Impacts of Intra-Annual Climate Variability and Change on Phosphorus Loads in the Great Lakes Basin

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INTRODUCTION

Riverine phosphorous loads vary with source strength, discharge, and landscape characteristics. In this work, we consider how **seasonal variability** in river discharges control phosphorous (P) loads and how **climate change** will impact discharges and corresponding P loads.

We focus on 14 watersheds in the U.S. Great Lakes basin (**Figure 1**), given the potential for riverine phosphorus exports to contribute to ecosystem impacts, such as harmful algae blooms in the Great Lakes. The 14 watersheds vary in terms of land use and hydrologic regimes (**Table 1**).

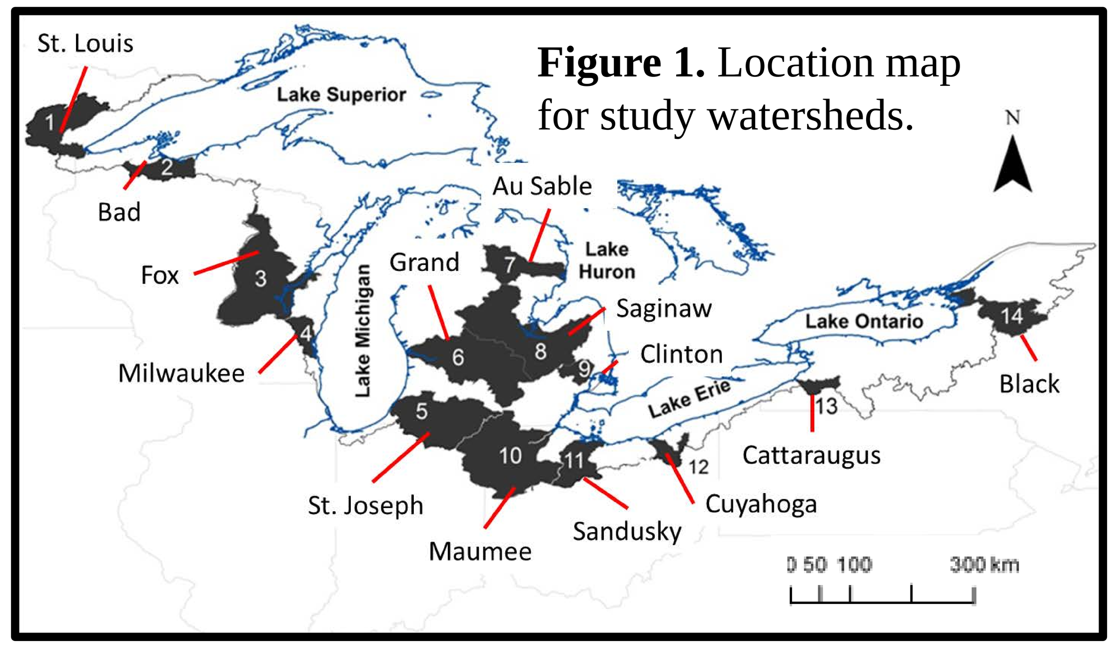


Figure 1. Location map for study watersheds.

Figure 2 summarizes the modeling framework. Climate datasets (precipitation and temperature) are input to a hydrologic model to calculate daily discharges for **historical-**, **near-future** and **far-future** periods. Daily discharges are then input to a calibrated, seasonal P load model to generate daily P loads.

Table 1. Characteristics of study watersheds.

Watershed	Drainage Area (km²)	Fraction of Land Use in 2006 (%) [1]			Median Discharge Normalized to Watershed Area	Seasonal Variability in Discharge (Q_{95}/Q_5) [2]
		Agr.	Urb.	For.		
Au Sable	5,159	13	8	77	1.01	2
Bad	3,427	6	4	88	0.86	28
Black	5,768	18	2	76	2.12	15
Cattaraugus	1,427	36	4	59	1.37	27
Clinton	1,921	21	52	24	4.55	11
Cuyahoga	2,070	18	46	33	1.15	16
Fox	16,383	43	8	43	0.65	5
Grand	14,215	54	15	29	0.71	16
Maumee	16,806	78	12	9	0.43	149
Milwaukee	2,224	45	29	25	0.62	13
Saginaw	15,761	48	13	38	0.52	45
Sandusky	4,607	79	10	10	0.52	701
St. Joseph	12,114	59	14	24	0.94	5
St. Louis	9,707	5	4	88	0.59	10

[1] Agr = agricultural; For. = forested; Urb. = urban. Source:LaBeau et al. 2014.
[2] Q_x is the discharge corresponding to x exceedance probability, according to historical records.

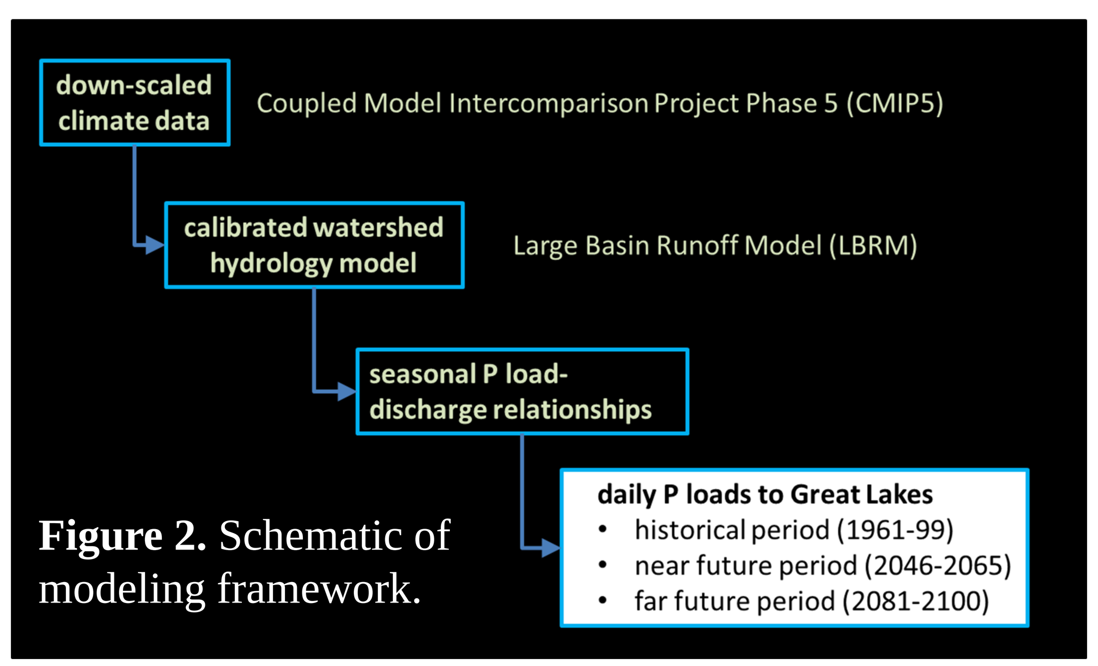


Figure 2. Schematic of modeling framework.

SEASONAL VARIABILITY in P LOADS

Seasonal load-discharge relationships were estimated using a linearized form of power law functions for each watershed, by fitting to historical data from 1961-1999, using a χ^2 test of goodness to fit to determine whether a serial-monthly model is justified.

$$\overline{L_T} = \overline{C_T Q_T} = \beta_0 + \beta_1 \overline{Q_T} + e_T$$

where

$\overline{L_T} = \log_{10}(\text{daily load})$ at time T

$\overline{C_T} = \log_{10}(\text{concentration})$ at time T

$\overline{Q_T} = \log_{10}(\text{discharge})$ at time T

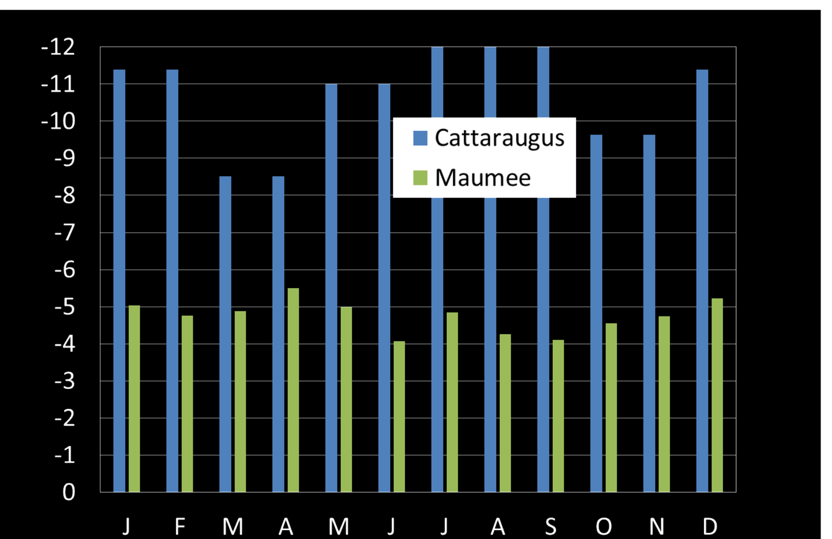
β_0, β_1 = coefficients for each watershed and seasonal period

e_T = model error (independent and normally distributed)

We refer to the coefficient, $\boldsymbol{\beta_0}$ as the **"concentration coefficient"** because it represents a concentration term in a linear load-discharge model and the coefficient $\boldsymbol{\beta_1}$ as the **"power coefficient."**

- Best-fit **seasonal periods ranged from monthly to three months**.
- Estimates of the concentration coefficient **ranged over more than 7 orders of magnitude**, over the study watersheds (see **Figure 3** for example).
- Over seasonal periods, the concentration coefficient **varied from less than one to more than 5 orders of magnitude**, depending on the watershed (see **Figure 3** for example).
- Estimates of the power coefficient ranged slightly less than unity to greater than two, reflecting **wide differences in the nonlinearity of the load-discharge relationship**.
- The seasonal standard deviation of the power coefficient ranged from 5% to 28% of the average across the seasons, again indicating **wide differences in the nonlinearity of the load-discharge relationship.**

Figure 3. $\log_{10}(\beta_0)$, the concentration coefficient, for the Cattaraugus and Maumee watersheds

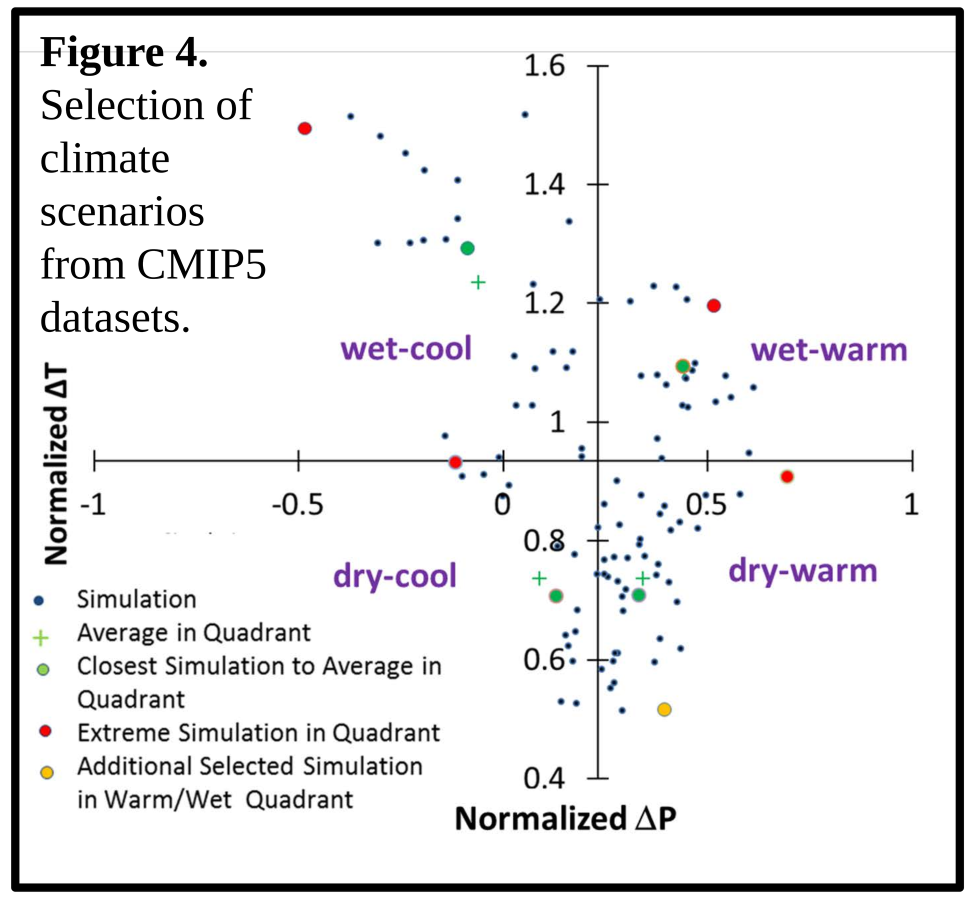


With one exception, the **seasonal models performed substantially better than the annual models,** based on the Nash-Sutcliffe efficiencies (NSEs). NSEs for the seasonal models are >0.50, indicating good model performance.

CLIMATE CHANGE IMPACTS - DISCHARGES

For the future climate periods (2046-2065 and 2081-2100), a suite of 9 bias corrected projections were made using the CMIP5 database, representing averages and extremes for four climate types, as shown in **Figure 4**.

Figure 4. Selection of climate scenarios from CMIP5 datasets.



Changes in selected discharge statistics, averaged across the 9 selected climate projections are presented in **Figure 5**.

- **Low flows** (characterized by Q_5) **are predicted to decrease on average by 12% and 19%.**
- **High flows** (characterized by Q_{95}) **are predicted to increase on average by 9% and 12%** over the near- and far-future periods, respectively.
- Median flows are predicted to change very little.
- If the timing of increases in high flows coincides with seasons in which load-discharge relationships produce particularly high loads, **climate change impacts are intensified**.

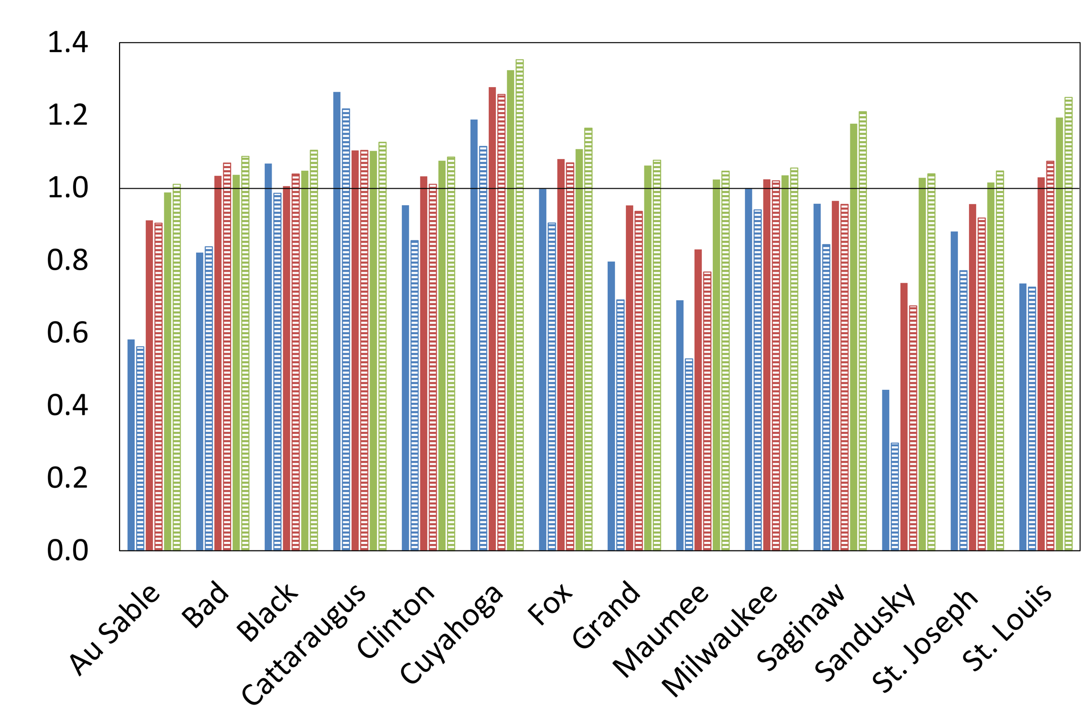
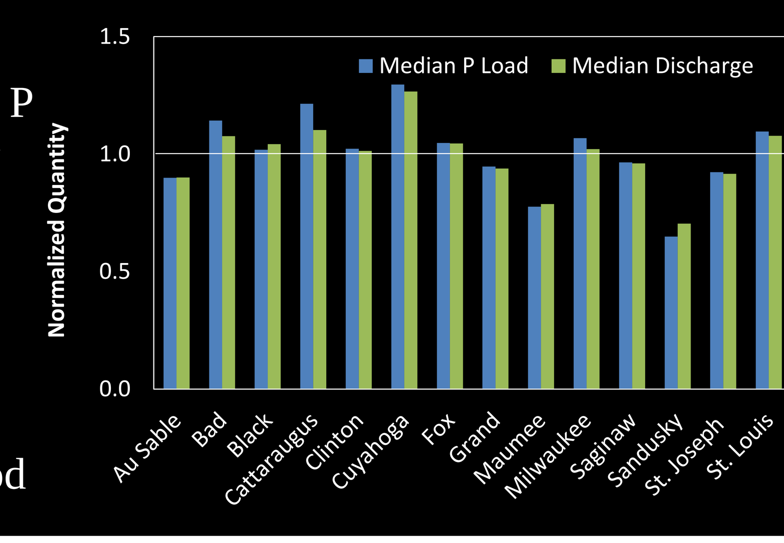


Figure 5. Near and far-future discharges, normalized to the historical period. QX indicates the recurrence interval.

CLIMATE CHANGE IMPACTS - P LOADS

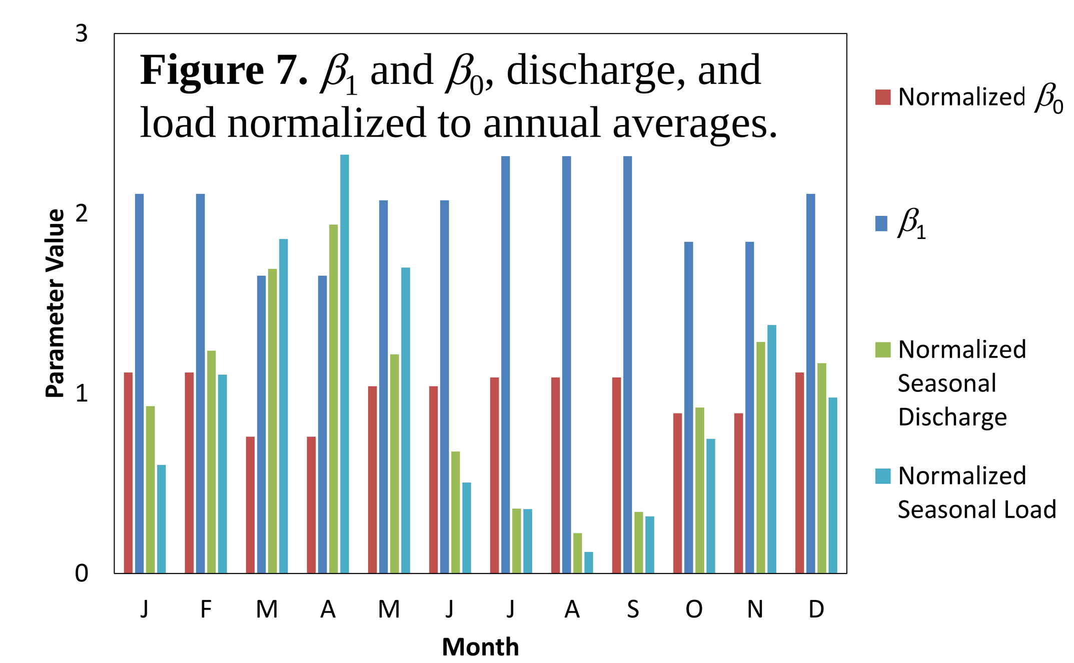
Figure 6 shows the median P loads for the far-future climate period (2081-2100) for each watershed. For most watersheds, the normalized quantities are quite similar, but for a few watersheds, (notably Bad and Cattaraugus), there are **substantial differences between the median discharges and loads, presumably because there are strong nonlinearities in the load discharge relationships.**

Figure 6. Median discharges and P loads for study watersheds in far-future period, normalized to medians for historical period



This phenomenon is explored in Figure 7, which shows results for one climate simulation (extreme wet-cool) for the Cattaraugus watershed. In the **spring months**, the **concurrence of high nonlinearity in the load-discharge model** (indicated by values of the power coefficient, β_1, substantially greater than one) **with high discharges is responsible for the overall nonlinear response of load to discharge for the Cattaraugus and the Bad watersheds.**

Figure 7. β_1 and β_0, discharge, and load normalized to annual averages.



TAKEAWAY MESSAGES

- **Seasonal load-discharge models are superior to annual models, in terms of accuracy.**
- **Seasonal load-discharge models are necessary to predict impacts of seasonal shifts in climate on P loads.**
- **Nonlinearity in load-discharge relationships can intensify the impacts of climate change.**
- **Efforts to reduce P loads should focus on watersheds most vulnerable to climate change, where seasonal shifts in climate coincide with higher nonlinearity.**