Total Phosphorus trends in Mississippi and Atchafalaya River Basin Watersheds: Exploring the roles of streamflow and watershed features 2000-2020.

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1. Abstract

A consistent method of analyzing riverine phosphorus concentrations and load trends across subbasins of the Mississippi Atchafalaya River Basin (MARB) can indicate whether and where nutrient loads and concentrations have increased or decreased over the long-term. This can help evaluate the success of federal and state nutrient reduction plans being implemented across the landscape and inform adaptive management of load reduction practices. In this study, water quality and streamflow monitoring stations meeting common criteria within sub-watersheds of the MARB were identified and flow normalized (FN) total phosphorus (TP) yield and concentration trends for the period of 2000-2020 were computed through the Weighted Regression on Time, Discharge, and Season (WRTDS), which allowed estimation of streamflow and non-streamflow components of trends. Of the 132 TP sites meeting screening criteria for load calculations and trend analysis, 33.3% and 50.8% had likely increases and decreases of FN concentrations, respectively, while FN yield showed a nearly opposite distribution of trends: 54.5% likely increases and 28.8% likely decreases. Watersheds dominated by urban and cultivated cropland tended to have high FN TP concentrations and yields, and many of the urban dominated watersheds had decreasing yield trends. Factors other than streamflow were dominant for 74.2% and 39.4% of sites for concentration and yield trends, respectively. Trends were weakly correlated with land cover and other watershed variables. Identifying causal factors for trends probably requires finer scale analysis of individual watersheds.

Keywords: Nutrient trends, Streamflow trend component, non-stationary flow normalization, Weighted Regressions on Time, Discharge, and Season (WRTDS) model.

2. Introduction

Elevated phosphorus (P) loads in surface waters were generally issues of local and regional concern during the 1960s and 1970s (Schindler et al. 2016). In the late 1990s, recognition that nutrients reaching the Gulf of Mexico were contributing to extensive benthic hypoxia expanded regional concerns to the entire Mississippi Atchafalaya River Basin (MARB) (Rabalais et al. 1996; Rabalais and Turner 2019). Covering more than 40% of the continental US, the MARB includes intensive and highly productive agricultural areas (Goolsby and Battaglin, 2001). Riverine P, stemming from fertilizer/manure inputs, municipal and industrial wastewater, stream channel erosion and legacy P sources (Stackpoole et al., 2019; Schmadel et al., 2024), discharge to the Gulf of Mexico partly carried by suspended particles and contribute to eutrophication, algal blooms, and hypoxia processes (Jickells, 2005; Adhikari et al., 2015).

Strategies to reduce the amount of riverine nutrients have been implemented at federal, state, and local agencies (Mississippi River Gulf of Mexico Watershed Nutrient Task Force, 2008). Compilation of long-term changes in P loads and concentrations across the MARB allows the evaluation of the effectiveness of these management practices implemented at various scales along with other factors that influence riverine P, such as changes in hydrology and land cover. To evaluate the changes of nutrient loads occurring through decades and distinguish the impacts of random year-to-year streamflow variations from long-term trends, the Weighted Regression on time, discharge, and season (WRTDS) was developed (Hirsch et al., 2010; Kreiling and Houser, 2016; Oelsner et al., 2017; Murphy and Sprague, 2019). A further development of the WRTDS tool allowed the computation of the impacts of streamflow non-stationarity on nutrient trends (Hirsch, 2018; Choquette et al., 2019). This upgrade enabled the separation of flow driven components of trends from all other factors that could impact flow normalized (FN) nutrient concentration and load trends (Murphy and Sprague, 2019), with the latter hereafter labeled non-streamflow component.

The WRTDS has been widely implemented to evaluate the long-term changes of P in the MARB at various spatial and temporal scales. Kreiling and Houser (2016) used WRTDS to evaluate the long-term trends of total P (TP) in six upper tributaries of the MARB finding declining FN concentrations in four rivers for the 1991-2014 period. Oelsner et al. (2017) compiled several constituents of water quality data from multiple agencies and conducted nutrient trends analyses for rivers and streams throughout the USA between 1972 and 2012 and results were synthesized by Murphy and Sprague (2018) showing that TP FN concentration trends were relatively insensitive to changes in streamflow, while FN load trends were somewhat more sensitive streamflow while also sensitive to other factors. However, in this study the influence of watershed characteristics on trends was not assessed. The National Water Quality Network (US Geological Survey, 2024) conducted a similar trend analyses for 110 USGS water quality monitoring sites across the U.S through 2022 although a synthesis of these results has not yet been conducted.

Nutrient availability and advective flow through watershed compartments are the main factors controlling the fate and transport of these pollutants (Speir et al., 2021). Both streamflow and non-streamflow components are influenced by basin features. Topography, soil, land use, and climate, determine flow processes such as rainfall-to-runoff transition, infiltration, and evapotranspiration (Goyette et al., 2019). Current and historical land use influence the non-streamflow component, establishing where fertilizer and legacy phosphorus could be present, as well as the location of point sources from urban wastewater discharge (Sharpley et al., 2013; Schmadel et al., 2024). Furthermore, the basin area determines the complexity of the studied hydrological system. In basins larger than about 200 square kilometers, various heterogeneous interconnected systems regulate the fate and transport of nutrients, as opposed to small drainage basins where nutrient sources and transport paths can be clearly identified (Alexander et al., 2002).

In this paper we conduct a methodologically consistent trend analysis of riverine TP concentration and yield (load/drainage area) across the MARB for the 2000-2020 period, estimating the relative influence of streamflow and non-streamflow components on trends. For the analysis, a harmonized and screened dataset of TP concentration and streamflow records was compiled. Finally, trend results and trends component influences were correlated with basin features (i.e., drainage area, relief, upstream dam storage, and dominant land use). Understanding how various factors influence P trends across the diverse subbasins within the MARB enables a fair assessment of applied environmental nutrient reduction policies by understanding the possible impacts that long-term flow variations could have on nutrient trends. Moreover, it would facilitate the projection of water quality trends under future possible scenarios (Murphy and Sprague, 2019). An analogous analysis was performed for nitrate-N (Botero-Acosta et al., 2025).

3. Materials and methods

The 20-year trend period (2000-2020) was chosen for this study with 2-year additional periods at the starting and ending periods to improve the accuracy of WRTDS load estimations of 2000 and 2020 loads. Preliminary analyses revealed that this 20-year trend period provided a sufficiently large number of sites meeting the data requirements for the trends analysis that would allow meaningful analysis of patterns across the MARB. Moreover, formal state nutrient loss reduction strategies started in the mid-2010’s, which makes this period of particular interest for the evaluation of implemented approaches.

3.1. Data harmonization and screening

The extensive TP concentrations reported in the Water Quality Portal for 30,369 sites within the MARB by multiple local organizations, often with inconsistent methods, nomenclature and units, were screened and harmonized to produce time series with consistent methods, units and naming conventions. The TP dataset gathered all records of P mixed forms in unfiltered water samples. Records from sites linked to the same stream segment were unified to increase the length of the time series at these locations. This process was done through the COMID feature of the National Hydrograph Dataset Plus (EPA, 2022).

The harmonization of the observed dataset plays a major role when analyzing historical changes of nutrient loads (Sprague et al., 2017). Representatives and documentation by various reporting agencies were consulted to clarify methods and units of ambiguous records. From TP data, 23.2% and 16.4% of phosphate and phosphorus ambiguous records respectively, were identified as P mixed forms through personal communication with agencies, while 28.7% and 19.4% of phosphate and phosphorus ambiguous records, respectively were resolved to P mixed forms by analyzing reporting analytical methods. All P mixed forms records with ambiguous reporting form (phosphate or phosphorus) were assumed to be in elemental form (Sprague et al., 2017), and 31 out of 72 organizations reporting P mixed form records with ambiguous fraction were resolved by inspecting all reported fractions for the specific organizations (Oelsner et al., 2017). Harmonized concentration data were included in trend calculations only after various screening criteria were met. This screening included the identification of duplicates, censored, missing, zero, negative, outliers, and composite, control and field analyzed records. The resolution of these records is reported in detail on (Botero-Acosta et al., 2025) Subsequently, site screening removed sites that had more than 50% of left-censored data, less than 70% quarterly coverage for the 2000-20 period, and less than 10% of decadal WQ data on days with high flow regime (SF>85 percentile).

Streamflow (SF) sites located upstream or downstream of WQ sites were selected from the USGS gage network when basin drainage areas had a maximum difference of 10% and no dams were located in between the sites. Data of dams built before 2013 were extracted from EPA (2022). SF data screening identified missing, zero and negative flow values. Missing records were filled for years having no more than 3 consecutive and 30 total missing records using the FillMiss function (USGS, 2016). All SF sites with longer nonconsecutive records for the 1998-2022 water year periods were excluded.

3.2. Total Phosphorus trends

WRTDS (Hirsch et al., 2010) was used to calculate annual flow normalized (FN) loads and concentrations. WRTDS has been widely used to characterize trends of nutrient loads (e.g., Oelsner et al., 2017; Stets et al., 2020; McIsaac et al., 2023) and to estimate the impacts of management practices and flow on resulting trends (e.g., Murphy and Sprague, 2019). Here, we used FN concentrations and loads assuming stationary and non-stationary flow to estimate the total TP trends and the contribution of flow and all other factors to trends results (Botero-Acosta et al., 2025). Analyses were conducted using the R statistical software program (R Core Team, 2017) and the EGRET R-package (Hirsch and De Cicco, 2015; Hirsch, 2018).

WRTDS concentration estimates were compared with observed values, and sites not having a satisfactory performance were removed from the trends sites dataset. For this screening the Peason correlation coefficient, the extrapolation metric and the flux bias statistic were estimated, and a visual inspection of residuals was performed to remove those sites with abrupt residual changes, indicating a step change in the concentration that WRTDS would not be able to accurately reproduce (Oelsner et al., 2017). Trends were then determined by the difference between estimated FN concentration or load for 2020 and 2000. All TP concentration and load (or yield) values referred to in the results section correspond to FN values. The FN values of the obtained time series were used in the long-term trends estimation to reduce the impacts of streamflow random variations on resulting nutrient time series (Hirsch et al., 2010; Murphy and Sprague, 2019).

To enable the comparison of trends results among sites across the MARB, absolute changes were normalized. Change in FN concentrations were normalized with respect to the value at the beginning of the trend period (2000) and expressed as a percent. Annual changes in FN TP load were normalized by drainage area, expressed as yield in kilograms per square kilometer, were used in the analysis. Likelihood of trends was evaluated through a bootstrap test in which a positive replicate fraction of 0.66 or larger would indicate a likely upward trend, 0.33 or smaller would indicate a likely downward trend, and values between 0.33 and 0.66 would represent a no likely trend (Hirsch et al., 2015; Yates et al., 2022).

The dominant trend component (streamflow vs non-streamflow) was defined as one that exceeded the other component by a factor of 1.5 (absolute values). Watersheds where neither component was dominant were classified as having mixed dominance. The percentage of Influence of trends components (streamflow or non-streamflow) were computed as:

$$\%\, Influence\ component\ A = \frac{abs(\%\, change\ component\ A)}{abs(\%\, change\ component\ A) + abs(\%\, change\ component\ B)} \qquad \text{Eq.1}$$

3.3. Watershed features

Watershed features were gathered for drainage basins draining to the monitoring sites and analyzed along with trends results similar to Botero-Acosta et al. (2025). Publicly available data were consulted to extract basin area, land use, elevation, and upstream dam storage information. Dominant land uses for years 2001, 2011, and 2019 were identified from National Land Cover Dataset (NLCD) maps as the adapted land use category (Table 1) covering the largest area of the drainage basin (Stets et al., 2020). The dominant land use for the 2000-2020 trend period was identified for those basins having the same land use category prevailing for the 2001, 2011, and 2019 NLCD maps. When the dominant category changed during the 2000-2020 period, the label “Varied” was assigned. In addition, changes of percentage coverage from 2001 to 2019 for each land use category were computed. A proxy for basin slope was included in our analysis: relief divided by drainage area (m/km^2). Relief was extracted for basins draining to trends sites from a 5x5 degree DEM. Finally, dam storage information was extracted from the National Hydrography Dataset Plus (NHD-Plus) (EPA, 2022). We focused on readily available data that require a minimum of assumptions and estimation and are relatively stable. Future analyses will examine additional variables that are more dynamic and require various assumptions and approximation, such as fertilizer, manure, crop uptake and municipal wastewater.

Table 1. NLCD categories grouped for watershed feature analysis.

Adapted land use categories	NLCD Category ID#	Description
Cultivated (tilled land)	82	Cultivated Crops -areas used to produce annual crops, such as corn, soybeans, vegetables, tobacco, and cotton, and perennial woody crops such as orchards and vineyards. Crop vegetation accounts for greater than 20% of total vegetation. This class also includes all land being actively tilled.
Forest	41	Deciduous Forest
	42	Evergreen Forest
	43	Mixed Forest
Urban	22	Developed, Low Intensity
	23	Developed, Medium Intensity
	24	Developed High Intensity
Water	11, 12	Water
Wetlands	90, 95	Wetlands
Pasture/Hay	81	Pasture/Hay
Other	21	Developed, Open Space- areas with a mixture of some constructed materials, but mostly vegetation in the form of lawn grasses.
	31	Barren Land (Rock/Sand/Clay)
	52	Shrub/Scrub
	71	Herbaceous

Categorizing watersheds by dominant land cover could obscure the impacts of land use changes that do not impact the dominant land cover. For instance, basins dominated by cultivated land cover may have had relatively modest expansions of urban land cover that could alter hydrology and nutrient loads but not change the dominant category as cultivated basins. Hence, the percentage of individual land cover with respect to basin area for 2001 and the change of this percentage during the trends period, were correlated with changes in TP concentration and yield. Correlations among watershed features and between watershed variables and water quality trend variables were analyzed through Pearson correlation (r), and the statistical significance of correlations was evaluated by testing the null hypothesis of no correlation with an alpha value of 0.05.

Finally, a cluster analysis was performed to identify similarities and discrepancies among cultivated trend sites with likely increasing and decreasing TP yield trends. For this, the data of predominantly cultivated sites was evaluated with the Ward's clustering method. The Ward's method uses the incremental sum of squares technique to calculate the distance between all objects in a cluster and its centroid and how this distance increase as clusters are merged (MathWorks, 2024). The data used in the cluster analysis was normalized (with center 0 and standard deviation 1) and scaled (from 0.15 to 0.85), to remove the impacts of scale differences between variables and outliers (Patel and Mehta, 2011; Dalatu and Midi, 2020).

4. Results

4.1. Watershed Features and TP Concentrations and Yields

Data harmonization and screening identified 132 sites that met the screening criteria and thus were included in the trend analyses. Sites were distributed across the MARB but were concentrated in the central portion of the basin (Figure S-1). Cultivated cropland was the dominant landcover for 55% of the basins, followed by forested land (21%) (Figure 1, Table 2). The dominant land covers remained unchanged during the 2000-20 period for all but two sites and these were labeled as “Varied”. Basin areas ranged from 70 km^2 to 17 x 10^5 km^2, with 57% of the sites ranging from 10^3 to 10^4 km^2. Relief per area had a minimum of 0.002 and a maximum of 4.6 m/km^2, with 55% of sites having less than 0.1 m/km^2. Upstream dam storage per drainage area ranged from 0 to 521,600 m^3/km^2.

Predominantly urban basins had the largest mean FN concentration and yield, for both initial and final years (Figure 2). Urban basins also had the largest FN yield ranges, while cultivated basins had the largest ranges of FN concentration. By the final year, maximum and mean values from urban dominated sites had declined, while the values from cultivated dominated basins had remained the same or increased. Watersheds with pasture as the dominant land cover tended to have larger mean and maximum FN yields than cultivated, forest, and varied dominated sites, but generally lower than those dominated by urban land cover.

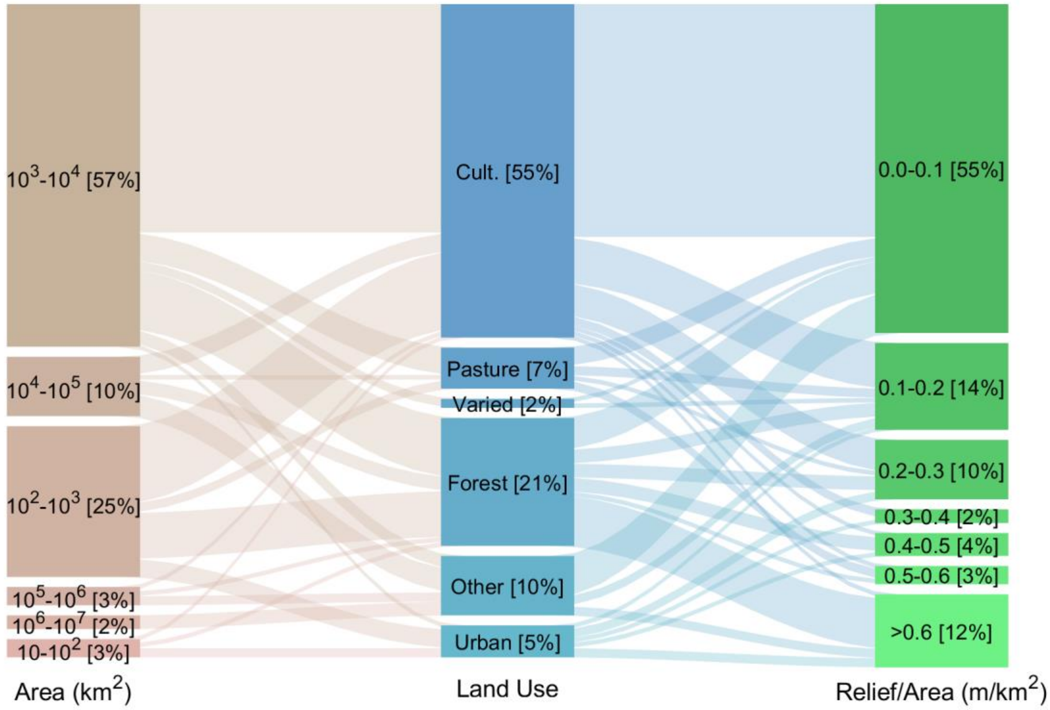

Figure 1. Main watershed features for the 132 total phosphorus (TP) trends sites and percentage of sites for each category.

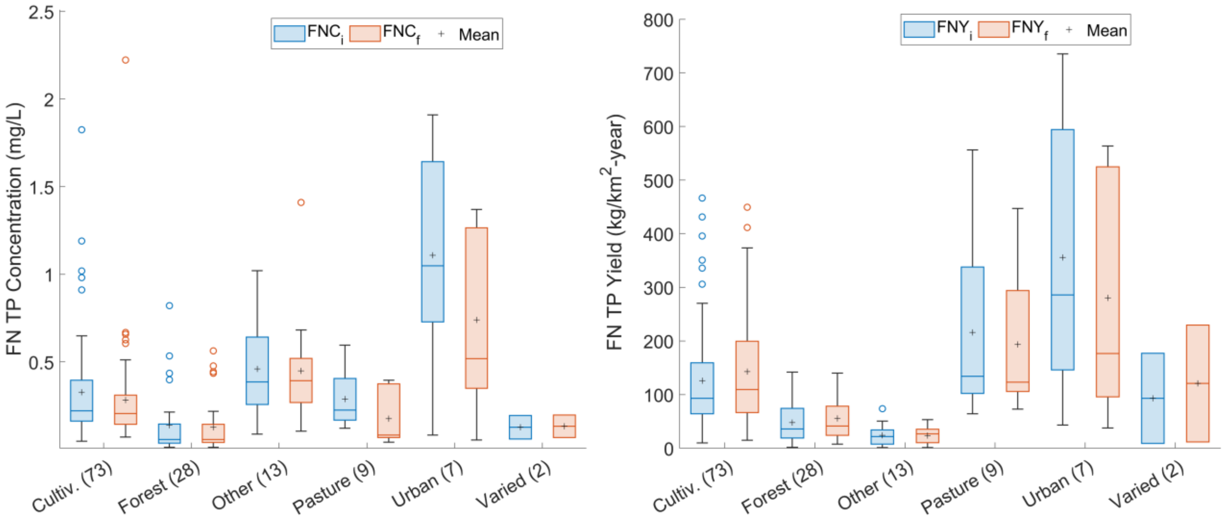

Figure 2. Box plots of flow normalized (FN) concentration and yield at the initial (*i*) and final (*f*) years of trends period per dominated land cover.

4.2. Overall trends

The percentage of sites with likely decreases of FN concentration (51%) exceeded the 33% of sites with likely increases (Table 2). For yield trends, the percentages of decreasing and increasing were approximately reversed with 29% of sites having likely decreasing and 55% of sites likely increasing trends. There is some geographic clustering of trend results, with several increasing FN concentration and FN yield trends in the central portion of the basin, and a cluster of decreasing trends in the northern portion of the basin (Figure 3 and Figure 4).

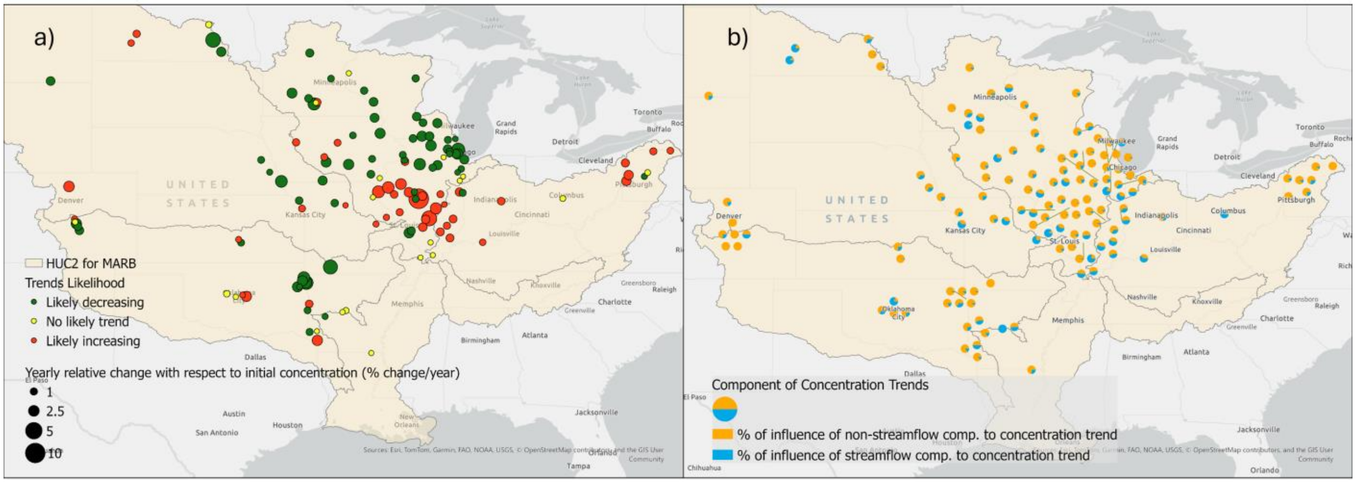

Figure 3. a) TP concentration trends for the 2000-2020 period (n=132). Size of circles were set based on annual percentage change; colors were set based on trends likely direction. b) Percent influence of streamflow and non-streamflow components.

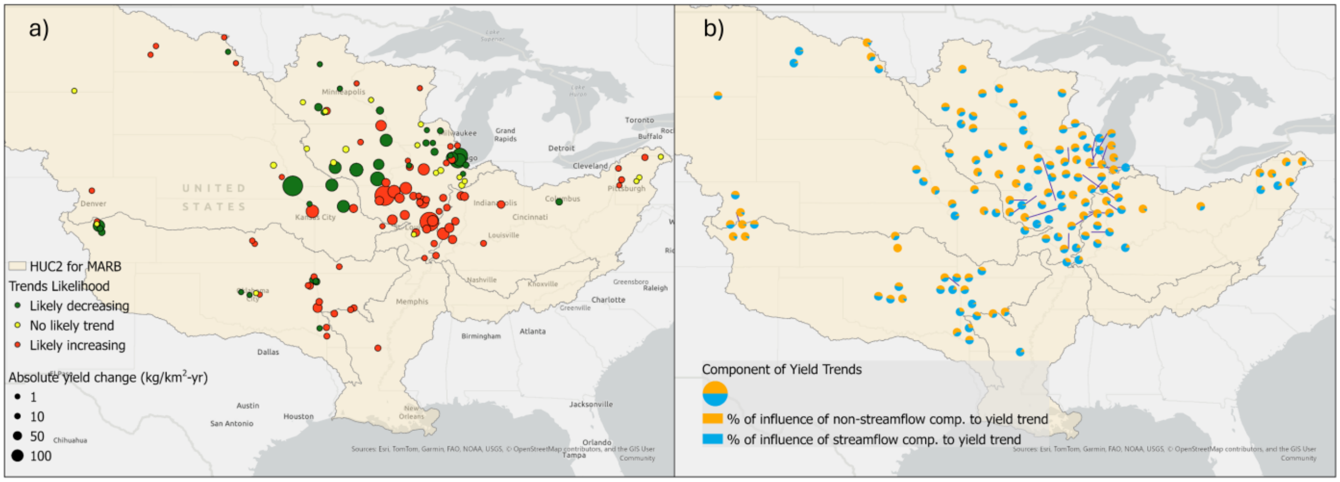

Figure 4. a) TP yield trends for the 2000-2020 period (n=132). Size of circles were set based on absolute magnitude of total trends; colors were set based on trends likely direction. b) Percent influence of streamflow and non-streamflow components.

Table 2. Distribution of sites by likely TP trends and dominant land cover.

			% of sites for concentration trend categories			*% of sites for yield trend categories*		
Dominant Land use	**% of sites**	**Total area (km2)**	**Likely Increasing**	**Likely Decreasing**	**No likely Trend**	**Likely Increasing**	**Likely Decreasing**	**No likely Trend**
Varied (2)	1.5%	4,814	50.0%	0.0%	50.0%	100.0%	0.0%	0.0%
Other (13)	9.8%	4,581,660	38.5%	38.5%	23.1%	46.2%	38.5%	15.4%
Pasture (9)	6.8%	33,463	11.1%	88.9%	0.0%	44.4%	55.6%	0.0%
Urban (7)	5.3%	2,822	0.0%	100.0%	0.0%	14.3%	85.7%	0.0%
Forest (28)	21.2%	356,996	32.1%	35.7%	32.1%	64.3%	10.7%	25.0%
Cultiv. (73)	55.3%	476,970	38.4%	50.7%	11.0%	56.2%	26.0%	17.8%
MARB (132)	**100.0%**	**5,456,724***	**33.3%**	**50.8%**	**15.9%**	**54.5%**	**28.8%**	**16.7%**

**Total drainage area is larger than the MARB because there are overlapping drainage areas in basins with multiple monitoring locations. For instance, the drainage area of the Mississippi River at Thebes includes all the upstream basins, including the Missouri River at Herman*

For the 73 basins dominated by cultivated cropland, the percentages of sites with likely increasing, decreasing and no trends are similar to the percentages for all 132 basins across the MARB as described above. For the 28 basins dominated by forest land cover, FN concentration trends were nearly equally divided among increasing, decreasing and no likely trend; but for FN yield, 64.3% of the forest dominated basins had likely increasing trends. For the nine basins dominated by pasture, 88.9% had likely decreasing FN concentration trends; but for FN yields, pasture dominated basins were nearly equally divided between likely increasing and decreasing trends. For the seven basins dominated by urban land cover, all had likely decreasing FN concentration trends, and all but one had likely decreasing FN yield trends.

4.3. Trend Components

Likely changes of FN TP concentration during the 2000-2020 period were more frequently dominated by the non-streamflow component (70% of sites), with 20% of sites likely increasing and 50% of sites decreasing. In contrast, FN TP yield likely changes were more evenly distributed among sites with non-streamflow dominance (36% of sites), streamflow dominance (27% of sites), and mixed dominance (20% of sites). With the non-streamflow dominated sites having both likely yield increases (16%) and decreases (20%), and the streamflow dominated sites having only significant yield increases (27% of sites) (Figure 5, Figure S-2, Figure S-3). Total FN yield trends were more strongly and positively related to the non-streamflow component for sites with decreasing trends (R^2= 0.85) than sites with increasing trends (R^2=0.65) (Figure S-4). The streamflow component was positively related to increasing total FN TP yields (R^2=0.47), but weakly (R^2= 0.21) and negatively related to decreasing total yield trends.

Table 3. Mean, maximum and minimum FN TP trends for dominant land uses. NS= Non-streamflow component

	% change/year Total trend concent. (%/year)			*% change/year NS trend comp. concent (%/year)*			*% change/year SF trend comp. concent. (%/year)*			*abs. change/year Total trend Yield (kg/km²-yr)*			*abs. change/year NS trend comp. Yield (kg/km²-yr)*			*abs. change/year SF trend comp. Yield (kg/km²-yr)*		
	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min
Varied (2)	0.36	0.64	0.08	-0.22	-0.10	-0.34	0.58	0.74	0.41	28	53	3	1	2	0	26	50	2
Other (13)	0.10	2.36	-1.60	-0.29	2.11	-2.32	0.39	1.28	-0.65	-1	12	-26	-5	6	-29	5	15	-2
Pasture (9)	-2.32	0.21	-3.91	-2.69	-0.26	-3.95	0.38	0.89	0.00	-22	47	-110	-93	-21	-273	70	164	30
Urban (7)	-1.78	-0.59	-3.46	-1.63	-0.11	-3.28	-0.15	0.35	-0.48	-75	32	-175	-94	4	-208	19	34	3
Forest (28)	0.11	2.43	-2.35	-0.13	1.94	-2.41	0.24	0.64	-0.13	8	63	-99	-3	18	-106	11	45	-7
Cultiv. (73)	-0.13	6.33	-4.18	-0.45	6.55	-4.39	0.32	1.16	-0.46	17	222	-226	-16	152	-374	33	149	-8
MARB (132)	**-0.28**	**6.33**	**-4.18**	**-0.58**	**6.55**	**-4.39**	**0.29**	**1.28**	**-0.65**	**6**	**222**	**-226**	**-22**	**152**	**-374**	**27**	**164**	**-8**

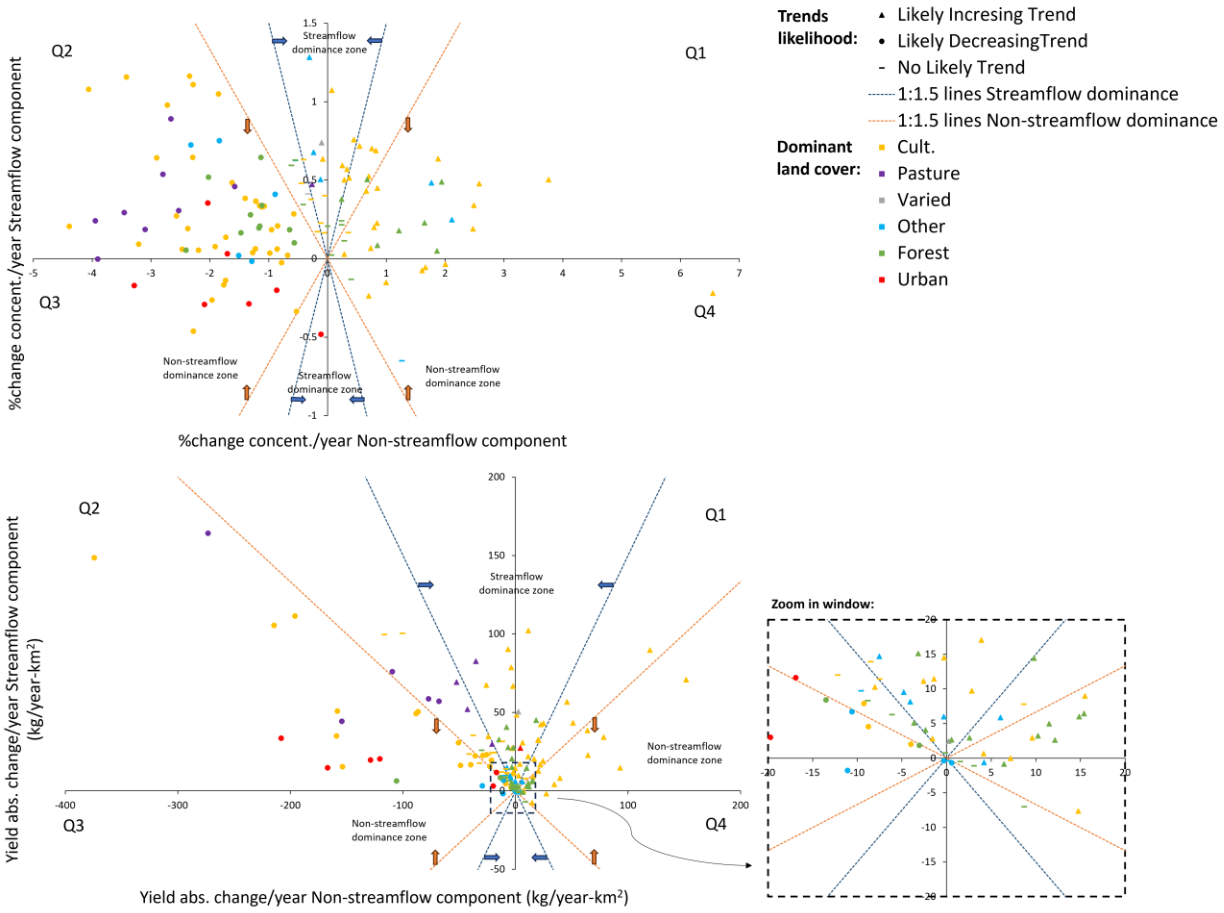

Figure 5. Non-streamflow component vs Streamflow component for TP concentration and yield trends. Markers and colors represent the trend likelihood and the dominant land use category, respectively.

Table 4. Percentage of sites per trend likelihood and quadrant in Figure 5.

	Concentration trend categories (% of sites)				*Yield trend categories (% of sites)*			
	Likely Increasing	Likely decreasing	No Likely Trend	Cumulative Quadrant	Likely Increasing	Likely decreasing	No Likely Trend	Cumulative Quadrant
Q1	22.73%	0.00%	3.79%	**26.52%**	31.06%	0.00%	0.76%	**31.82%**
Q2	4.55%	40.15%	9.85%	**54.55%**	20.45%	26.52%	12.88%	**59.85%**
Q3	0.00%	10.61%	0.00%	**10.61%**	0.00%	1.52%	0.00%	**1.52%**
Q4	6.06%	0.00%	2.27%	**8.33%**	3.03%	0.76%	3.03%	**6.82%**

Figure 5 illustrates the TP trends likelihood, the dominant land cover, and the magnitude of each trends component for all TP trends sites. The graph domain can be divided using two methods, by dominance zones of streamflow and non-streamflow components and by quadrants. The former indicates the relative importance of each trends component with respect to the total absolute change observed in the FN TP variable during the 2000-2020 period at the site, and the latter splits the sites into 4 regions (quadrants) with increases or decreases of each trends component. Quadrant 1 (Q1) indicates sites with increases in both streamflow and non-streamflow components, while quadrant 3 (Q) indicates decreases in both components. Quadrant 2 (Q2) and 4 (Q4) represent increases in one component and decreases in the other component. Of the sites in Q1, nearly all had increased TP yield except one site had no trend (Table 4). Most sites were in Q2 in which the vast majority had decreasing concentration trends and a slight plurality had decreasing yield trends. Relatively few sites were in Q3 or Q4.

4.4. Correlation Analysis

Correlation analysis identified strong positive correlations between the non-streamflow component and the total trend for both yield (r=0.89) and concentration (r=0.98) changes of riverine TP, as well as positive correlation between total concentration and yield trends (r=0.57) (Figure S-5). The percentage of urban land was positively correlated to 2000-values of TP yield (r=0.50) and concentration (r=0.58) and was also slightly negatively correlated to changes in TP yield (r=-0.36) and streamflow trend component of concentration (r=-0.38). The percentage coverage of pastures had a positive correlation with streamflow component of TP yield trend (r=0.46) but a slightly negative correlation (r=-0.21) with the non-streamflow component and no correlation with total TP yield trend.

Land cover changes based on NLCD for 2001 and 2019 revealed that the greatest increases in basin area coverage for individual sites were observed for Other (14.9%) and Urban (10.2%)

categories (described in Table 1). The maximum decreases were 13.6% followed by 12.8% of basin area for the Forest and Cultivated categories, respectively. The correlation analysis between TP concentration and yield trends, and land cover changes (Figure S-6) provided a strong negative relationship between changes in pasture coverage and changes on the streamflow trend component of TP yields (r = -0.54), which might be related to the slight positive correlation between the latter and changes in cultivated land (r = 0.35) to the extent that these land cover changes involved conversion of pasture to cropland.

4.1. Cluster analysis for cultivated basins

The Ward's clustering analysis for the FN yield dataset composed of sites with predominantly cultivated basins identified five clear clusters, denoted with the numbers 1 to 5 (Figure S-8), from the variables listed in Figure S-7. Sites belonging to each cluster and yield trend likelihood were plotted in Figure 6. Results evidenced that the largest likely decreases of FN yield (green clusters, mean total TP trend -131.4 kg/km^2-yr) occurred at sites located towards the central region with large initial yield values and large reductions in the NS trend component. The largest likely increases (yellow cluster, mean total TP trend 84.2 kg/km^2-yr) had the combined impact of large SF and NS yield trends components and occurred in the southern region at basins having medium initial FN yields. Smaller likely increases were observed for the black cluster (mean total TP trend 45.5 kg/km^2-yr), also located towards the south, having smaller increases on the SF and NS components, and smaller initial yield values with respect to the yellow cluster. Finally, the red cluster (mean total TP trend 18.5 kg/km^2-yr), grouped all sites with large slopes and small initial yield values, mostly having small likely changes of TP yield

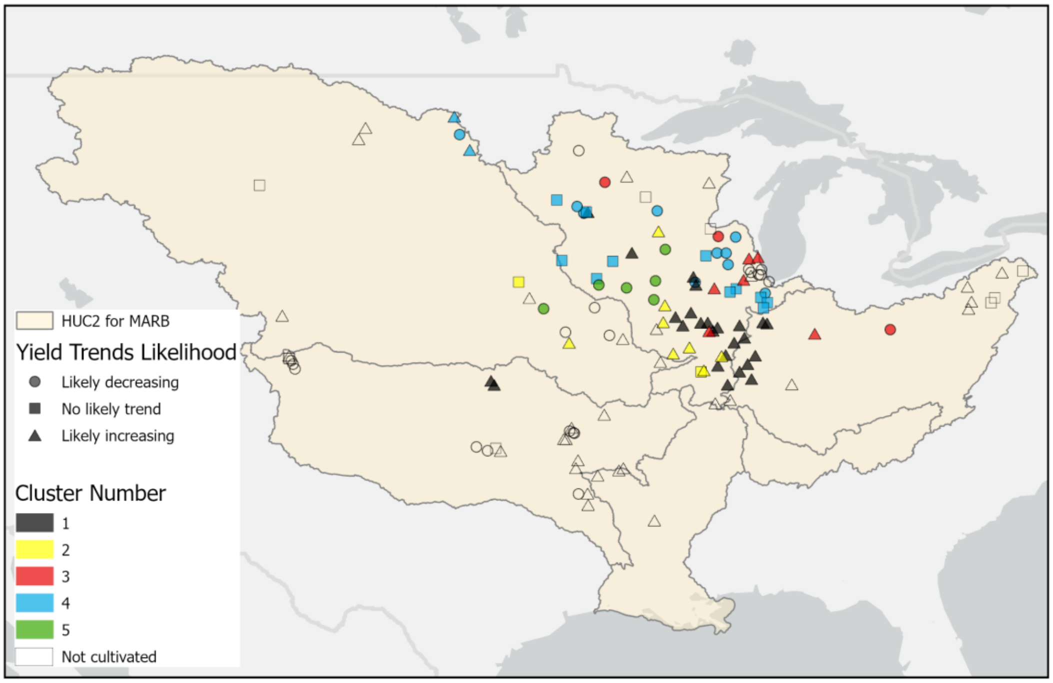

Figure 6. Yield trends likelihood and location of sites belonging to identified clusters (denoted 1-5) for predominantly cultivated basins.

5. Discussion

Our results indicated that watersheds dominated by urban, pasture, and cultivated land covers had the largest FN TP yields in 2000 and 2020 (Figure 2). These land cover categories typically include main sources of P in the MARB: sewage effluents from urban areas, fertilizer application on cultivated land, and manure losses from unconfined animals in pastures/rangeland . While a majority of FN yields from urban and pasture dominated basins tended to decrease during the 2000-20 period, a majority of TP yields from cultivated basins tended to increase (Table 2). A slim majority of cultivated basins had likely decreasing concentration trends, while nearly all the urban and nearly all the pasture dominated basins had likely decreasing concentration trends during our analyzed period. The percentage of sites with likely increases and decreases during the 2000-20 period inverted for concentration and yield variables, with more sites having likely increases of FN yield (55% of sites) than FN concentrations (33% of sites). For both FN variables a cluster of increases was observed in the central region of the basin. Our results contrast with those of Sprague and Lorenz (2009), who reported a historical significant regional increasing trends of flow adjusted concentration values in the central region of the continental U.S. (which contains most of MARB area) significantly corelated to inputs from fertilizers. According to Sprague and Lorenz (2009) there were more increases than decreases of flow-adjusted TP concentration values in this region during the 1993-2003 period, while our results show that more sites had likely decreases than increases of FN concentration throughout the MARB. Reasons for this discrepancy could be changes in practices from the 1993-2003 period to the 2000-2020 period, basin characteristics of the analyzed trend sites, and methodological differences as their concentration values were not subjected to the WRTDS flow normalization.

Sites simultaneously having likely decreases in concentration and likely increases in yield corresponded to 16% of the sites, almost all having streamflow or mixed dominance for the yield trends, and associated with predominantly Pasture, Forest, and Cultivated basins. These results indicated the larger role of streamflow component on riverine TP yield increases. These results are in some ways similar to those reported for 110 sites across the continental USA for the 1982 to 2012 period in which likely FN TP concentration trends tended to be dominated by the non-streamflow component while yield trends had relatively more mixed and streamflow dominance component (Murphy and Sprague, 2019). However, Murphy and Sprague reported only 5% of sites with streamflow dominance in load trends compared to our value of 27%. This difference may be due to differences in sites and time periods analyzed.

Sites with likely increases for both concentration and yield (39 sites), were predominantly cultivated basins located at the south portion of the Upper Mississippi Region (central region of the MARB) (Figure 3 and Figure 4). Although streamflow had a major influence on these sites, other factors were also influential. In most of these sites both concentration and yield were dominated by the same component (10 sites by streamflow component and 16 sites by non-streamflow).

The percentage of sites having likely increasing or decreasing trends in each dominance zone and quadrant of Figure 5 and Table 4 conveys the relative importance of streamflow vs. non-streamflow components on resulting trends. Q2 is of special interest given the extensive literature in which increased annual flows correlate with increased annual TP loads at a site (Gentry et al., 2007; Basu et al., 2010; Jarvie et al., 2012; Baker et al., 2014; Dolph et al., 2019; Rowland et al., 2021). Our results show that more than half of the sites (54.5% and 59.8% for concentration and yield trends sites, respectively) are located in Q2, for which the majority for concentration (73.6% of sites in Q2) and close to half of them for yield (44.3% of sites in Q2) experienced likely decreasing total trends. The separation of trends likelihood inside Q2 was highly related to the component dominance zones, with all increases of TP concentration inside the flow dominance zone, and all increases in TP yield in the flow dominance or mixed-dominance zones. In our trends dataset, none of the 40 sites with streamflow dominance on yield trends, and only 1 of the 18 sites with streamflow dominance on concentration trends experienced decreases, regardless of other characteristics (Figure 5, Figure S-2, Figure S-3). In other words, all but one of the 67 sites with likely decreases in concentration had non-streamflow component dominance.

Focusing on a few sites with the largest magnitude trends reveals some site-specific factors that can be influential yet difficult to generalize across the MARB. A site with by far the largest increase in TP total concentration trend for the 2000-20 period was in the Cultivated category with a maximum annual concentration increase of 6.3%/yr with respect to 2000 values (Table 3). This site (Sangamon River at Riverton, IL) had 96.76% influence of the non-streamflow component for the concentration trends and was impacted by unusually large increases in wastewater P discharge from Decatur (McIsaac et al., 2023). The maximum annual yield increase of 222.4 kg/km^2 was calculated for Bear Creek at Marcelline, IL, a site draining cultivated land with little urban land cover, relief per area of 0.094 m/km^2 and three upstream dams (with a storage of 1.37x10^6 m^3). This location has 68.2% of non-streamflow component influence on yield trends (Figure 4). The second largest annual FN TP yield increase (209 kg/km^2) was observed at Hurricane Creek (Illinois), a cultivated basin with a relief per area of 0.229 m/km^2 and one upstream dam (1.28x10^5 m^3). This site has experienced large flow increases during the 2000-2020 period, which were evidenced in the importance of both trend components (42.9% for streamflow and 57.1% for non-streamflow). These three sites are part of the cluster of sites with increased concentrations and yields in the central part of the MARB. The variation in conditions among the sites illustrate some of the difficulty of identifying a common cause for the geographic cluster of sites with increased concentrations and yields.

Sites with the largest decreases in TP concentration belonged to Cultivated and Pasture categories with maximum annual decreases of 4.2%/yr and 3.9%/yr with respect to 2000 values, respectively, these sites were located in North Dakota and Missouri (Figure 4). The largest yield decrease (226 kg/km^2) was observed in Nishnabotna River, IA, draining largely cultivated land with a 0.032 m/km^2 relief per area Figure 4. This site had 71.6% influence of non-streamflow component on yield trends, indicating its dominance over the flow component. Average annual flow at this site doubled from early 2000 to late 2010. These abrupt variations might have been treated as random variations and underestimated during the flow normalization process, which produced larger FN yields for 2000, that led to the reported reduction. However, a historical analysis of streamflow records at this site (1930-2020) showed a clear increasing long-term tendency. To overcome this issue, a longer time series of nutrient concentration (>30 years) would be recommended to better capture the long-term impacts of flow in riverine nutrient trends. This will be possible if sites maintain sampling in the upcoming decades.

Correlation results and analysis by dominant land cover indicated basins with large urban areas tended to have large yields of TP at the beginning of trend period and tended to decrease. All urban basins (7) but one experienced likely decreases of concentration and yield, with non-streamflow being the dominant yield and concentration trend component. The only urban basin having likely decreases for concentration with likely increases of yield had flow dominance for both yield and concentration trends. Reductions of TP concentrations in U.S. urban basins have been previously reported for the 1992-2012 period by Stets et al. (2020). These reductions may be explained by improved wastewater treatment, and an increase in the magnitude and frequency of extreme rainfall events, producing more runoff without fertilizer inputs from cultivated land, causing a diluting impact on concentrations.

Although, TP yield values have been positively correlated to catchment area and basin slope (e.g.,Allafta et al., 2021), our results did not evidence significant correlations of riverine TP changes with neither of these variables (slope analyzed through the relief/area variable). This could be explained by the correlations of basin area and slope with the percentage of area for each land cover. For our dataset, slope (represented by relief/area) was significant and strongly positively correlated (r=0.58) with percent of forest land and significant and negatively correlated (r=-0.45) with percent area of cultivated land. This indicated that the steeper the basin, the more forested coverage and the less cultivated land, similarly to what occurred in Jacobson et al. (2011). Cultivated or urban land covers are related to TP yield increases (Sharpley and Smith, 1989; Lou et al., 2015; Allafta et al., 2021), while forested land has been related with low TP values due to its limited P inputs and dense vegetation cover that intercepts raindrops and reduces erosion (Zhuang et al., 2015; Kim et al., 2018; Allafta et al., 2021). On the other hand, basin area was found to be significant and slightly correlated (r=0.35) with percent of Other land cover, which represents barren and shrub covered land, not having significant P inputs.

When we focused the analysis on the yield trends of predominantly cultivated sites, the non-streamflow component had the largest impact on likely decreases of yields (Figure S-7) while the majority of sites with yield increases were dominated by the streamflow component or had mixed dominance (Figure S-9). Cluster results showed a large group of sites with likely increasing trends associated with cultivated basins located at the south-central region (black and yellow clusters), with the black cluster having smaller initial FN yields and SF trend components compared to the yellow cluster. Plotting the changes in the percentage of basin area with cultivated and urban land during the trends period for each cluster (Figure S-10), evidenced that sites in the yellow cluster tended to experience a larger expansion of cultivated land during the analysis period compared to the black cluster. Although also experiencing cultivated land expansion, the green cluster, located in the central region had the largest decreases. This may possibly be explained by regional differences in the implemented nutrient management practices. Overall results showed a trend toward FN TP yield increases at lower latitudes.

5.1. Uncertainties and limitations

Flow normalized concentrations and yields are estimates of values that are hypothetically expected to occur under “normal” flow conditions based on past statistical probabilities, not on mechanistic modeling of the interactions of concentration and flow. Since flows are rarely “normal” (however normal is defined), FN concentrations and loads may differ substantially from actual concentrations and loads in a given year, which are causes of eutrophication and are the targets of nutrient reduction efforts. Flow normalization can be useful in estimating relative impacts of changes in hydrology versus other factors, these estimates should be understood to be a mean value when integrated over the frequency distribution of discharge.

Trend period selection can impact the trends magnitude and direction, since trends are estimated as the difference in concentration and yield between initial and final years. The identification of long-term flow variations and their impacts in the trends results might be impacted if the trends period is not long enough to discern random variations from non-stationary flow variability, especially at sites with extreme flow events.

Analysis of factors influencing riverine nutrient trends is limited by available data and resources. Data such as fertilizer and manure applications and crop nutrient uptake are undergoing a process of updating and refinement that is expected to be completed in 2025. These updated data should be incorporated into future studies of factors influencing riverine nutrient trends.

6. Conclusions

Of the 132 sites in the MARB that met our data screening criteria for TP trend analyses, 33% had likely increasing FN concentration trends, 51% had decreasing FN concentration trends and the remaining had no likely trend between 2000 and 2020. Fewer sites (29%) had likely decreasing FN yield trends, including six of seven basins dominated by urban landcover. Likely increasing yield trends occurred at 55% of sites and the remaining 16% had no likely yield trend. The streamflow component of FN concentrations and yields were greater than zero for 81% and 92% of the sites, respectively (Q1 and Q2 in Figure 5), indicating increases in streamflow were widespread across the MARB. Nearly all of the 55% of the sites with likely increasing TP yield trends had streamflow components greater than zero and were somewhat evenly distributed between positive and negative non-streamflow components. Nearly all of the 29% of sites having decreasing TP yield trends had streamflow components greater than zero and negative non-streamflow components, indicating that TP load reductions occurred even where long-term streamflow trends increased.

Long-term changes of streamflow were the dominant component of likely trends in FN TP concentration and yields for only 10% and 27% of the sites, respectively. All other factors, herein referred to as non-streamflow component, were the dominant component for 70% and 36% of the sites for concentration and yield trends, respectively. Among sites with non-streamflow trend dominance, likely decreases of TP concentration were more common than increases, while likely increases and decreases of TP yields were both observed with similar frequency. The non-streamflow component was strongly correlated ($r>0.89$) with changes (total trends) in FN TP concentrations and yields. This non-streamflow component includes all factors other than flow variation, such as fertilizer, manure, point source discharges, stream channel erosion, legacy nutrients and sinks, none of which were quantified in our analysis, and warrant further detailed investigation.

Statistical analyses of patterns and trends across the MARB as related to basic watershed characteristics resulted in weak correlations with limited generalizability. Thus, better understanding of factors influencing temporal and spatial variation in TP concentration and yield tends requires consideration of a wider range of factors (e.g., nutrient budgets) and/or regionally relevant factors (e.g., climate, soils, tile drainage).

7. Data availability

Sites information and detailed results of FN concentration and loads will be made available at the Great Lakes to Gulf Virtual Observatory web site (https://greatlakestogulf.org/nutrient-trends).

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