areas (it also increased with agricultural areas)
- Accounting for annual climatic variability helped explain temporal changes in the flow-weighted effective nutrient concentrations among the six watersheds
  - Higher flows during the growing season → higher effective concentrations (non-point sources)
- Spatial effects are more important to account for as compared to inter-annual temporal variability