Jordan Lake Bayesian-Mechanistic Water Quality Modeling

to Assess Historical and Projected Eutrophication

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River Basin Association
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Modeling Efforts in NCPC Study

3-D lake model

Nutrient loading → in-lake chlorophyll a

High spatio-temporal resolution

Detailed representation of biophysical processes

5-year study period

UNC-Charlotte team:
James Bowen
William Langley
Babatunde Adeyeye

Hybrid lake model

Coarse (e.g., monthly) resolution

Nutrient mass balance with Bayesian calib. & uncertainty quant.

35-year study period

NC State team:
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Daniel Obenour
Matthew Aupperle
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Hybrid watershed model

Watershed management → nutrient loading

Coarse (e.g., yearly) resolution

Nutrient loading and transport with Bayesian calib. & uncertainty quant.

35-year study period.

NC State team:
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Lake Modeling
Research Questions:

a) How important is the sediment layer as a source or sink for nutrients, relative to watershed loads?

b) What are the primary controls on lake chlorophyll concentrations (e.g., nutrients, flushing, temp.)?

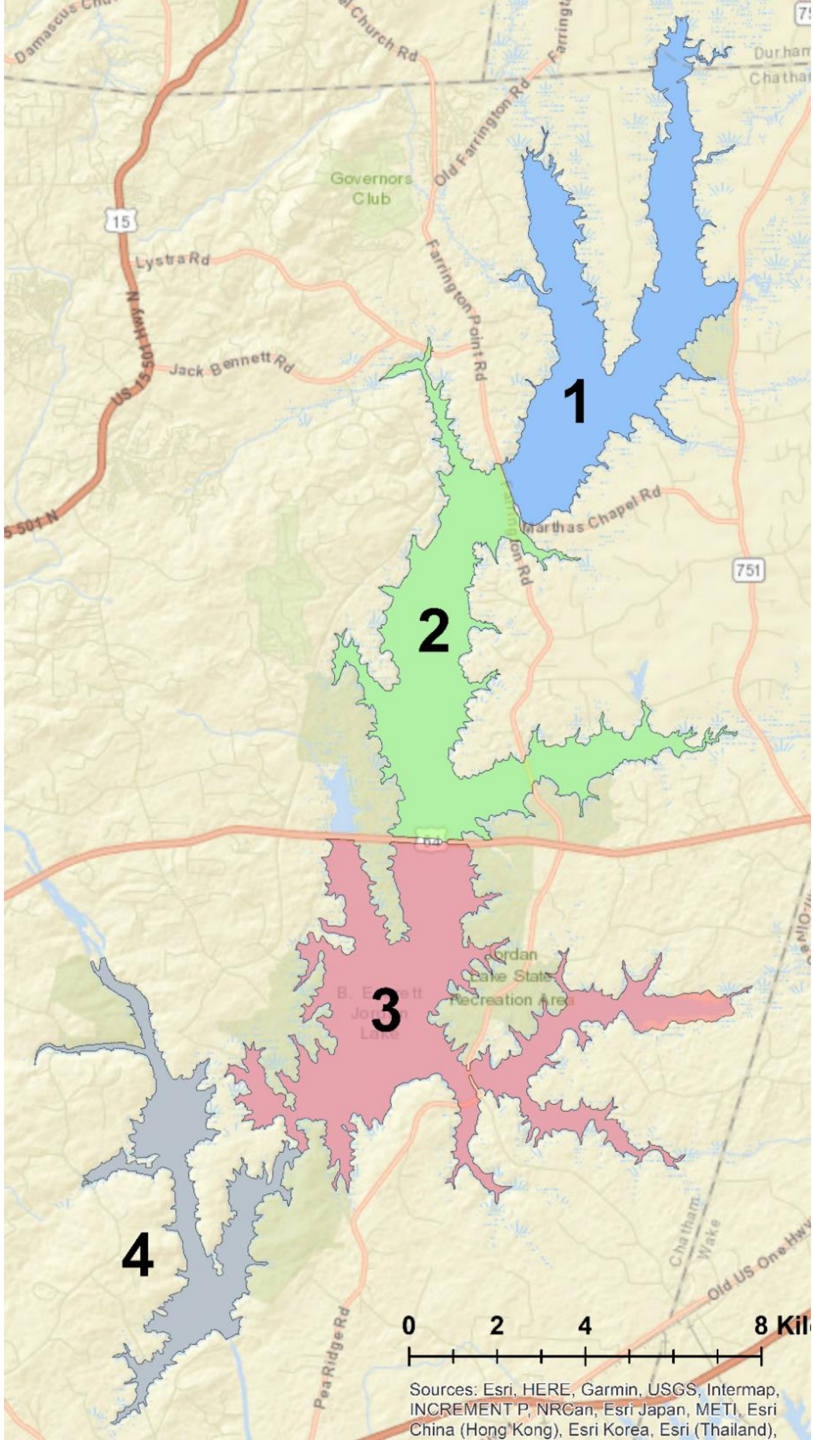
c) How do the answers to (a) and (b) vary over time and in different regions of the reservoir?

Management/ Policy Implications:

a) Compare the efficacy of various N & P watershed loading reductions for reducing algal levels in the reservoir (e.g., to 40 µg/L criterion).
b) Estimate how long it will take for the benefits of watershed loading reductions to be fully realized.
c) Estimate future lake eutrophication trajectories under status quo or increased nutrient loading.

Study area and time period

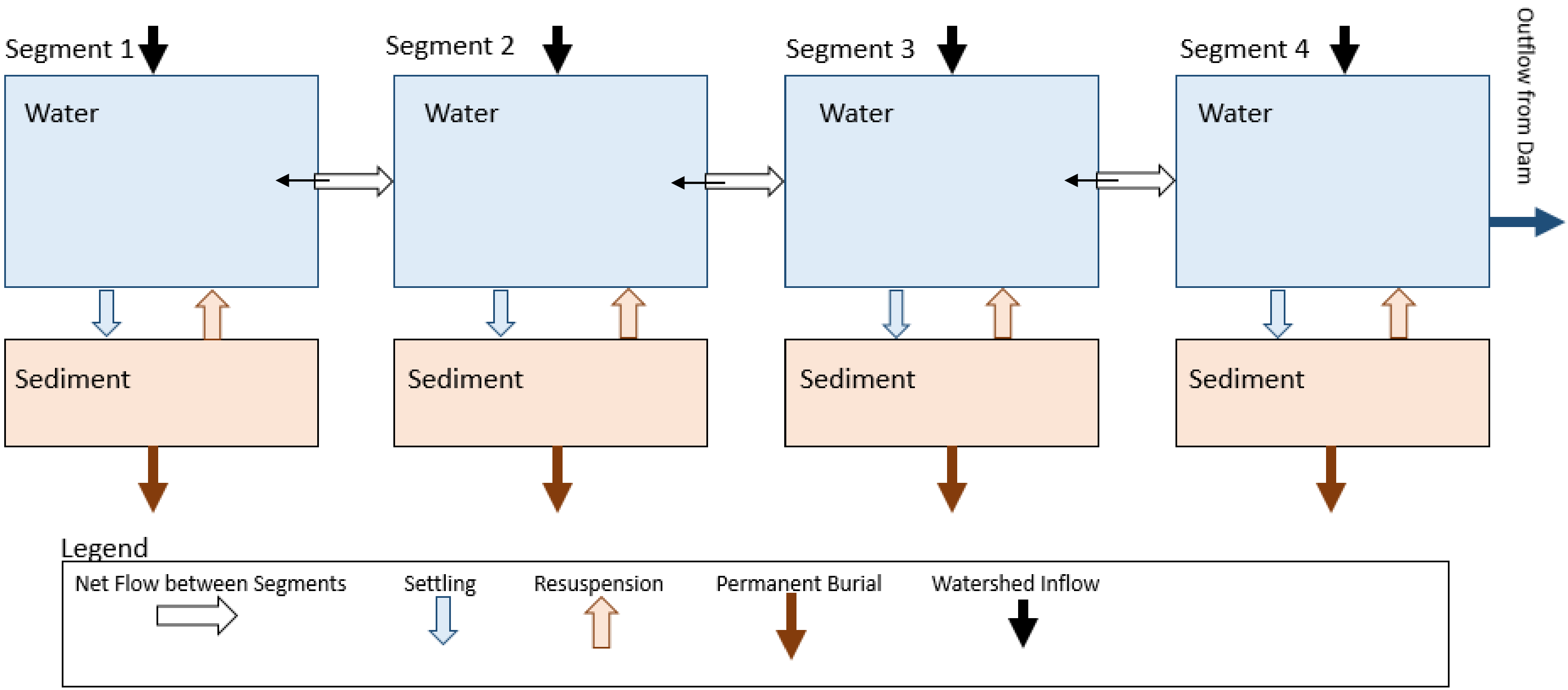
- Lake is longitudinally segmented based on major constrictions.
- Lake is modeled over three decades at a monthly time step (1983-2018)



Bayesian-Mechanistic Approach:

a) Develop a multi-decadal mass-balance water quality model to simulate nitrogen and phosphorus.
b) Embed model in a Bayesian framework where uncertain prior information on nutrient cycling rates is updated through calibration to observed data.
c) Link reservoir nutrient levels to chlorophyll and other factors through regression modeling.
d) Apply the nutrient and chlorophyll modeling system to evaluate future management and climate scenarios.

Nutrient Model Schematic



Model formulation – Water column

$$\frac{dM_i}{dt} = +\left(Q_{\text{in},i} * C_{\text{in},i}\right)(1-\psi)$$ Watershed nutrient loading, less initial loss

$$+\,(S_i * R)\,{\theta_R}^{T-20}$$ Internal nutrient loading from sediment

$$-\,M_i\left(k + \frac{v * A_i}{V_i}\right){\theta_v}^{T-20}$$ Settling of nutrients to sediment layer

$$+\begin{cases} \mathrm{Q_{i-1,i}} * \dfrac{\mathrm{M_{i-1}}}{\mathrm{V_{i-1}}} - \mathrm{Q_{i,i+1}} * \dfrac{\mathrm{M_i}}{\mathrm{V_i}} & \text{regular flow (north to south)} \\ \mathrm{Q_{i+1,i}} * \dfrac{\mathrm{M_{i+1}}}{\mathrm{V_{i+1}}} - \mathrm{Q_{i,i-1}} * \dfrac{\mathrm{M_i}}{\mathrm{V_i}} & \text{reverse flow (south to north)} \end{cases}$$ Advection of nutrients

Model formulation – Sediment layer

$$\frac{dM_i}{dt} = +\ M_i\left(k + \frac{v * A_i}{V_i}\right)\theta_v{}^{T-20}$$ Settling of nutrients to sediment layer

$$-\ (S_i * R)\ \theta_R{}^{T-20}$$ Recycle of nutrients to water column

$$-\ (S_i * B)$$ Permanent burial of nutrients/ denitrification

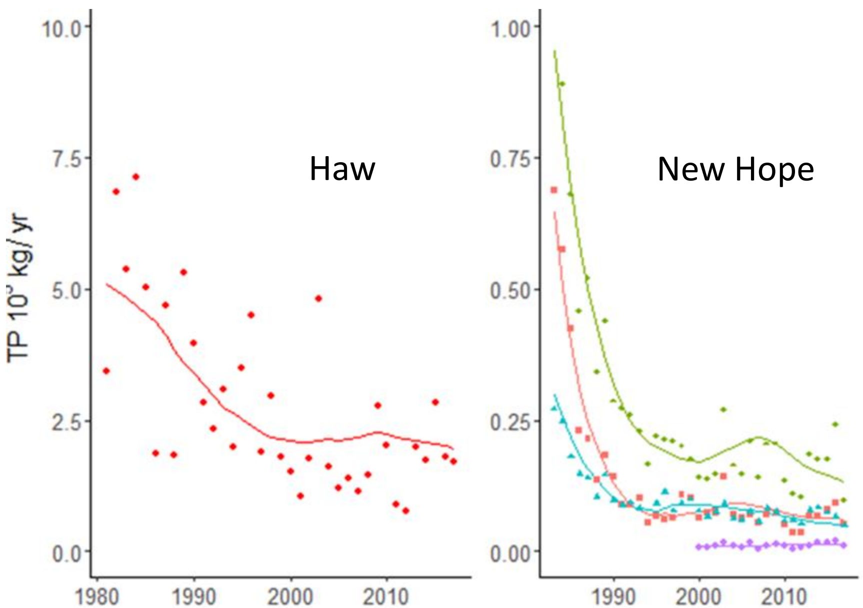
Related Modeling Studies:

Chapra, S. C., & Canale, R. P. (1991). Long-term phenomenological model of phosphorus and oxygen for stratified lakes. *Water research*, *25*(6), 707-715.

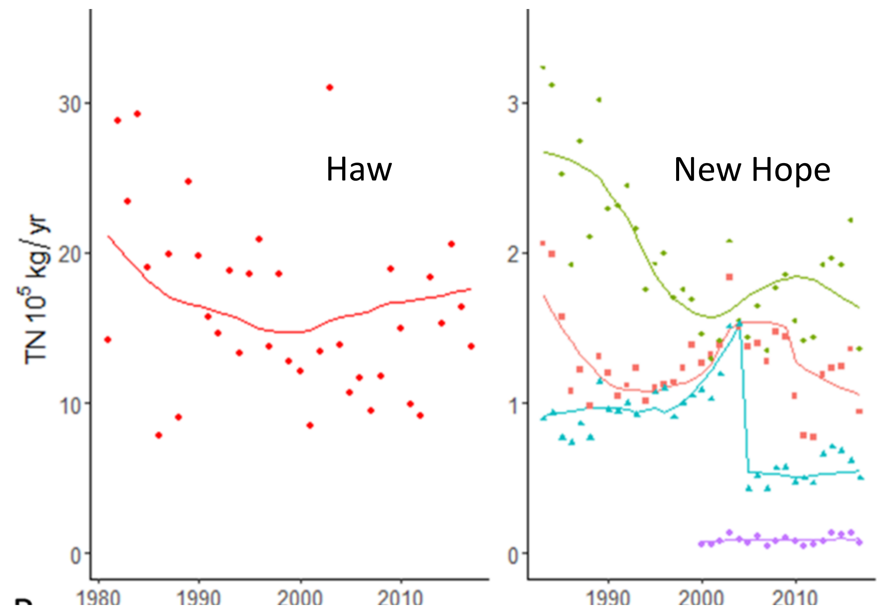
Jensen, J. P., Pedersen, A. R., Jeppesen, E., & Søndergaard, M. (2006). An empirical model describing the seasonal dynamics of phosphorus in 16 shallow eutrophic lakes after external loading reduction. *Limnology and Oceanography*, *51*(1part2), 791-800.

WRTDS load estimates

Total Phosphorus

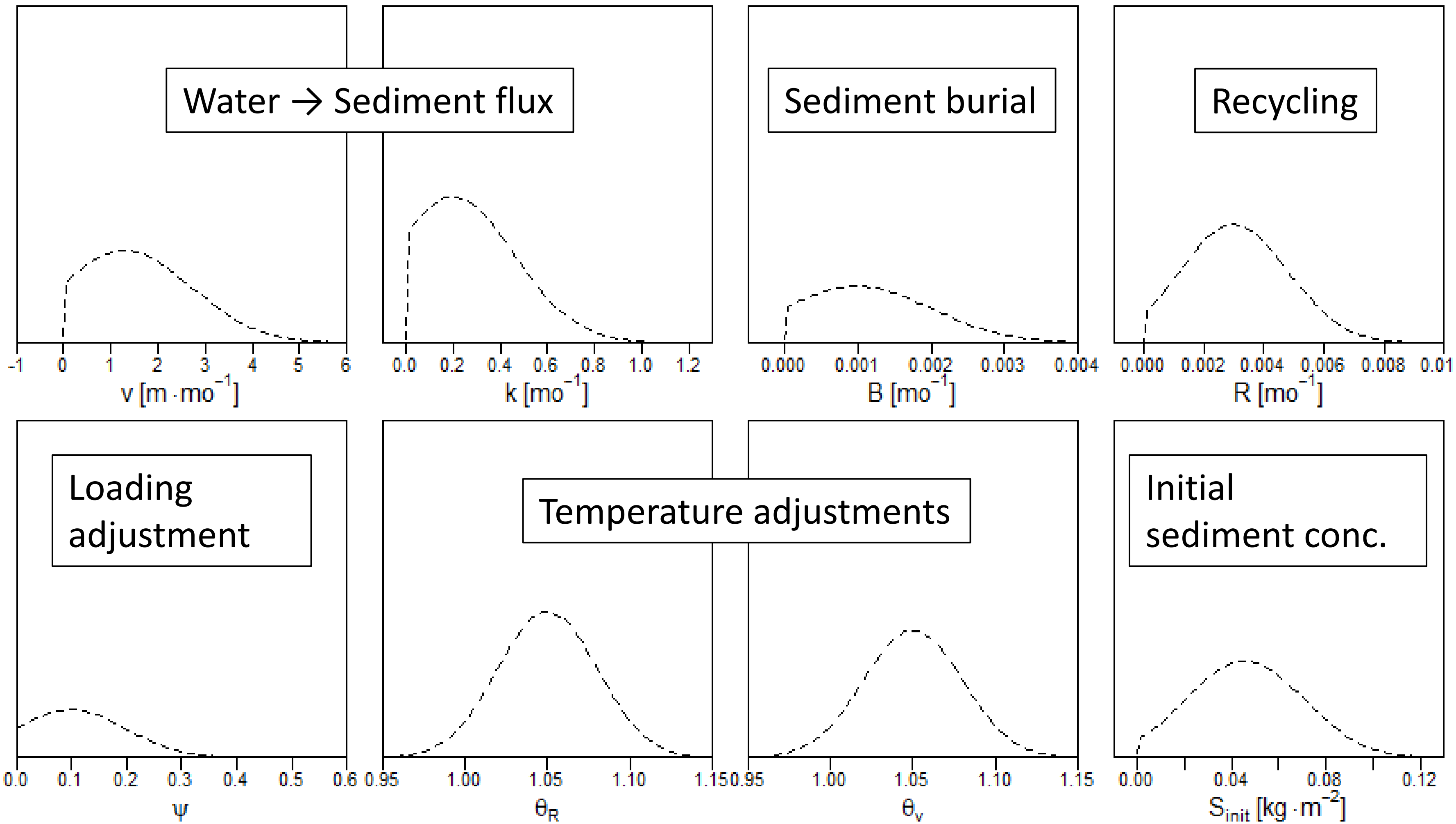


Total Nitrogen

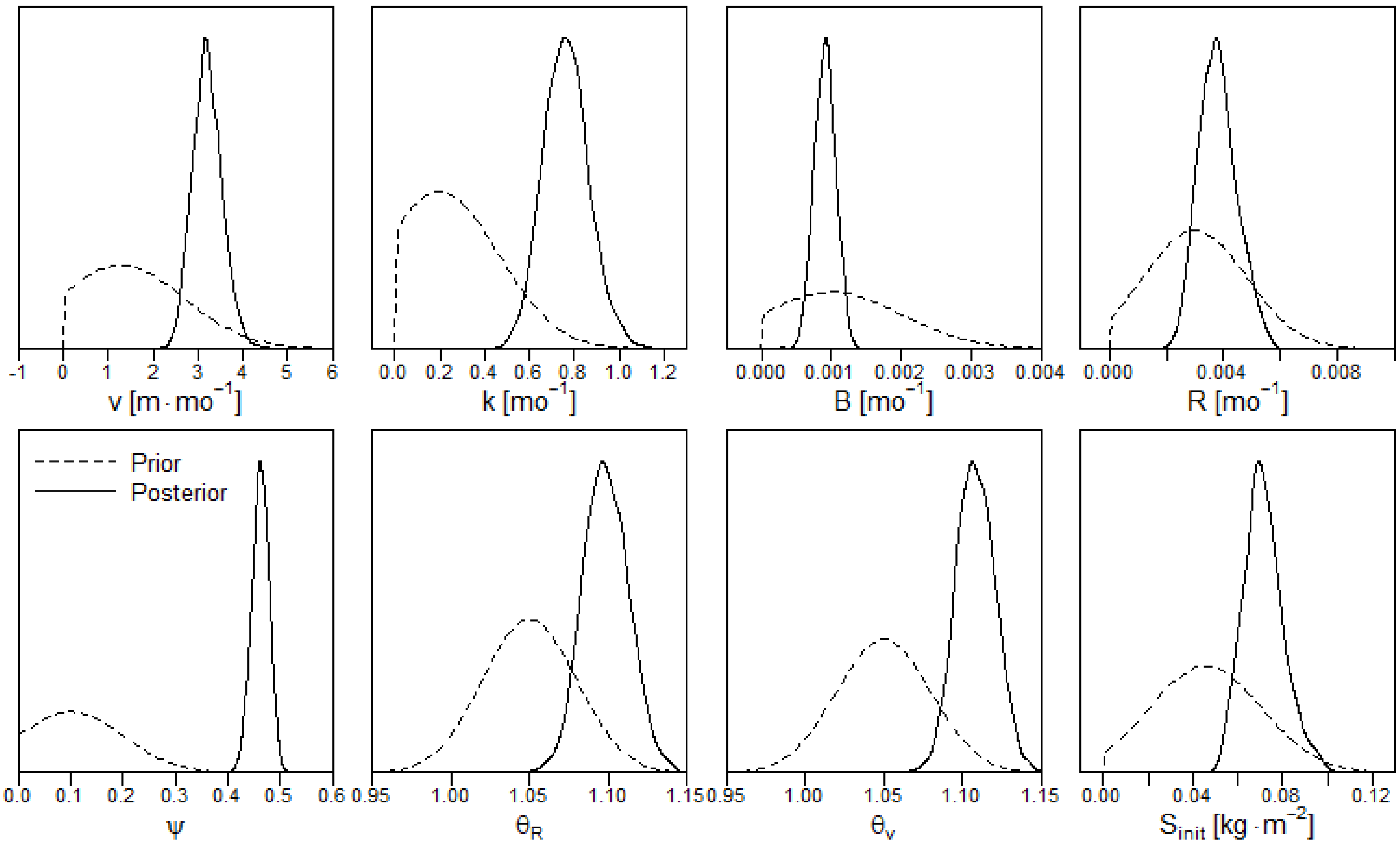


Modeling Results

TP model parameters - Priors

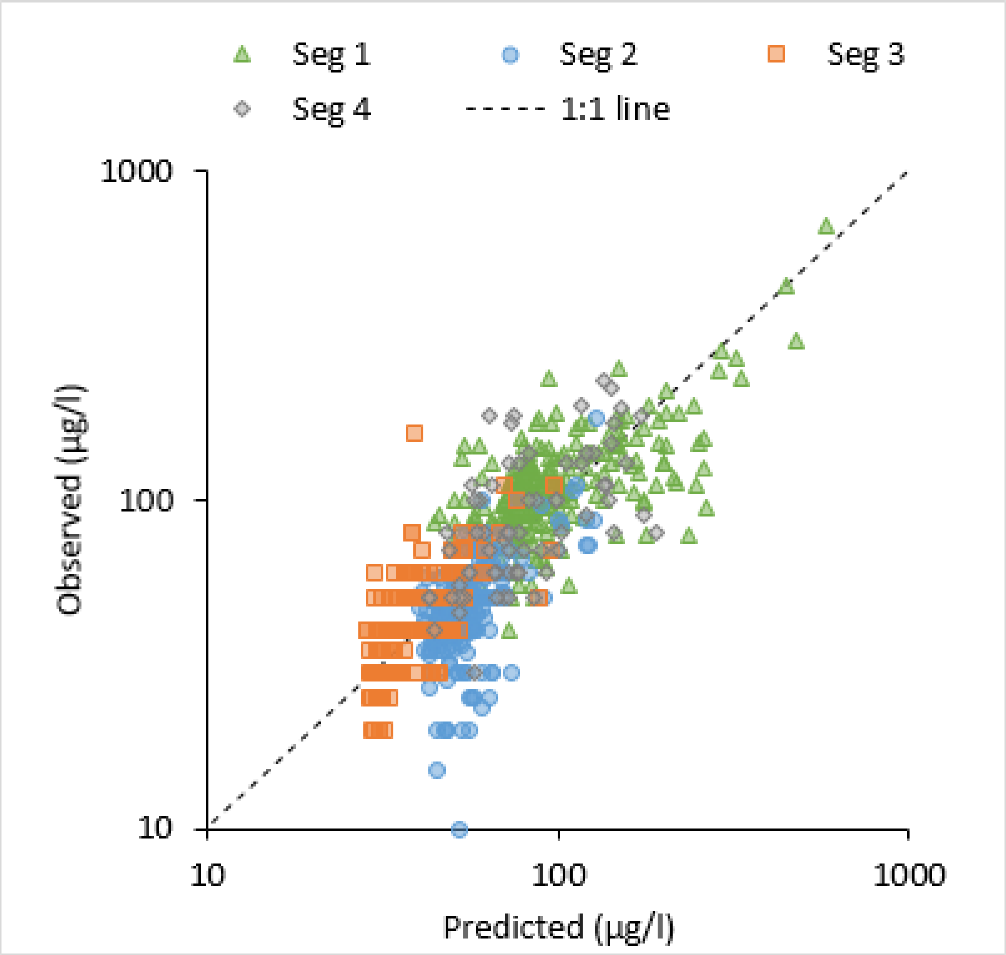


TP model parameters - Posteriors

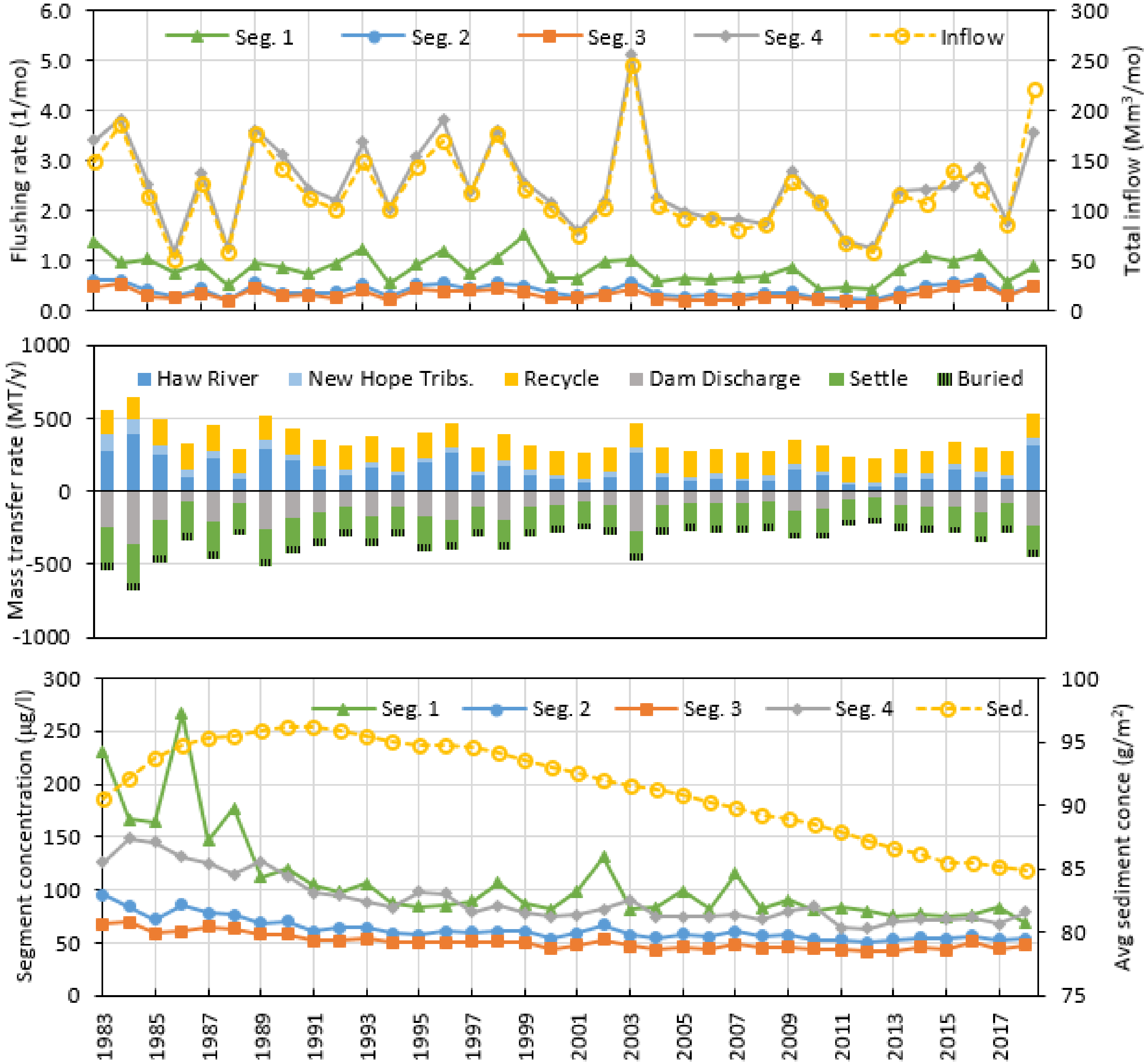


TP model performance

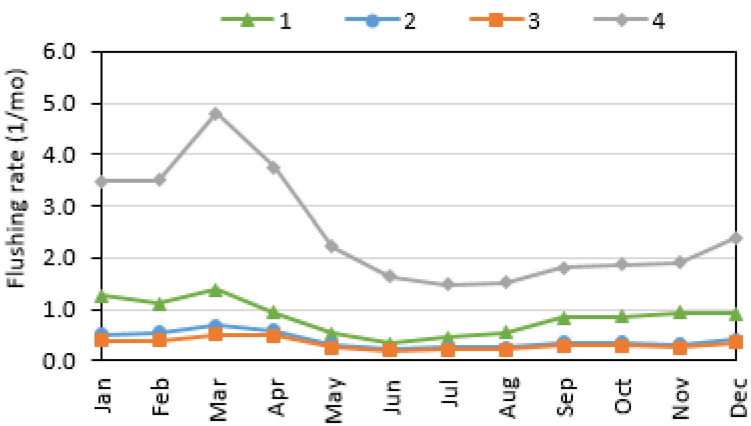
- Surface nutrient concentrations
- Overall R^2=0.58

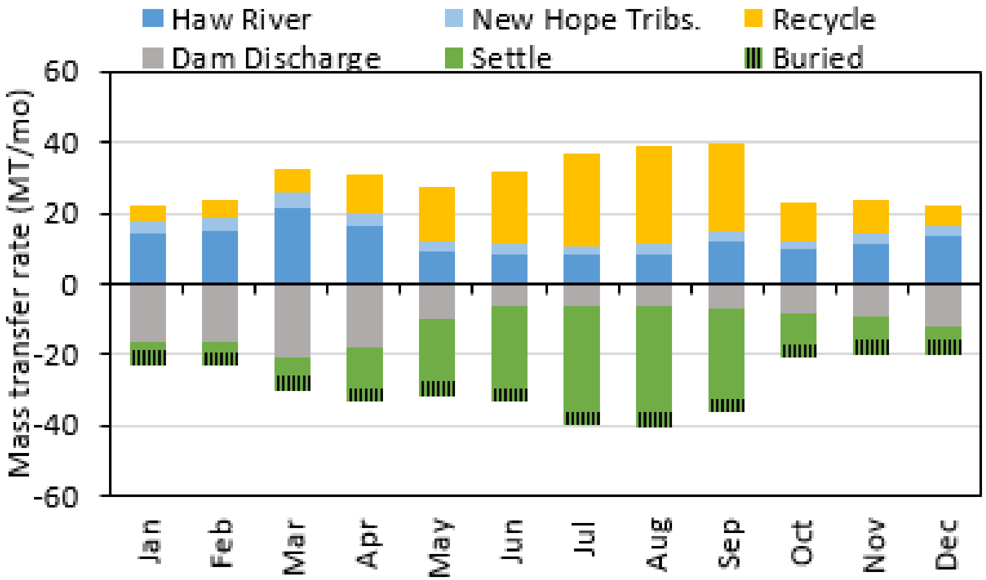


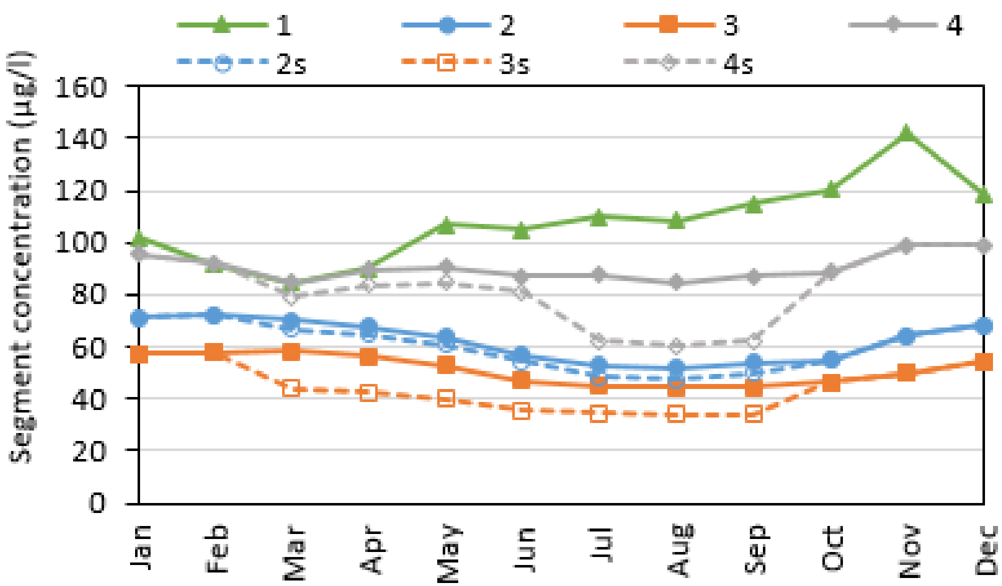
TP Yearly Results



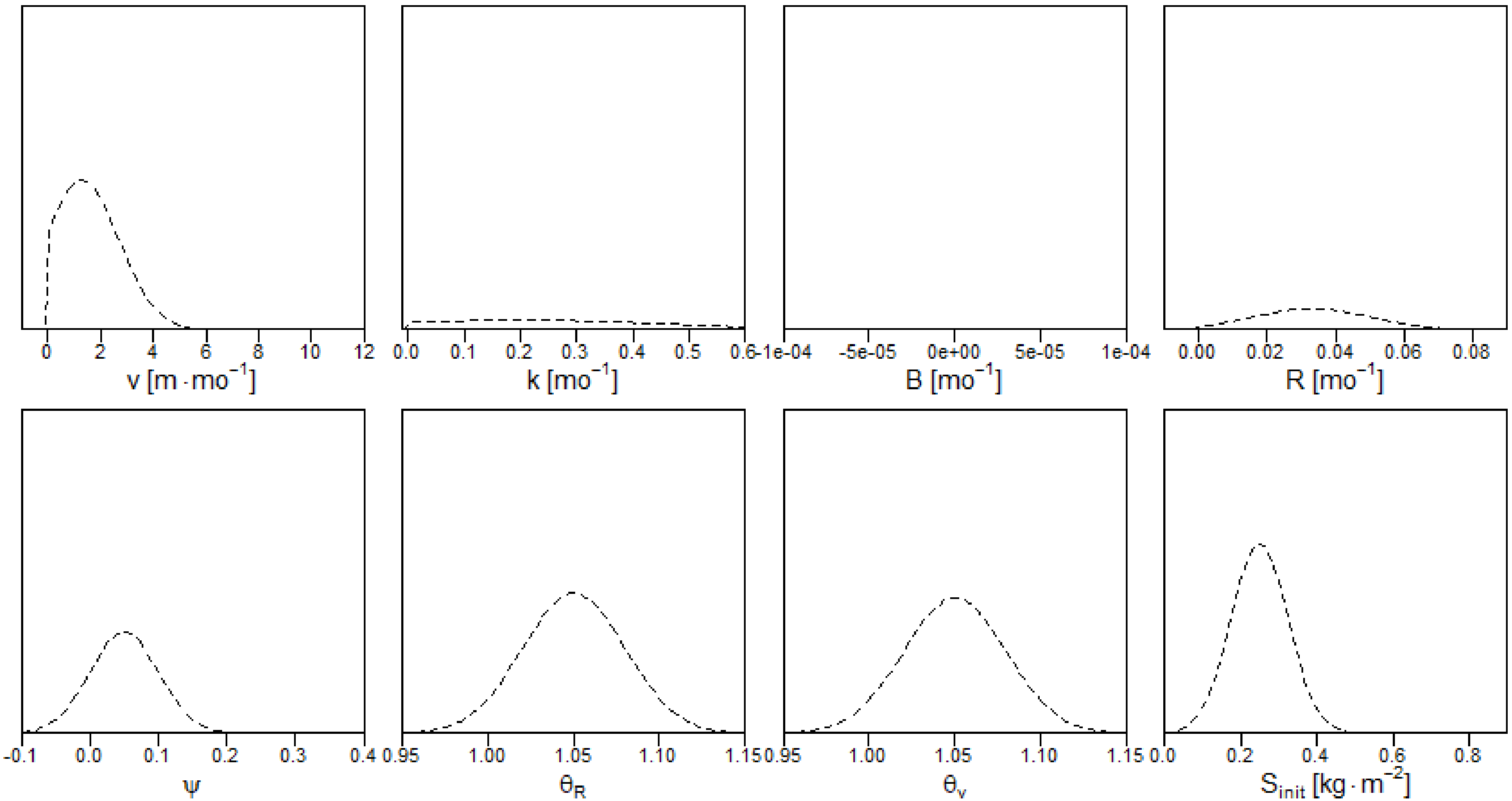
TP Monthly Results



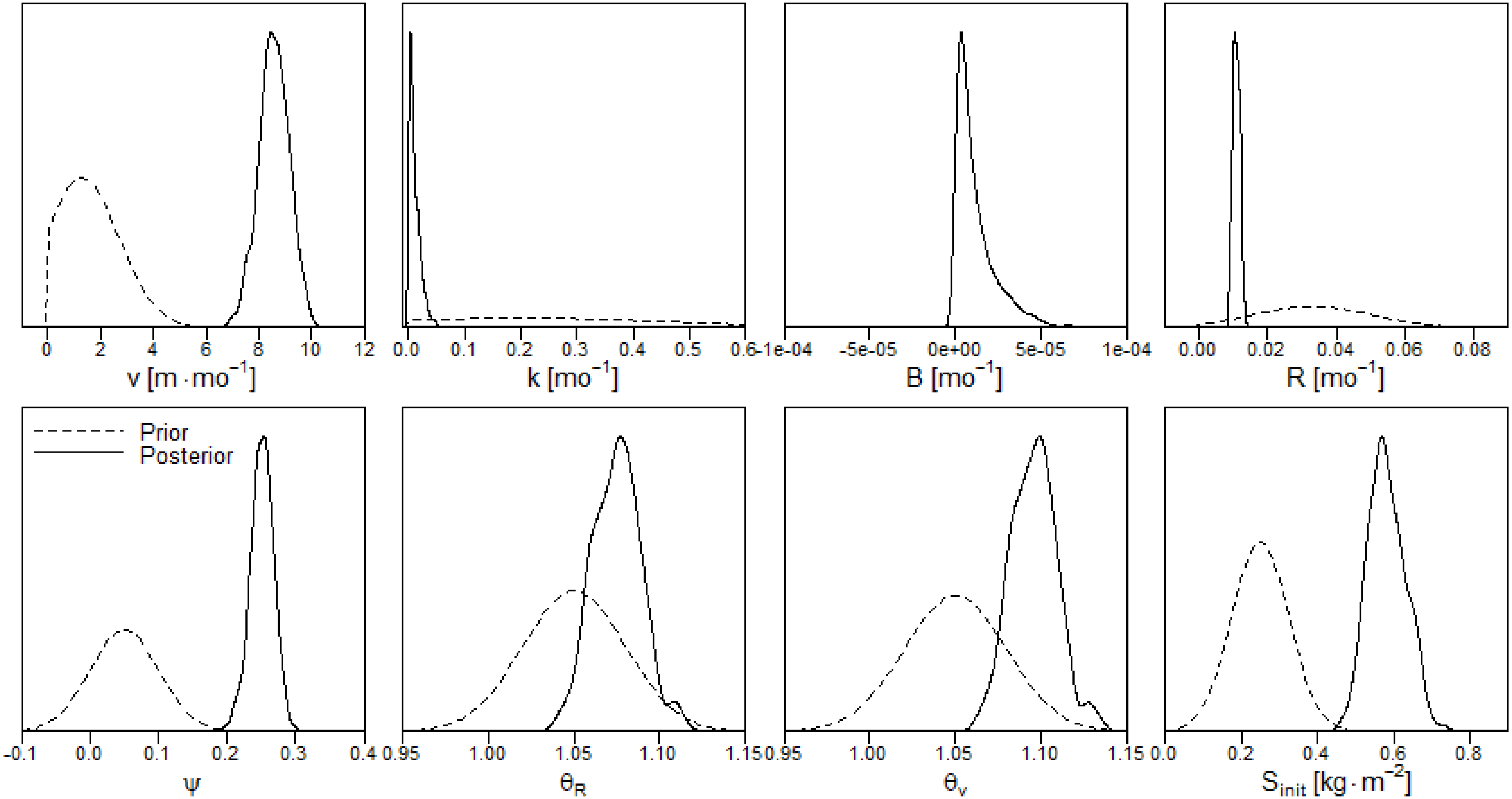




TN model parameters - Priors

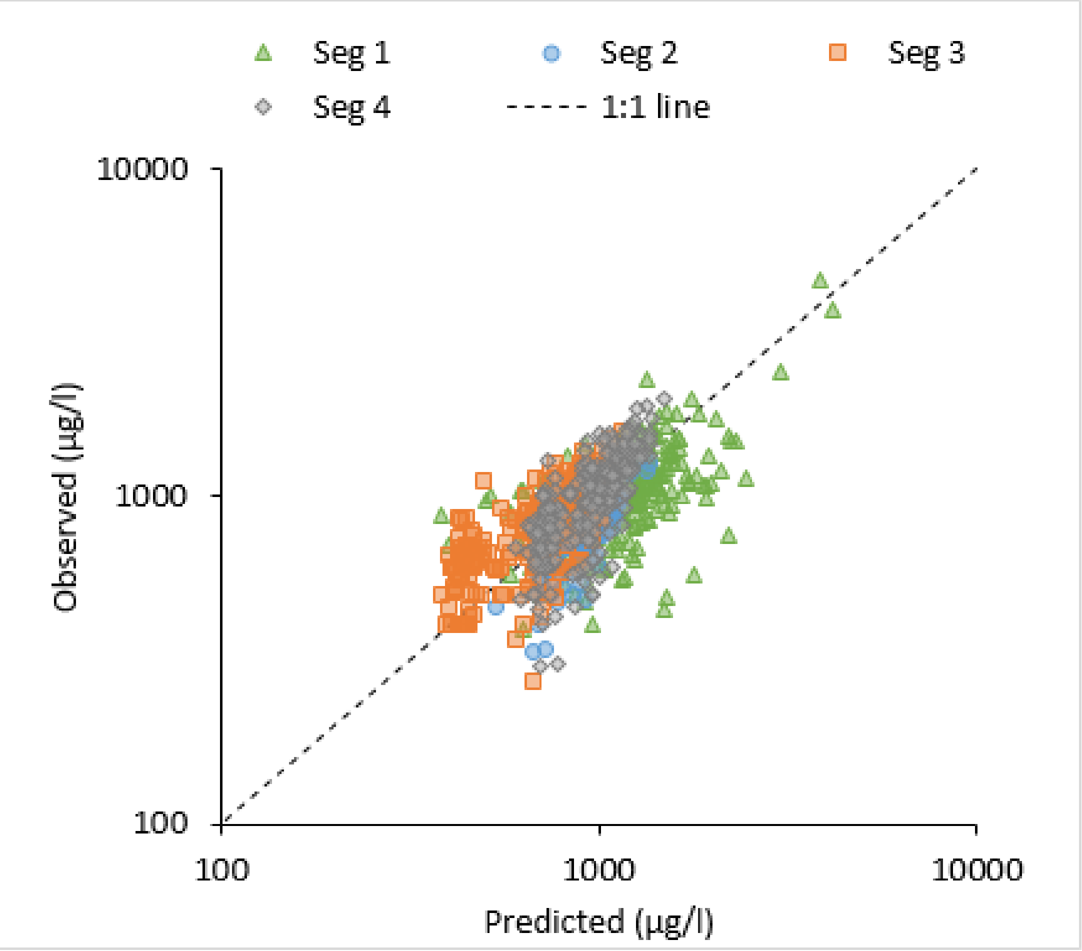


TN model parameters - Posteriors

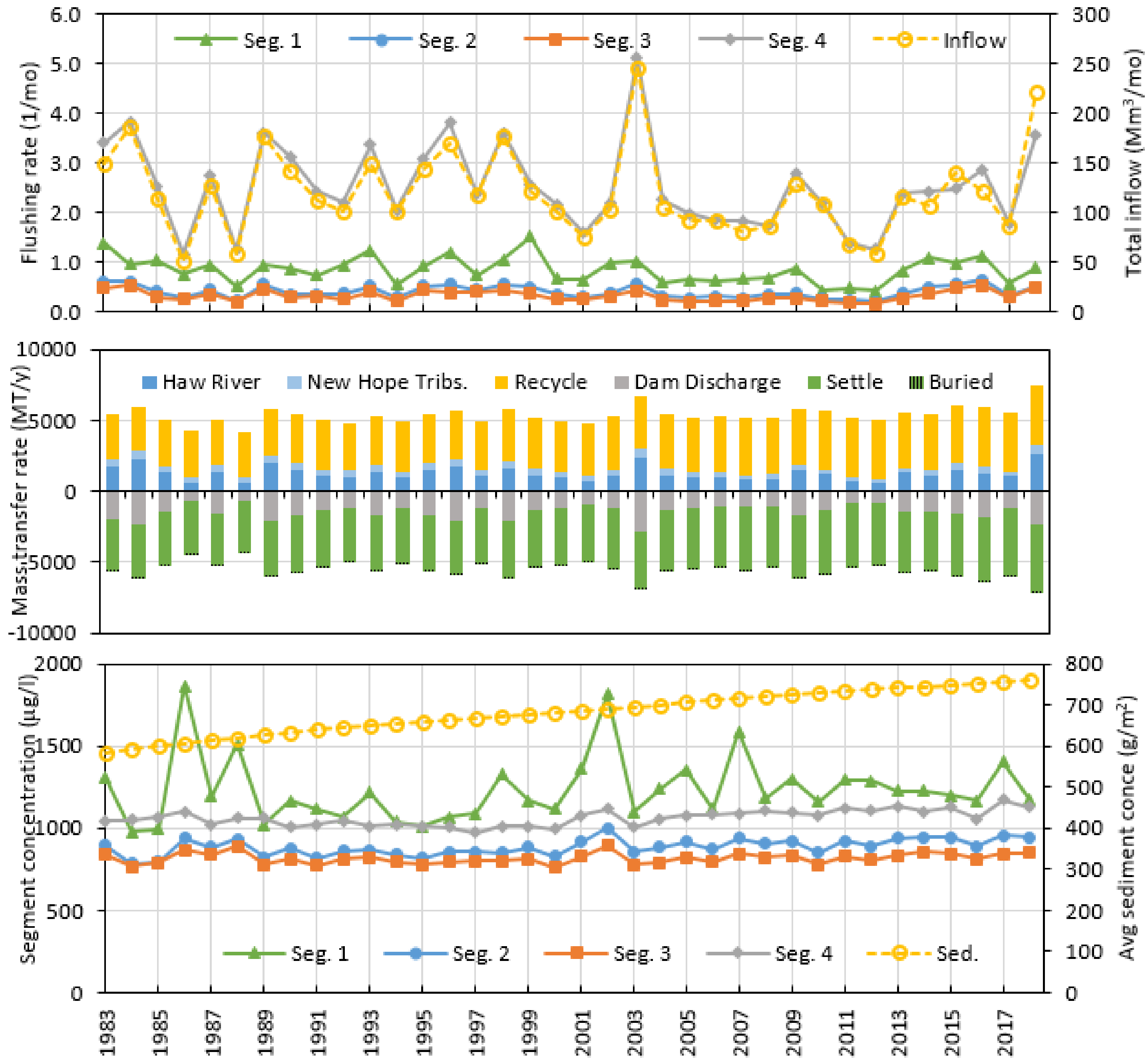


TN model performance

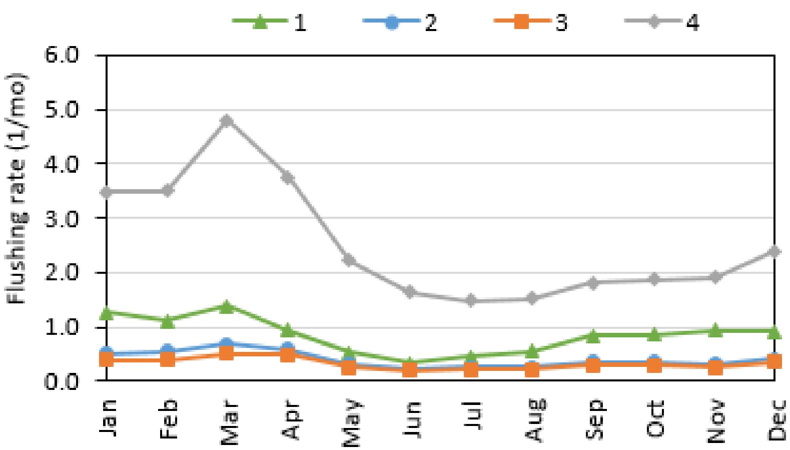
- Surface nutrient concentrations
- Overall R^2=0.41

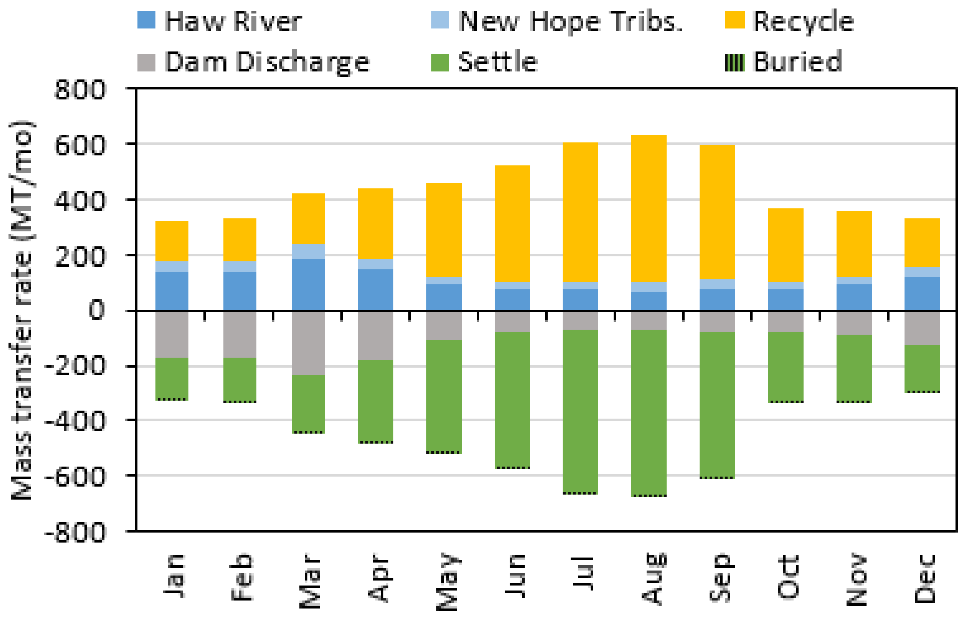


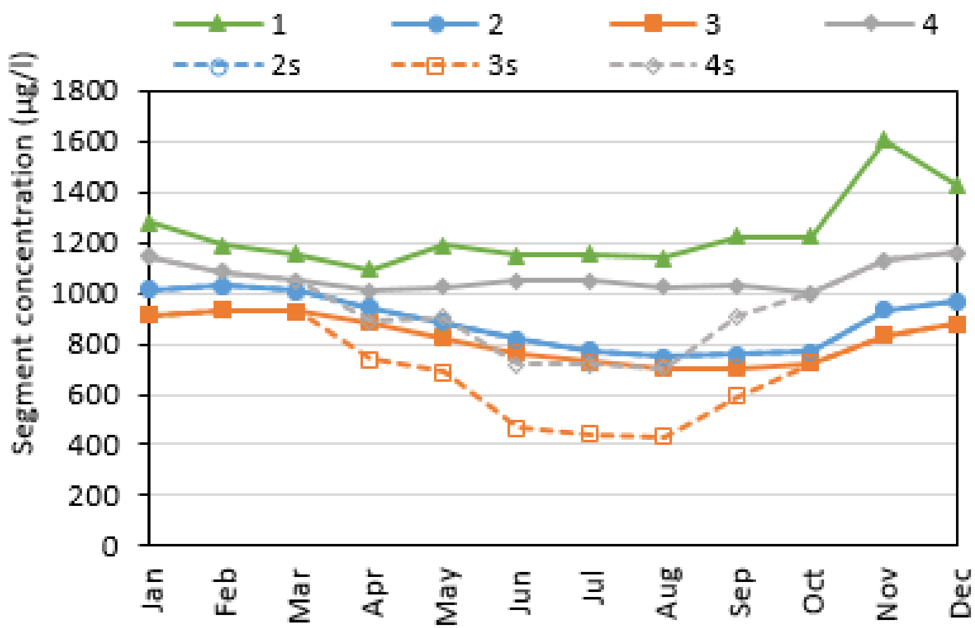
TN Yearly Results



TN Monthly Results







Chlorophyll model formulation

$$\log(chl) = \beta_L \log(M_{NP}) + \beta_F \log(F) + \beta_T \log(T) + \beta_0$$

where

- $M_{NP} = \min(\mathrm{TN}/\beta_{\mathrm{NP}}, \mathrm{TP})$ [μg/l]
- $F =$ flushing rate [1/mo]
- $T =$ water temperature [°C]

A separate model was developed for each reservoir segment and season.

Related Modeling Studies:

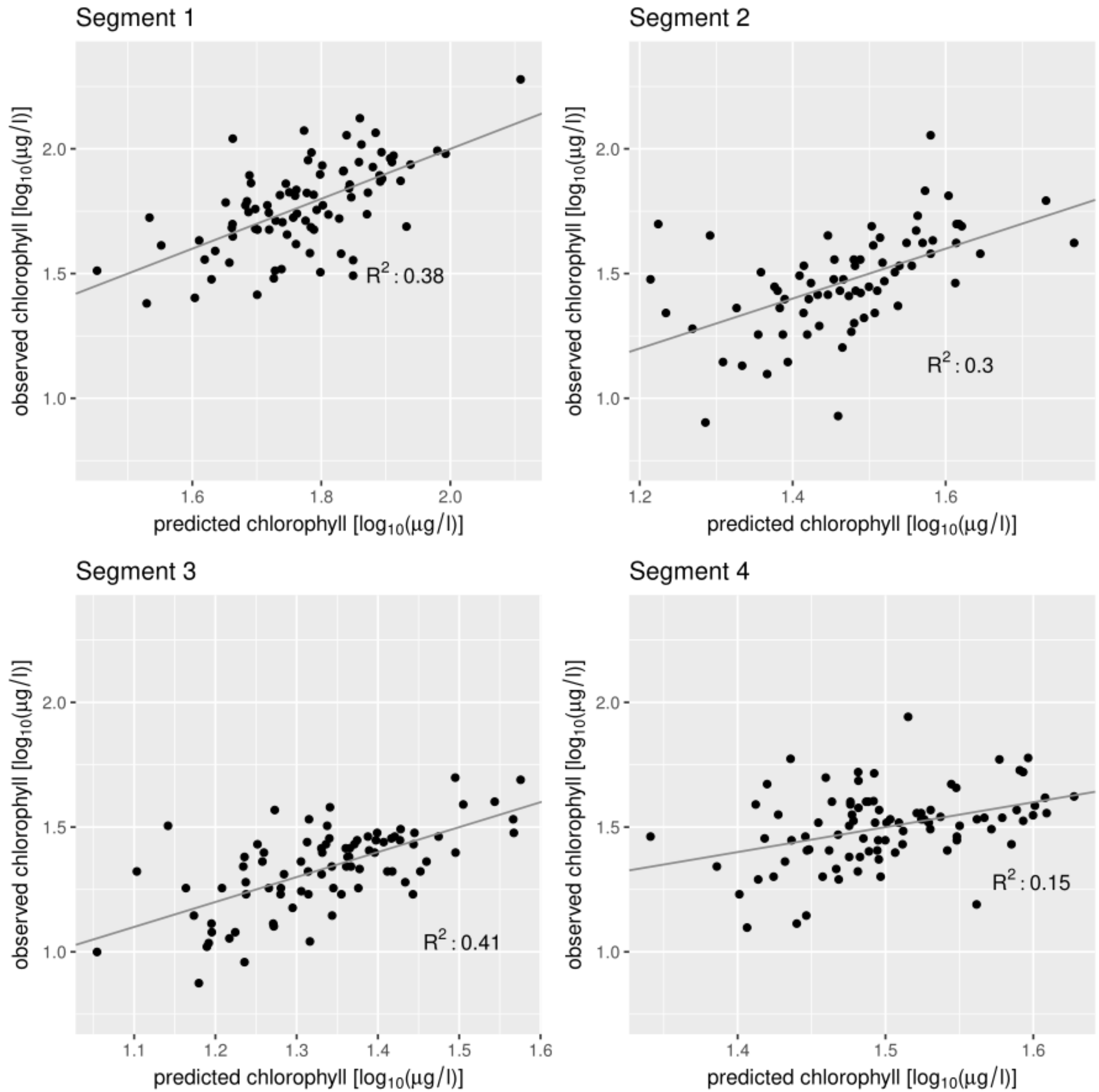
Dolman A.M. & Wiedner C. (2015) Predicting phytoplankton biomass and estimating critical N : P ratios with piecewise models that conform to Liebig's law of the minimum. *Freshwater Biology*, 60, 686–697.

Chl-a model performance

Overall R^2=0.59

Median parameter estimate (summer)

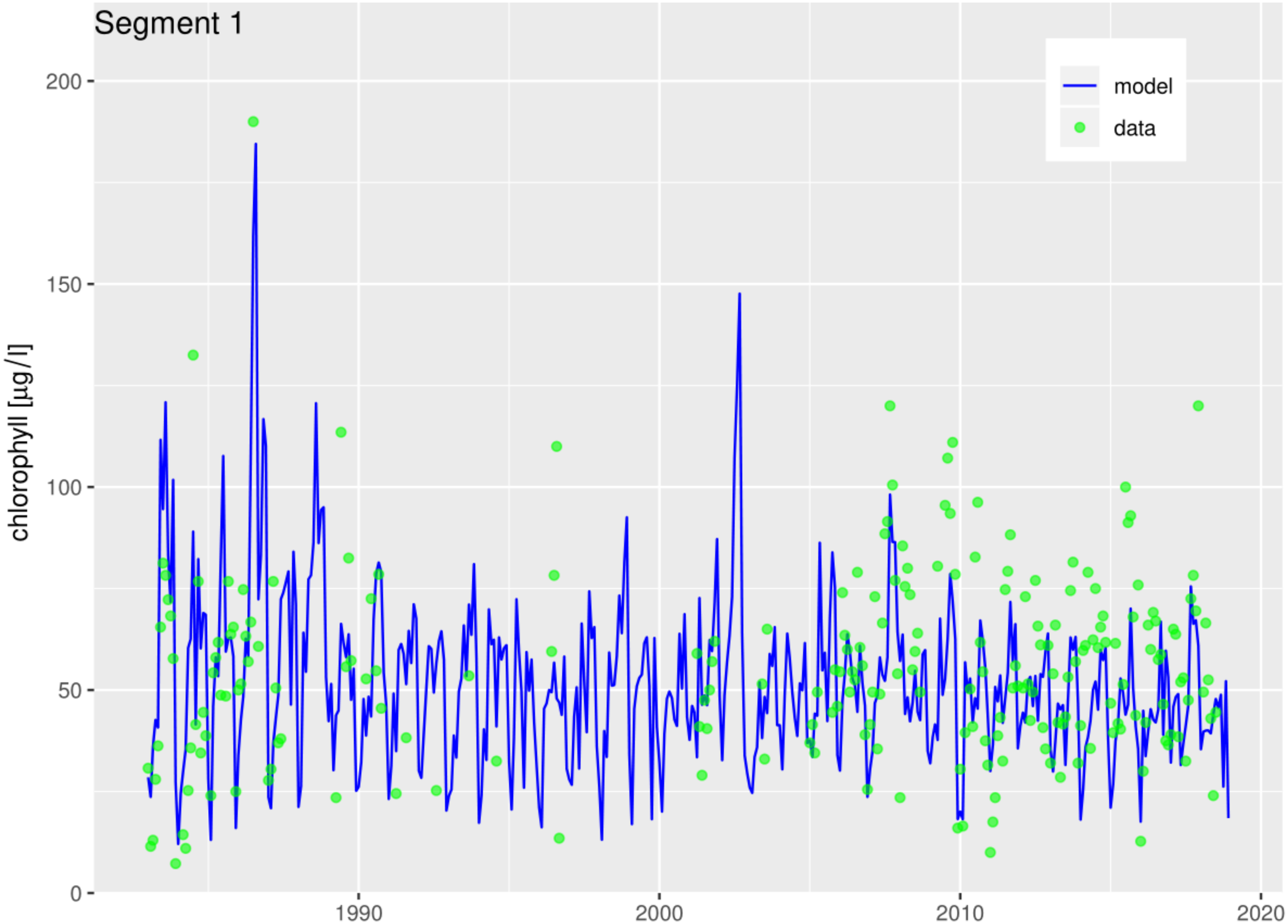
- β_L = 0.9
- β_{NP} = 12
- β_F = -0.02
- β_T = 1.1



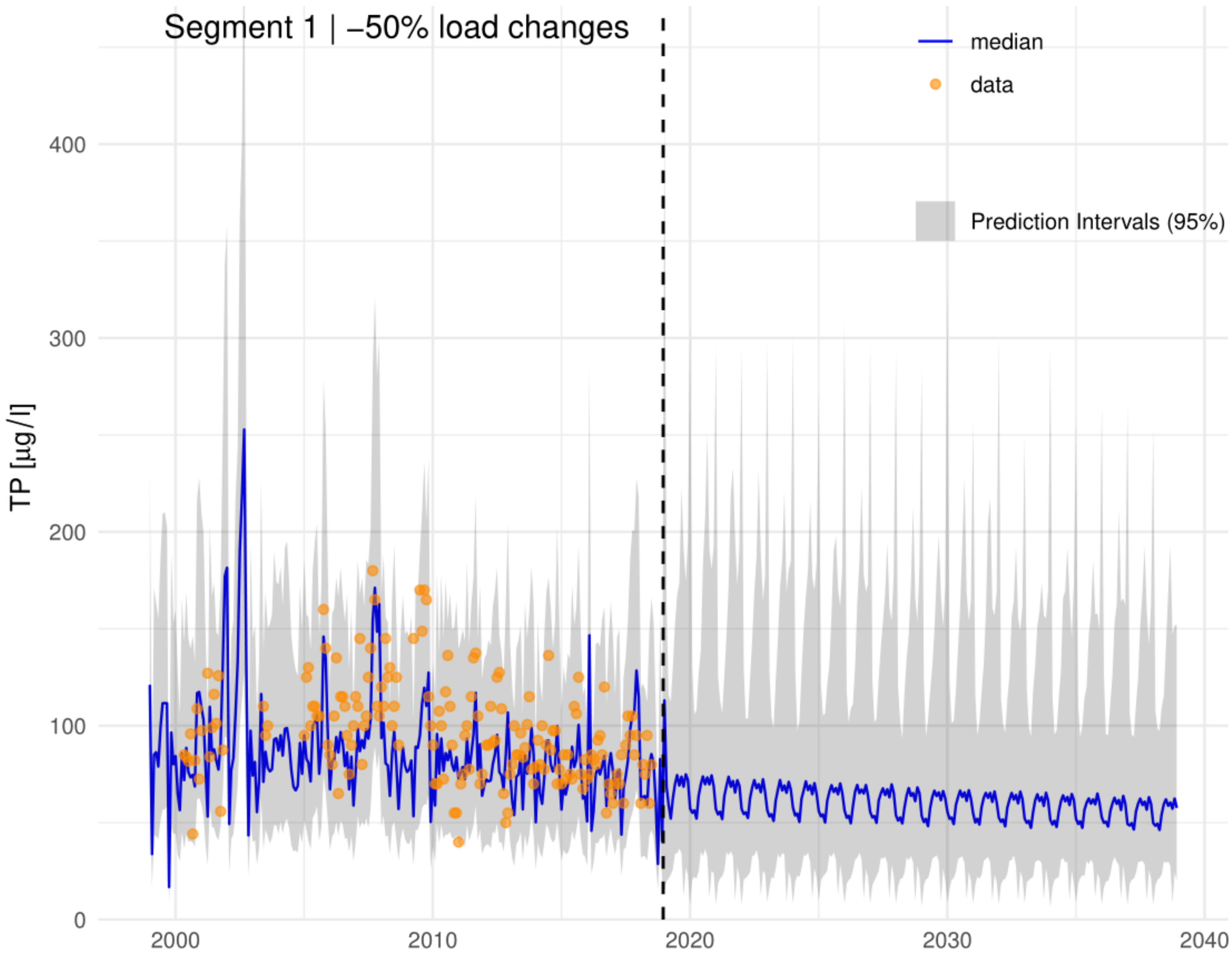
(summer models)

Future Scenarios

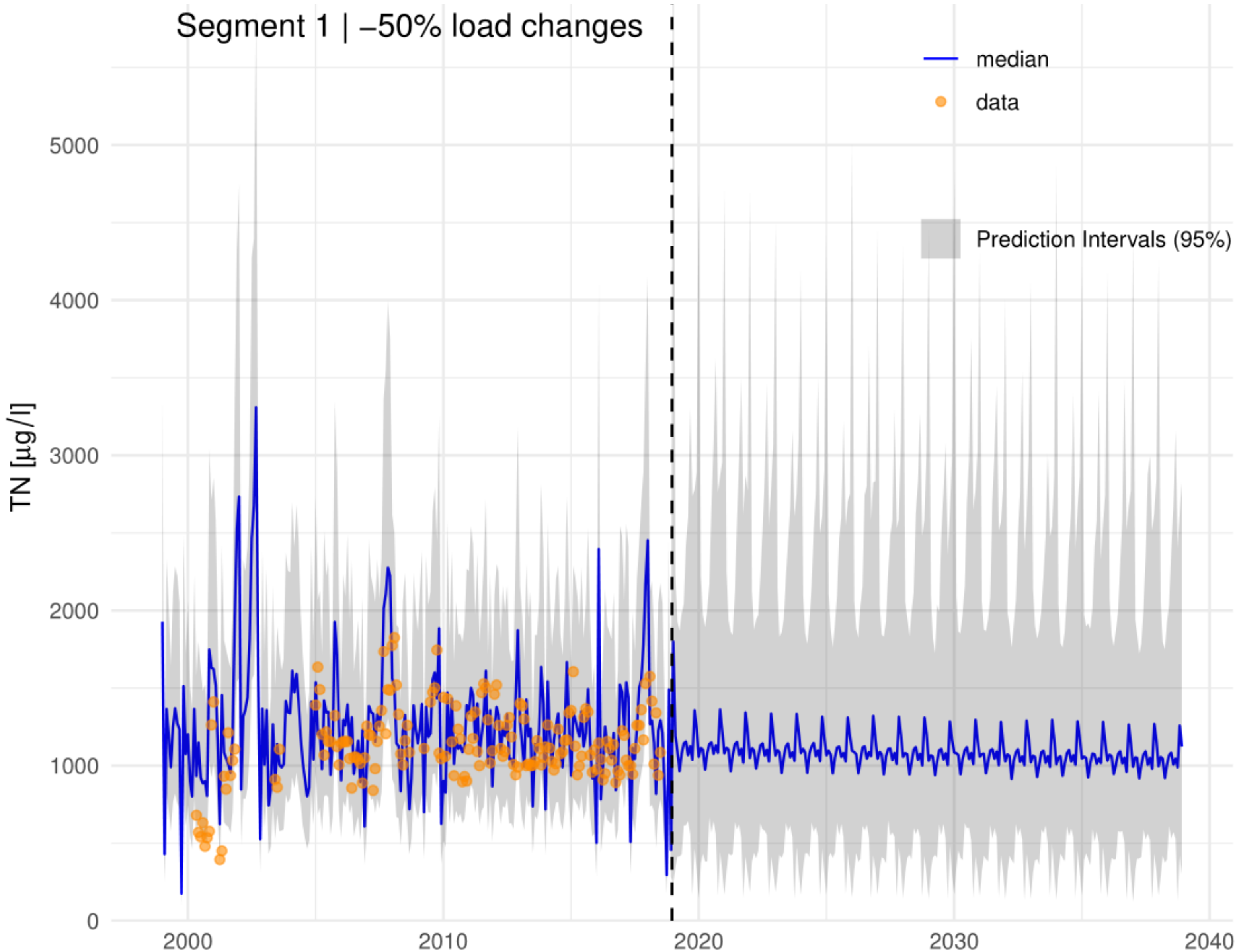
Combining the TN, TP, & Chl a models



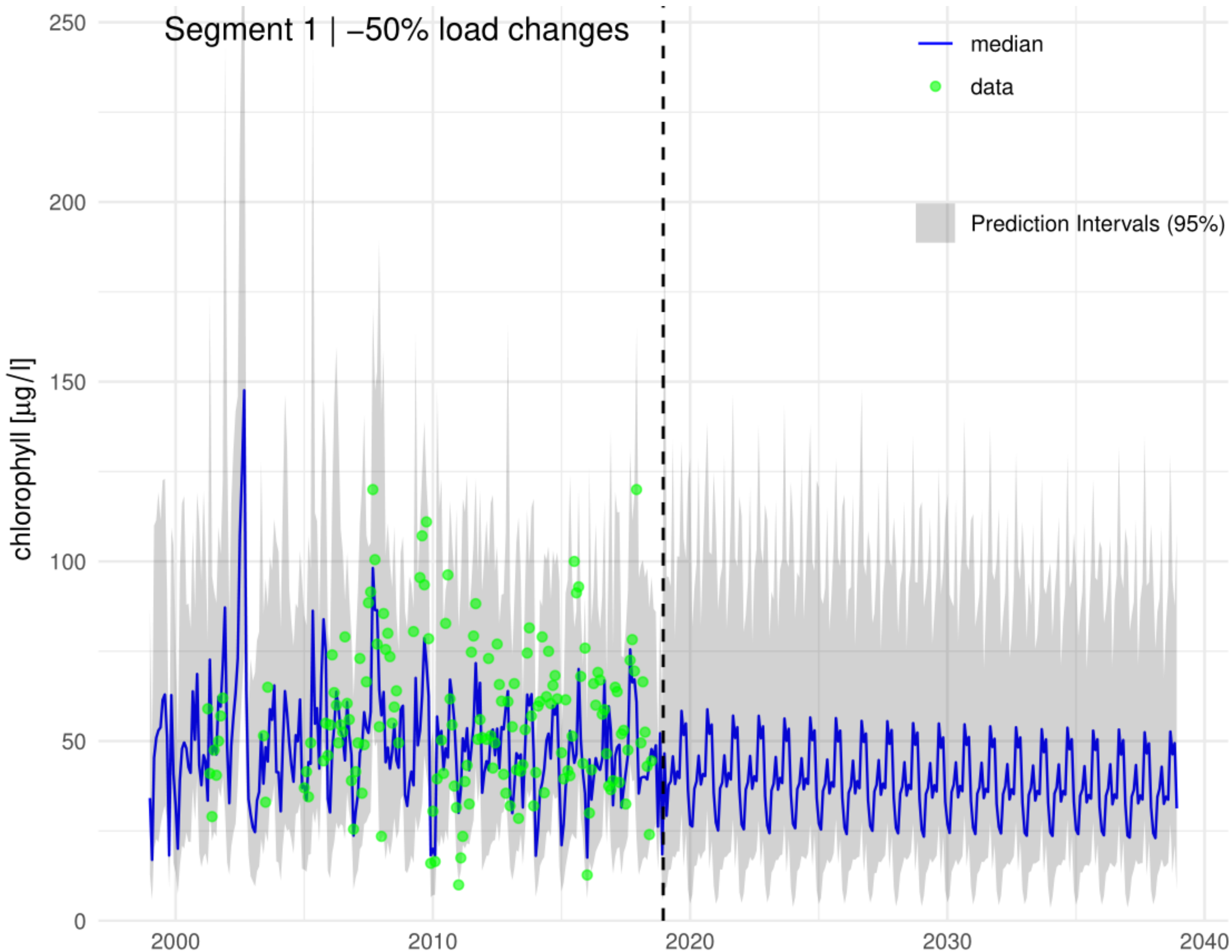
TP response to loading reduction



TN response to loading reduction



Chl a response to loading reduction



Percent change in Seg #1 chl a

Loading adjustment	Historical	2019	2028	2038	2058
-100	0	-18	-33	-42	-55
-75	0	-12	-24	-31	-41
-50	0	-7	-16	-21	-28
-25	0	-2	-8	-11	-16
0	0	4	-1	-2	-5

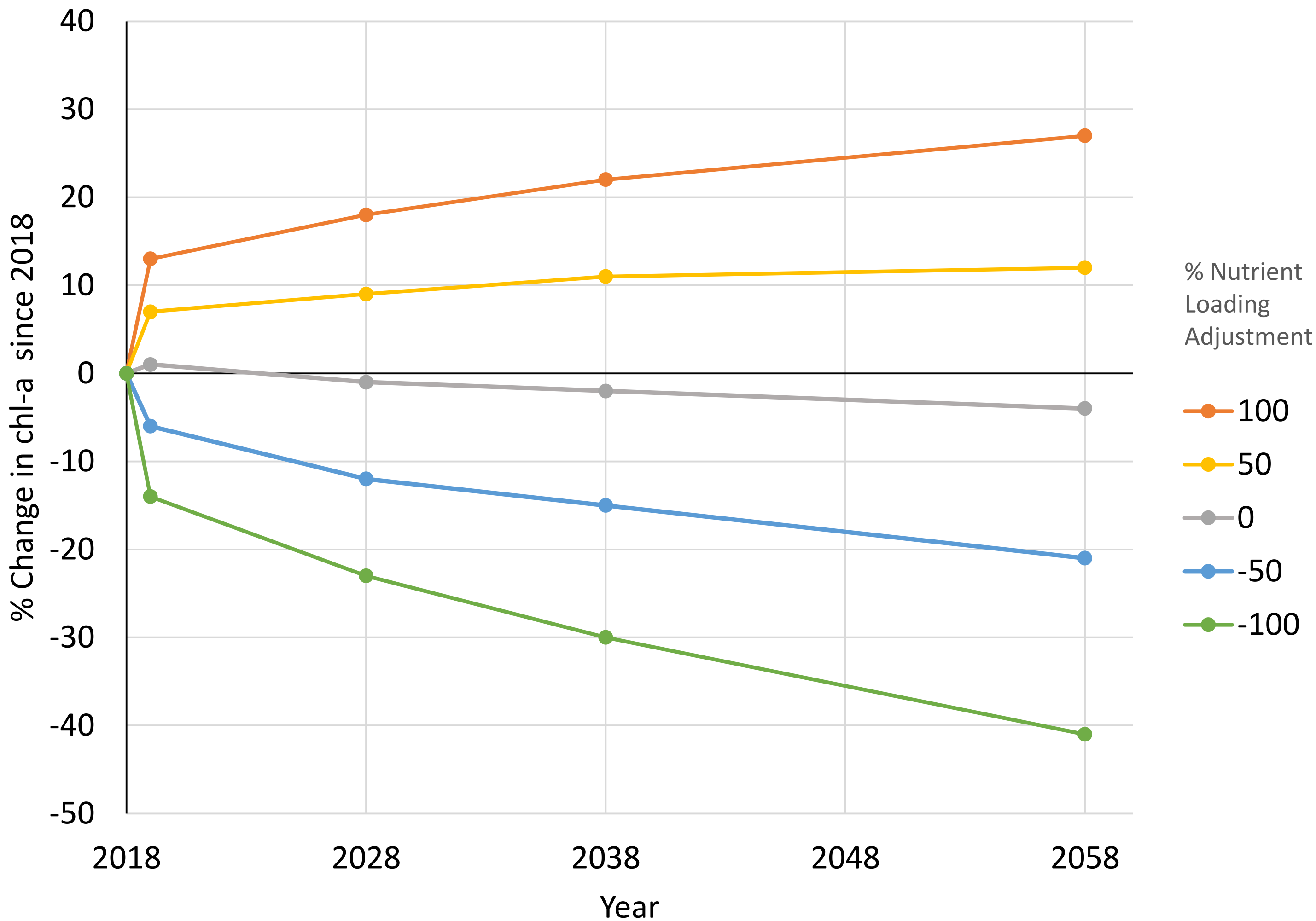
Probability of mean Apr-Oct chl a < 40 ug/L in Seg #1

Loading Adjustment	Historical	2019	2028	2038	2058
-100	0.05	0.47	0.69	0.84	0.98
-75	0.05	0.3	0.49	0.66	0.86
-50	0.05	0.17	0.29	0.40	0.62
-25	0.05	0.09	0.13	0.18	0.28
0	0.05	0.04	0.06	0.09	0.12

Percent change in lake-wide chl a

Loading adjustment	Historical	2019	2028	2038	2058
-100	0	-14	-23	-30	-41
-75	0	-9	-17	-22	-30
-50	0	-6	-12	-15	-21
-25	0	-3	-6	-8	-12
0	0	1	-1	-2	-4
25	0	4	4	4	4
50	0	7	9	11	12
75	0	10	14	16	19
100	0	13	18	22	27
-50NH	0	-5	-10	-13	-19
50NH	0	6	7	8	10
-50HR	0	0	-2	-4	-7
50HR	0	2	1	0	-2

Percent change in lake-wide chl-a



Lake Modeling - Key Takeaways:

- Major multi-year, seasonal, and spatial trends in lake nutrients and chlorophyll are successfully represented by the model.
- It will take decades for the reservoir internal loads (reservoir bottom sediments) to fully respond to external (watershed) loading reductions.
- Both N and P were found to be commonly limiting algal production, suggesting that a dual-nutrient reduction strategy would be beneficial.
- Reducing nutrient loading to the New Hope Arm of the reservoir will produce much greater benefits than reducing Haw River loads.
- Bringing upper Jordan Lake (Seg #1, above Farrington Rd) into compliance with state water quality criteria would require >50% load reductions from New Hope Arm tributaries.
- Future work?
  - Integrate lake-specific sediment flux information into the model.
  - Integrate nitrogen fixation into the model.
  - Assess specific compliance criteria and N & P loading reduction scenarios.

Overall (all 3 models)

- The eutrophic state of Jordan Lake is largely due to internal nutrient loading (from reservoir bottom sediments), reflecting decades of watershed loading.
- Every 10% reduction in nutrient load will produce a 1.5-4.5% chl-a reduction initially, followed by greater improvements over time.
- Urban lands in the New Hope watershed are the greatest P contributor to Jordan Lake eutrophication.
- Point source discharges in the New Hope watershed are the greatest N contributor to Jordan Lake eutrophication.
- The majority of land in the New Hope watershed remains undeveloped. Future urban development has the potential to greatly increase nutrient loading, which will further increase algal levels in Jordan Lake over time.

Thank you for listening!

For more details:

http://nutrients.web.unc.edu/resources/