Nutrient loading and non-stationarity – the importance of differentiating the independent effects of tributary flow and nutrient concentration

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Abstract:

The “phosphorus loading concept”, or more generally the “nutrient loading concept”, arose from Richard Vollenweider’s work in the 1960-70s that showed correlations between phosphorus loads and various eutrophication symptoms. The initial success of target loads developed for the Great Lakes solidified the concept that nutrient loading causes eutrophication, and load targets have become common tools to reduce eutrophication. Using concepts from the field of causality we offer additional context to the nutrient loading concept to show that the correlation between nutrient load and eutrophication is spurious; load and eutrophication have common drivers, tributary flow and tributary nutrient concentration, but load itself is not causal. Consequently, in-lake conditions are not invariant to the same load delivered at differing flow-concentration combinations. We then use a simulation model to evaluate the consequences of delivering the same load at various flow-concentration combinations from the Maumee River into Lake Erie. We show that load reductions under increased tributary flows may cause in-lake phosphorus concentration increases, potentially offsetting the anticipated effect of the load reduction. Thus, particularly under a scenario where climate change may cause systematic flow changes, it will be important to expand the nutrient loading concept to consider the independent effects of tributary flow and nutrient concentrations, to assess the effectiveness of nutrient reduction strategies.

Introduction

Effectively managing eutrophication is a long-standing problem (Hasler 1969). The "phosphorus loading concept" (Vollenweider & Dillon, 1974), or more generally, the "nutrient loading concept" (Brett & Benjamin, 2008) arose in the effort to quantify "critical loading levels" that would provide a rigorous basis for managing phosphorus inputs to reduce eutrophication severity (Vollenweider, 1976). The concept evolved from analyses that demonstrated a relationship among lakes between phosphorus loads and various eutrophication measures (Vollenweider, 1975). This empirical evidence, and the concurrent development of lake input-output models (Chapra, 1977), provided an approach to estimate acceptable, lake-specific phosphorus loads and led to the adoption of phosphorus load targets to curtail eutrophication in the Laurentian Great Lakes, including Lake Erie (International Joint Commission, 1978). The success of the resultant phosphorus load reductions (DePinto et al., 1986; Makarewicz & Bertram, 1991), established a precedent for using load targets to manage water pollution, and the concept that excessive nutrient loads cause eutrophication has become a fundamental paradigm.

Nutrient load targets offer a tangible metric for evaluating eutrophication management progress, and generally, load manipulation is likely to influence eutrophication severity. However, early in the development of the loading concept Edmondson (1970) observed that "doubling the rate of flow would surely have an effect different from that made by doubling the concentration of nutrients in the same volume of influent", while Vollenweider and Dillon (Vollenweider & Dillon, 1974) emphasized that nutrient concentration rather than supply controls lake phytoplankton and macrophyte levels. More recently, Stamm et al. (2014) debated the merits of phosphorus load vs concentration management.

Confusion on the issue of load vs. concentration occurs because load (mass/time) conflates two factors, influent (or tributary) nutrient concentration (mass/volume) and influent (or tributary) flow (volume/time), which have distinct effects on lake nutrient concentration and productivity. While influent nutrient concentration directly influences lake nutrient concentration, influent flow affects nutrient delivery and distribution within a lake. In addition to influencing lake nutrient concentration, influent flow affects water residence time and water clarity, which control phytoplankton growth. Confusion eases with the recognition that influent flow and influent concentration are the common causal factors driving both load and eutrophication, thus load and eutrophication may be correlated but load, itself, is not causal.

Causal Analysis

Concepts from the field of causality (Pearl, 2000; Pearl et al., 2016) are useful to clarify this distinction. A hypothetical, causal relationship among events A, B, and C can be depicted as a series of ellipses and directed arrows in which the ellipses denote events and the arrows denote causal dependencies among the events (Figure 1). Using this depiction, a causal sequence in which event A causes event B, which in turn causes event C (Figure 1a) can be compared with a similar causal relationship in which A causes B, which causes C, but in addition A has a direct effect on C (Figure 1b). In the first causal relationship A's influence on C is indirect, occurring through the intermediary, B, there is no direct influence of A on C. In the second relationship A has both an indirect (via B) and direct effect on C.

In the first relationship (Figure 1a), if B is known, then knowing A in addition to knowing B conveys no new information about the occurrence of C. In probabilistic terms this is referred to as conditional independence, the probability of C given A and B is the same as the probability of C given B or, $p(C|A, B) = p(C|B)$. This situation is known as "directional-separation" (or simply d-separation); B is said to block (or separate) the effect of A on C; everything about the effect of A on C is conveyed via B. In the second relationship (Figure 1b) A and C are not conditionally independent given B, knowing A in addition to B conveys more about the occurrence of C than knowing only B. In many problems the presence or absence of d-separation is key to deducing causal structure.

The prevailing view of the causal relationship between nutrient load and lake nutrient concentration is that influent flow and influent nutrient concentration determine nutrient load and nutrient load then causes eutrophication (Figure 2a). This causal relationship is analogous to that of Figure 1a; load effectively separates influent flow and concentration from lake nutrient concentration; in other words, knowing tributary load and concentration reveals nothing more about lake nutrient concentration than knowing just load. As Edmondson (1970) observed, however, differing combinations of influent flow and concentration will result in the same load, but will cause different lake conditions. Thus, given load, lake nutrient concentration is not conditionally independent of influent flow and concentration; knowing influent flow and concentration reveals more about lake nutrient conditions than knowing only load. Therefore, it is implausible that load is directly causal.

A depiction more consistent with the aforementioned observations of Edmondson (1970) and Vollenweider and Dillon (1974), shows influent flow and influent nutrient concentration causing both nutrient load and lake nutrient concentration (Figure 2b). In this depiction there is no arrow indicating a dependency between load and in-lake concentration, because knowing load conveys no more information than knowing tributary flow and concentration. The absence of a causal path indicates that the correlation between load and lake concentration is spurious (Pearl et al., 2016). The term spurious is sometimes applied dismissively to an observed correlation, implying that the correlation is accidental or deceptive. However, the term was originally used to describe correlations arising from underlying, latent dependencies (Pearson 1897; Pearson et al., 1899), analogous to the relationship in Figure 2b.

Lake Erie Model Simulation

To evaluate possible consequences of experiencing the same nutrient load at differing tributary flow and phosphorus concentration combinations we present a simulation using Lake Erie as an example. In the early 2000s massive algal blooms began to reoccur in Lake Erie's western basin (Michalak et al., 2013) prompting establishment of updated, lower phosphorus targets (Annex 4 Objectives and Targets Task Team 2015). The Maumee River is the primary driver of algal growth in western Lake Erie (Kane et al., 2014; Baker et al., 2014) and has been experiencing recent flow increases that reflect concurrent precipitation increases (Stow et al., 2015), thus it is of interest to evaluate the independent effects of Maumee River flow and concentration on phosphorus concentrations in the lake.

We analyzed the transport of phosphorus entering Lake Erie via the Maumee River using currents from the National Oceanic and Atmospheric Administration (NOAA) Lake Erie Operational Forecast System (Kelley et al., 2018) based on the Finite Volume Community Ocean Model (FVCOM), and a Lagrangian particle tracking model distributed with the FVCOM code package. In the particle model, advection is determined by:

$$\frac{d}{dt}X(t) = V(X(t), t) \qquad (1)$$

where $X(t)$ is the three-dimensional particle position at time t, and $V(X(t), t)$ is the three-dimensional, time-varying velocity field. Hourly currents, $V(X(t), t)$, were obtained from a version of LEOFS in which hourly Maumee River inflows were included based on observations from the U.S. Geological Survey (USGS; http://waterdata.usgs.gov/nwis) at USGS site 04193500 in Waterville, OH. The contribution of advection to the particle position was updated by integrating equation (1) using an explicit fourth-order Runge-Kutta approximation with a time step, Δt=600 s. Vertical mixing due to turbulent eddy diffusivity was simulated using the random-walk method implemented for the General Ocean Turbulence Model (Gräwe, 2011). For the hydrodynamic simulation, hourly surface forcing was prescribed from the Great Lakes Coastal Forecasting System (Schwab & Bedford, 1994), which uses real-time coastal observations to generate a spatially-interpolated meteorological field for over-lake conditions.

We included the two main inputs to western Lake Erie, the Detroit and Maumee Rivers, in the model (Figure 3a). The Detroit River was considered as an open boundary with specified water elevation and temperature, while the Maumee River was specified as a flow boundary with hourly river flux and temperature. Although the Detroit River flow is much greater than that of the Maumee River, phosphorus concentrations in the Detroit River are extremely low and it is not considered to stimulate algal blooms (Michalak et al., 2013), thus it was not manipulated in our numerical experiments.

Passive particles were released hourly from the Maumee River; the number of particles released was proportional to the river discharge. For all experiments we used 118,930 particles; the phosphorus mass of each particle differed with the phosphorus load. The initial phosphorus mass represented by each particle, (C_0), changed with time in proportion to the phosphorus concentration in the river, based on daily Maumee River phosphorus concentration data from the National Center for Water Quality Research (https://ncwqr.org/monitoring/data/). After release particle position with time was determined (equation 1) and, due to net loss, the phosphorus mass of each particle decreased at a rate expressed by:

$$\frac{d}{dt}C(t) = -\frac{wC}{z} \qquad (2)$$

where $C(t)$ is the particle mass at time t, w is the net settling velocity, 8.15×10^{-7} m s^{-1}, previously used by Schwab et al. (2009) for phosphorus loss in Lake Erie, and z is water depth (m).

We examined the effect of experiencing Maumee River phosphorus loads under differing flow-concentration combinations on phosphorus mass and concentrations in western Lake Erie, in a matrix of numerical experiments (Table 1). For a realistic base case (Table 1, D) we used 2008 Maumee River data (Figure 3b), the baseline year for the updated Lake Erie phosphorus load targets. Then we systematically increased and decreased Maumee River flows and concentrations by factors of 1.5 and 0.67, respectively, for a total of seven flow-concentration combinations at three different loads (0.67, 1.0, and 1.5 times the 2008 load). Experiments in the same row had the same Maumee River phosphorus concentration, with flow and load increasing from left to right. Experiments in the same column had the same flow with phosphorus concentration and load decreasing from top to bottom. Experiments along each diagonal had the same load, with differing flow-concentration combinations.

We used bar graphs to show the percent differences in phosphorus mass between experiments in the western basin from February-September and Hovmöller diagrams (1949) to depict phosphorus concentration differences between experiments along three transects (Figure 3a). All three transects originate near the mouth of the Maumee River. Transect 1 approximates the typical trajectory of the Maumee River, particularly during higher flows; transects 2 and 3 capture more general mixing conditions including the influence of the Detroit River.

Same load, differing flow/concentration combinations

Our experimental setup offered five comparisons to evaluate the effect of having the same load at differing flow-concentration combinations: three on the main diagonal (D-A, G-D, and G-A) and one on each off-diagonal (E-B, and F-C). In each case we subtracted the western basin phosphorus conditions that resulted from the phosphorus load at the lower flow, higher concentration from the conditions resulting from same the load at the higher flow, lower concentration.

The load along the main diagonal matched the 2008 load, and in each of these three comparisons, experiments with higher river flows and lower phosphorus concentrations resulted in generally higher phosphorus concentrations and more phosphorus in the western basin (Figure 4), driven by dynamic transport conditions and depth-based deposition rates. A slight decrease in the western basin phosphorus mass in February in the G-D and G-A comparisons (Figure 4, e and i) occurred because, under the relatively high February flow in experiment G (1.5 times the 2008 flow), the resulting currents carried a portion of the Maumee River plume into the central basin, thus phosphorus was not retained in the western basin. The differences in phosphorus mass and concentration were most pronounced in the G-A comparison, even though the Maumee River phosphorus concentration in experiment A was more than twice that of experiment G. A sensitivity analysis, systematically reducing and increasing the net loss (equation 2) by factors of 0.8 and 1.1, respectively, showed similar results.

The off-diagonal results are similar to those of the main diagonal. At 1.5 times the 2008 load phosphorus mass and concentration in the western basin were generally higher in experiment E than B, and at 0.67 times the 2008 load western basin phosphorus mass and concentrations were higher in Experiment F than C. The spatial and temporal extent of higher phosphorus concentrations is more pronounced at the higher flow (Figure 5, b-d) than at the lower flow (Figure 5, f-h), further illustrating the dominant role of flow at this range of conditions.

Differing loads, differing flow/concentration combinations

The comparisons of equal loads at differing flow-concentration combinations demonstrated that loads delivered at higher flows produced higher in-lake phosphorus concentrations. This occurred because higher flows transported phosphorus faster, with less time for loss, thus moving it further into the lake, effectively increasing the phosphorus delivery efficiency. This result suggests that bigger loads could produce lower in-lake concentrations if the bigger loads occur at lower flows, as lower flows decrease the delivery efficiency. Our experimental setup offered two comparisons to evaluate this possibility, experiments A vs. F, and B vs. G (Figure 6); in both cases the bigger loads (A and B) exceeded the smaller loads (F and G) by 50%.

Both comparisons showed the bigger loads resulted in more phosphorus mass in the western basin (Figure 6, a and e), however the phosphorus concentration difference distributions along each transect were variable over time (Figure 6, b-d and f-h). Generally, the bigger loads produced lower concentrations in February and March, higher concentrations in April and May, and relatively similar concentrations from June-September. The lower February-March concentrations occurred when Maumee River flow was relatively high (Figure 4b). During this time the higher flow of the smaller load experiments (F and G) carried more phosphorus further from the mouth of the Maumee River. As flow decreased substantially into April the bigger loads began to produce higher phosphorus concentrations, particularly nearer the mouth of the Maumee River, and as flow decreased from May into the summer months the flow effect was reduced. Thus, although more phosphorus entered the lake with the bigger loads, producing a greater standing mass, concentration patterns were idiosyncratic, reflecting the differential delivery efficiency of the influent flows, and concurrent differences in hydrodynamic mixing patterns.

Discussion

Recent exploration of the nutrient loading concept has generally emphasized a comparison of steady-state, input-output models fit to cross-system lake data, using alternative model forms or subsets of lake data (Brett and Benjamin, 2008; Cheng et al., 2010; Shimoda and Arhonditisis, 2015). To our knowledge, this is the first analysis using a high-resolution simulation model to directly explore the effects of load at differing tributary flow-concentration combinations in a large lake, where input-output model assumptions are not supported. Our goal was not to make specific phosphorus concentration predictions, but rather to explore the more general question of what happens in a receiving waterbody when the two components of phosphorus load, influent concentration and flow, are manipulated independently. Over a range of conditions plausible for the Maumee River, our results showed that equal phosphorus loads delivered at differing flow-concentration combinations resulted in differing phosphorus concentrations, and differing spatial and temporal distribution patterns in Lake Erie's western basin. Generally, higher flows produced higher in-lake concentrations because, over the range of conditions tested, higher flows moved phosphorus further, faster, with less attenuation.

Thus the impact of nutrient load reduction strategies may be reduced or even rendered ineffective as a result of increasing tributary flow. As modeled, this included only the effect of time in phosphorus settling, it did not consider the possible effects of higher turbulence, which may occur with higher flows, in reducing the phosphorus settling velocity (equation 2).

The ability of higher flows to offset lower tributary concentrations is limited; high flows cause source concentrations to attenuate less, not to increase. Clearly, if influent concentrations were sufficiently lowered, phosphorus concentrations in the lake would also decline, even if flow increased. These results may seem almost self-evident, however management plans based on target loads are unlikely to consider this possibility. The updated Lake Erie phosphorus target loads, for example, do not accommodate the effect of changing tributary flow even though Maumee River flow increases are well-documented (Stow et al. 2015).

Nutrient load targets are implicitly premised on the assumption of hydrologic stationarity or, more specifically, that the mean, variance, and autocorrelation of precipitation and influent flow are essentially unchanging. However, Milly et al. (2008) emphasized that, in an era of uncertain climate change, this assumption is increasingly tenuous, making future water management decisions more problematic. Load targets have been a useful management tool because, over the several decade time-period in which they have been used, the stationarity assumption has generally been reasonable. Thus, expanding the nutrient loading concept to consider the independent effects of tributary flow and nutrient concentration over a range of plausible combinations will be an important consideration when setting load targets into the future. Spurious relationships may be useful for prediction as long as the latent structure is relatively constant, but hydrologic non-stationarity invites reconsideration of this important, supporting assumption.

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Table 1

Numerical experiments with different combinations of total phosphorus concentration and flow from the Maumee River.

Phosphorus load relative to 2008 / Experiment		Flow relative to 2008		
		0.67	1.00	1.50
Phosphorus concentration relative to 2008	1.5	1.00 / A	1.50 / B	
	1	0.67 / C	1.00 / D	1.50 / E
	0.67		0.67 / F	1.00 / G

Figure Captions

Figure 1

Panel a

A hypothetical causal structure in which event A causes event B, which causes event C. The ellipses indicate events and the directed arrows indicate causal pathways.

Panel b

A hypothetical causal structure in which event A causes event B, which causes event C. In addition to the indirect effect of A on C via B, A also has a direct effect on C. The ellipses indicate events and the directed arrows indicate causal pathways.

Figure 2

Panel a

Causal structure depicting nutrient load as the direct cause of lake nutrient concentration, with influent flow and influent nutrient concentration as the causes of nutrient load. The dashed arrow between influent flow and influent nutrient concentration indicates that concentration may be dependent on flow. For simplicity eutrophication is represented as lake nutrient concentration; a more complex diagram could also show influent flow influencing factors including water residence time and water clarity, which, in turn, influence phytoplankton and macrophyte levels.

Panel b

Causal structure depicting influent flow and influent nutrient concentration as the direct causes of both lake nutrient concentration and influent nutrient load. The dashed arrow between influent flow and influent nutrient concentration indicates that concentration may be dependent on flow. For simplicity eutrophication is represented as lake nutrient concentration; a more complex diagram could also show influent flow influencing factors including water residence time and water clarity, which, in turn, influence phytoplankton and macrophyte levels.

Figure 3

Panel a

Depth (meters) of Lake Erie's western basin showing the three transects along which model results are displayed.

Panel b

2008 flow and total phosphorus load from the Maumee River.

Figure 4

Differences in phosphorus mass and concentration at the same load with differing concentration-flow relationships. Each set of four panels depicts a comparison of experiments along the main diagonal of experiment matrix (Table 1). Panels a-d show experiment D-experiment A, panels e-h show experiment G–experiment D, panels i-l show experiment G- experiment A.

Figure 5

Differences in phosphorus mass and concentration at the same load with differing concentration-flow relationships. Top four panels depict a comparison of experiments along the upper off-diagonal of experiment matrix, bottom four panels depict a comparison of experiments along the lower off-diagonal (Table 1). Panels a-d show experiment E-experiment B, panels e-h show experiment F–experiment C.

Figure 6

Differences in phosphorus mass and concentration at the differing loads with differing concentration-flow relationships. Both sets of four panels depict a bigger load at lower flow, higher concentration – a smaller load at higher flow, lower concentration. Panels a-d show experiment A – experiment F, panels e-h show experiment B- experiment G.

Figure 1a

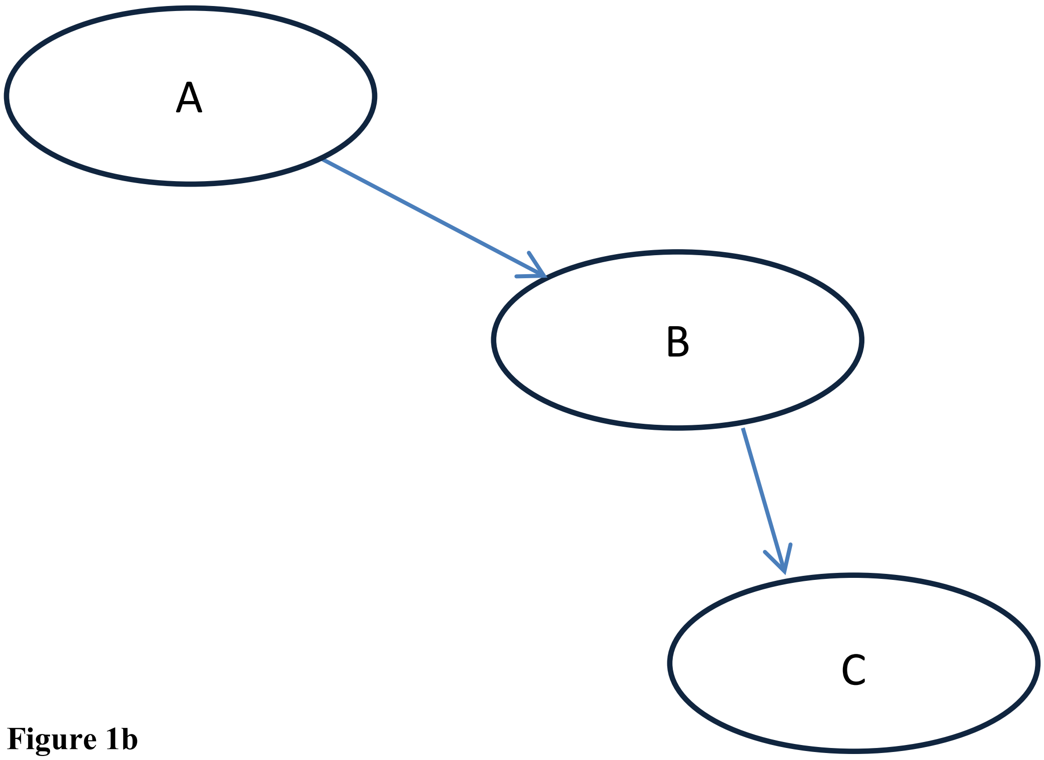


Figure 1b

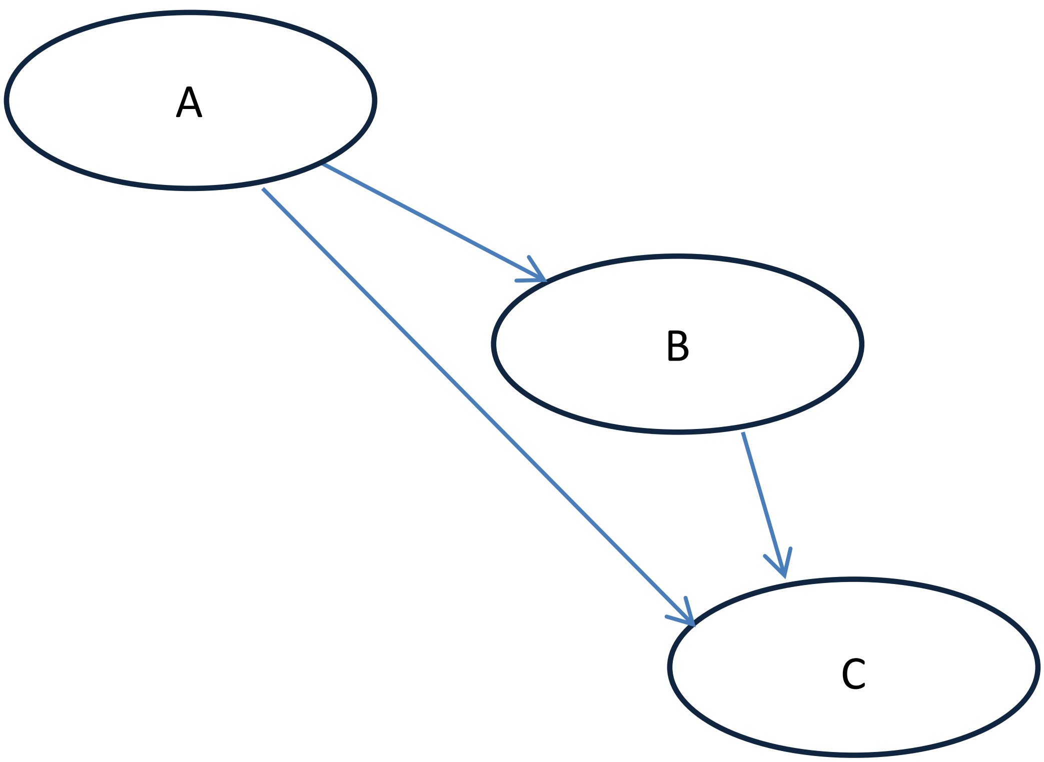


Figure 2a

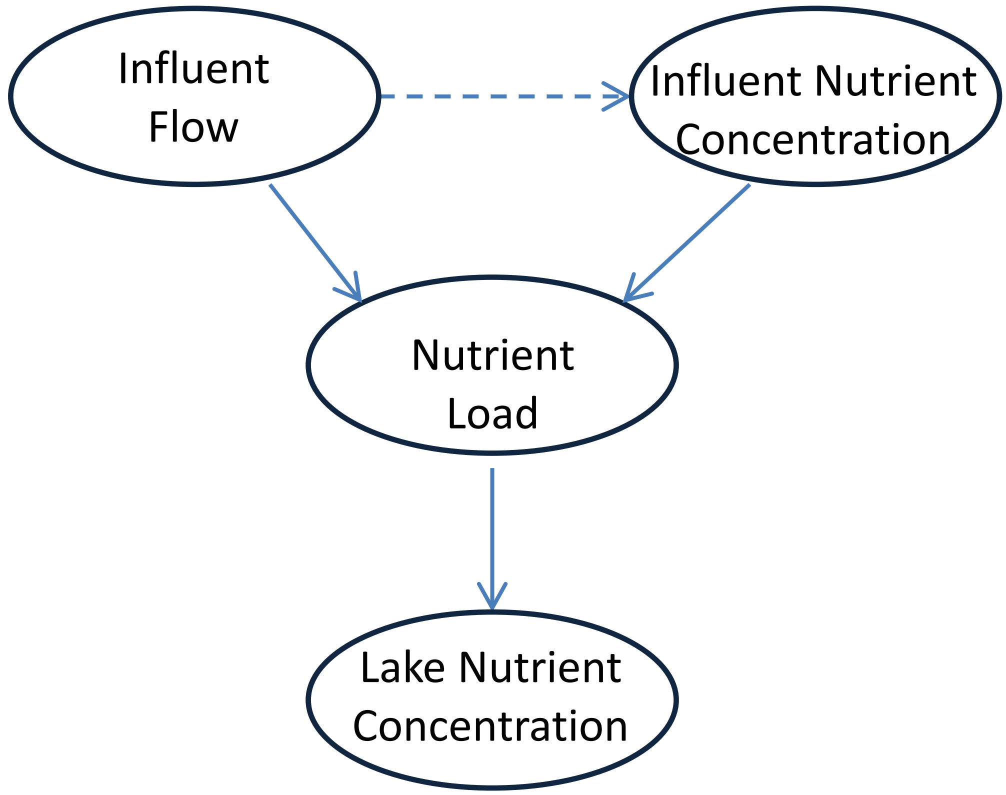


Figure 2b

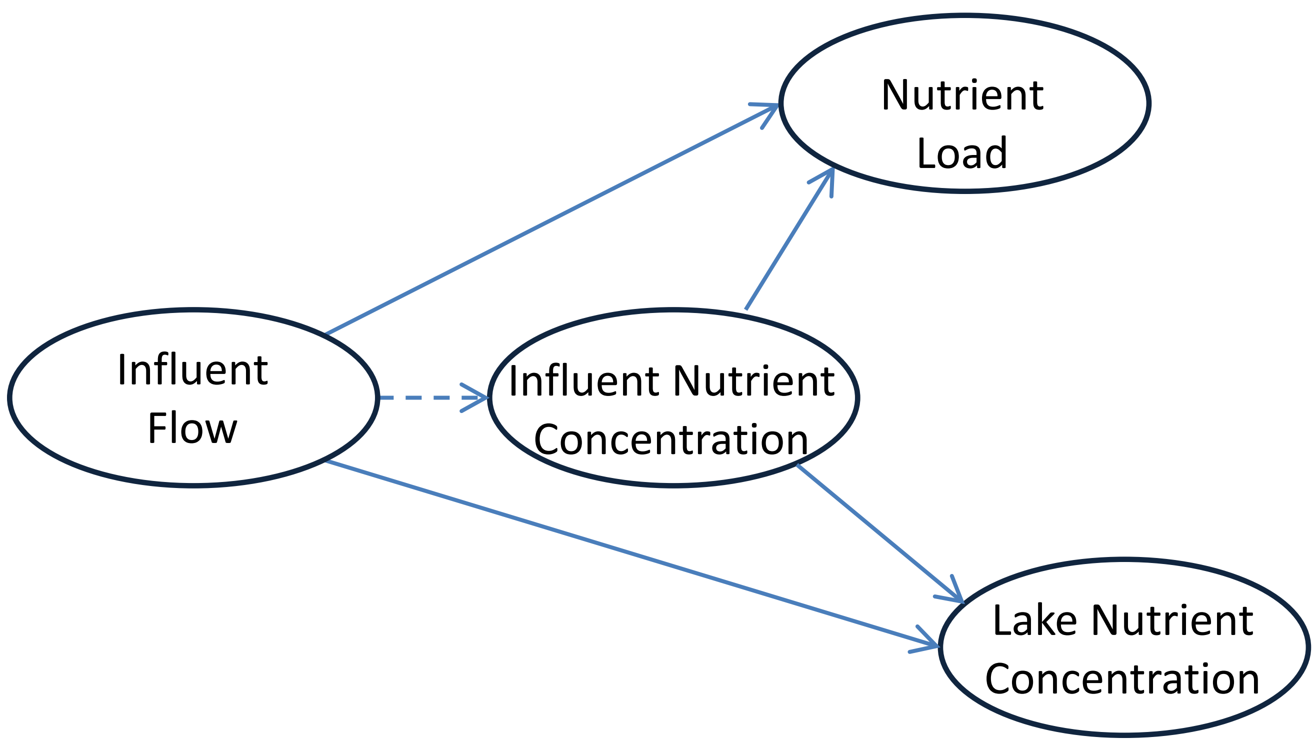
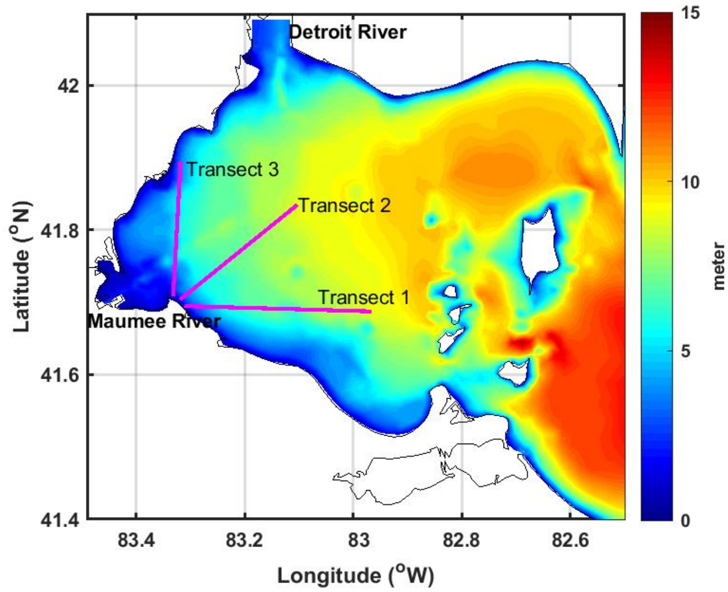


Figure 3

Panel a



Panel b

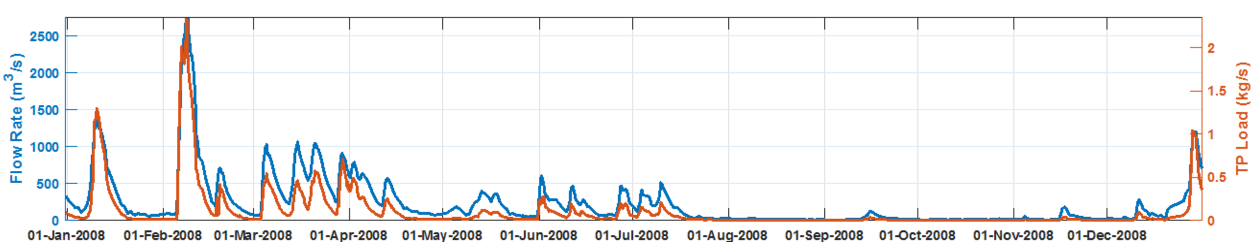


Figure 4

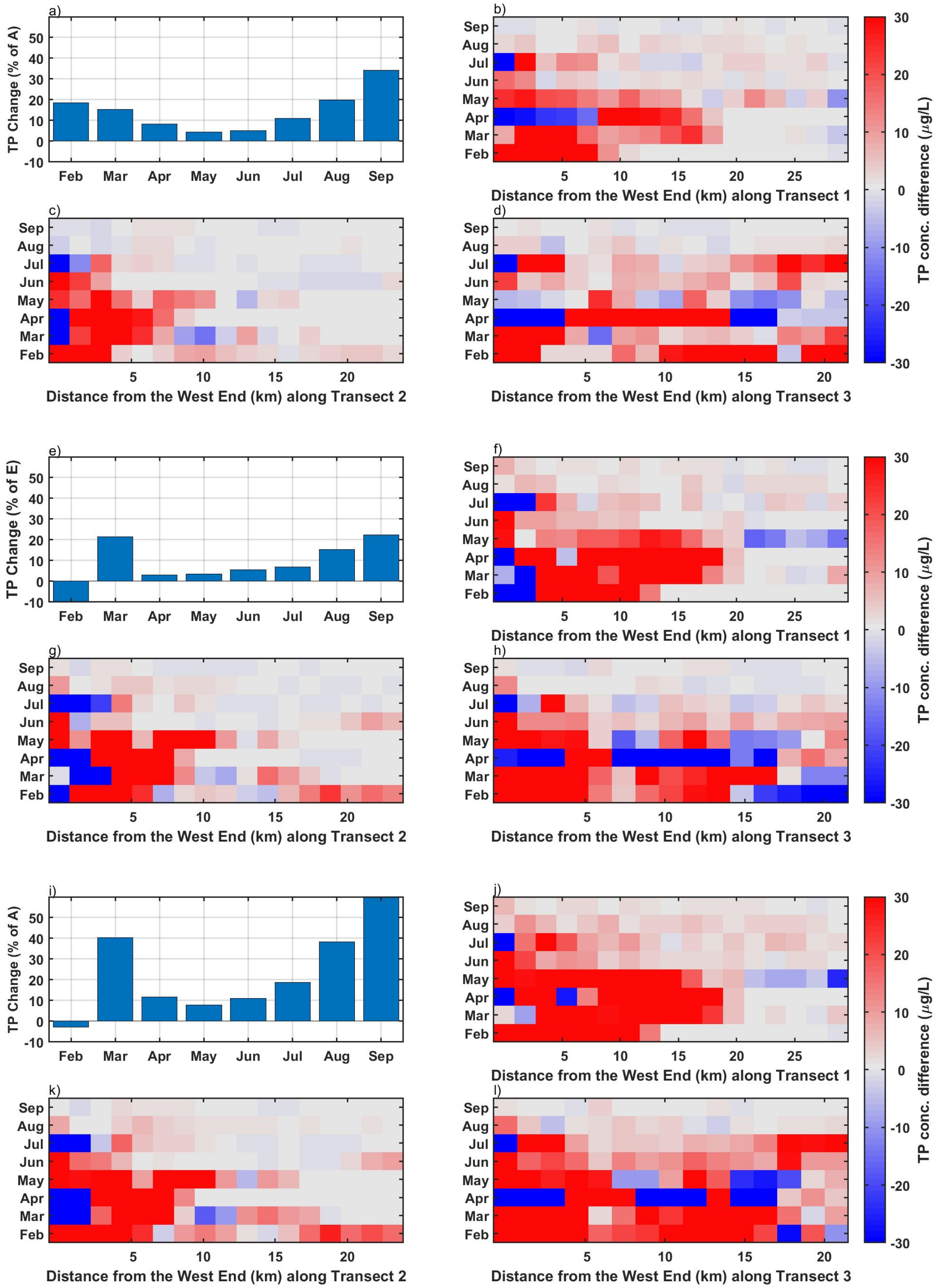
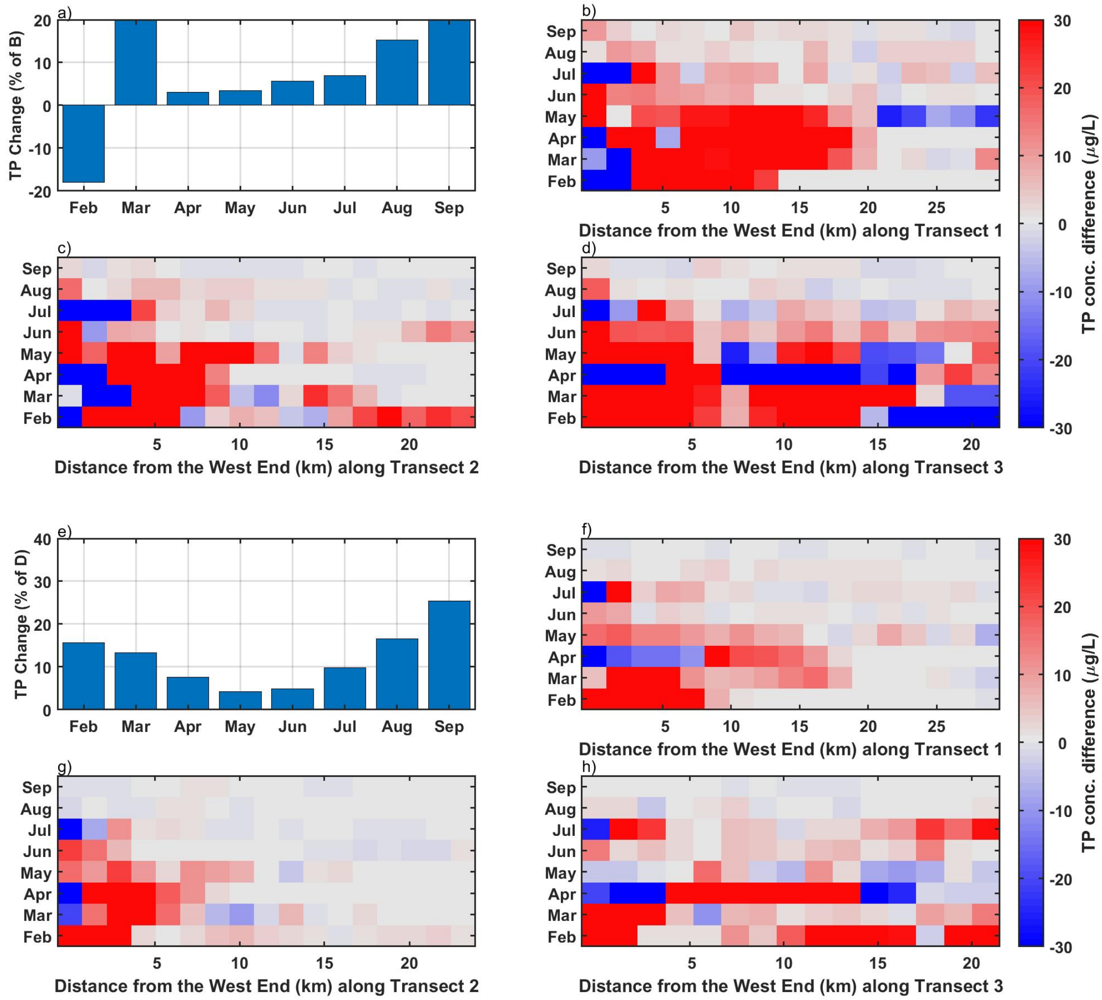

a)
TP Change (% of A)
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
b)
Distance from the West End (km) along Transect 1
c)
Distance from the West End (km) along Transect 2
d)
Distance from the West End (km) along Transect 3
TP conc. difference (μg/L)
e)
TP Change (% of E)
f)
Distance from the West End (km) along Transect 1
g)
Distance from the West End (km) along Transect 2
h)
Distance from the West End (km) along Transect 3
TP conc. difference (μg/L)
i)
TP Change (% of A)
j)
Distance from the West End (km) along Transect 1
k)
Distance from the West End (km) along Transect 2
l)
Distance from the West End (km) along Transect 3
TP conc. difference (μg/L)

Figure 5


a)
b)
c)
d)
e)
f)
g)
h)
TP Change (% of B)
TP Change (% of D)
Feb
Mar
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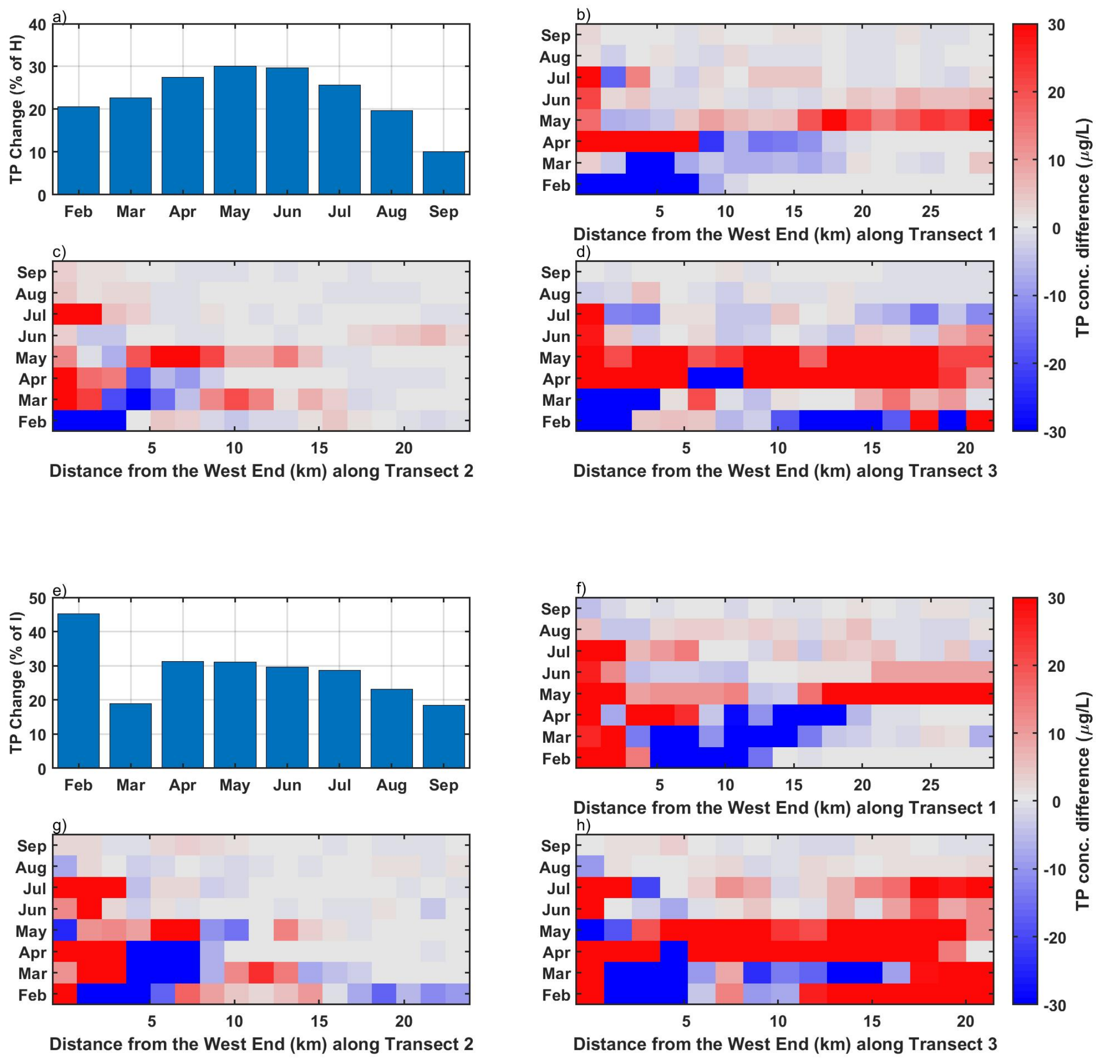
Jun
Jul
Aug
Sep
Distance from the West End (km) along Transect 1
Distance from the West End (km) along Transect 2
Distance from the West End (km) along Transect 3
TP conc. difference (μg/L)

Figure 6


a)
TP Change (% of H)
40
30
20
10
0
Feb Mar Apr May Jun Jul Aug Sep
b)
Sep Aug Jul Jun May Apr Mar Feb
5 10 15 20 25
Distance from the West End (km) along Transect 1
c)
Sep Aug Jul Jun May Apr Mar Feb
5 10 15 20
Distance from the West End (km) along Transect 2
d)
Sep Aug Jul Jun May Apr Mar Feb
5 10 15 20
Distance from the West End (km) along Transect 3
30 20 10 0 -10 -20 -30
TP conc. difference (μg/L)
e)
TP Change (% of I)
50
40
30
20
10
0
Feb Mar Apr May Jun Jul Aug Sep
f)
Sep Aug Jul Jun May Apr Mar Feb
5 10 15 20 25
Distance from the West End (km) along Transect 1
g)
Sep Aug Jul Jun May Apr Mar Feb
5 10 15 20
Distance from the West End (km) along Transect 2
h)
Sep Aug Jul Jun May Apr Mar Feb
5 10 15 20
Distance from the West End (km) along Transect 3
30 20 10 0 -10 -20 -30
TP conc. difference (μg/L)

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