Diverging trends in nitrate and phosphorus loads and yields across Illinois watersheds, 1997–2022

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Abstract

Illinois is a major contributor of nutrients to the northern Gulf of Mexico. As such, the State of Illinois initiated efforts to curb nutrient runoff over the last several decades. To evaluate progress towards these reductions, water-quality data were used to estimate incremental loads and yields of nitrate plus nitrite (NO3) and total phosphorus (TP) from 1997–2022 for 49 Illinois watersheds, defined using eight-digit hydrologic unit codes (HUC8), draining to the Mississippi River Basin. To estimate changes in NO3 and TP loads, recent loads from the period 2018 through 2022 were compared to baseline loads from 1997 through 2011. Nonpoint and point source loads, dissolved phosphorus (DP) loads, and water yields were also estimated. The sum of the incremental NO3 loads from the 49 HUC8s decreased 9% despite a 19% increase in water yield. Much of this decline occurred in HUC8s that had NO3 yields greater than 17 pounds per acre per year (lbs/acre/yr) during a 1997–2011 baseline period. The sum of all incremental HUC8 TP loads increased 25% despite a 27% reduction in point source discharge. Loads and yields were substantially larger for both NO3 and TP in the Chicago area. Outside the Chicago area, central and northern Illinois had higher NO3 yields than southern Illinois and a reverse pattern for TP where higher yields occur in southern Illinois. Nonpoint sources made up an estimated 82% and 78% of the NO3 and TP yields, respectively, across the HUC8s. In general, point source yields have mostly decreased over time, while nonpoint source yields varied depending on location and reflect the changes in the total yield.

Keywords

Water quality; nutrient pollution; nitrogen; phosphorus; Illinois; Mississippi River Basin; HUC8

1. Introduction

The northern Gulf of Mexico has experienced expansive areas of hypoxic conditions every summer since the start of monitoring in 1985 (Turner et al., 2012). The Gulf of Mexico hypoxic or ”dead zone” has ranged in size from 40 to 22,700 square kilometers (km^2) (15 to 8,800 square miles [mi^2]) in mid-summer and averaged 11,100 km^2 (4,300 mi^2) from 2018–2022, making it the second largest anthropogenic-driven hypoxic zone in the coastal ocean behind the Baltic Sea (Carstensen and Conley, 2019; Rabalais and Turner, 2019; Smith, 2024). The Gulf of Mexico dead zone forms and expands primarily in response to excessive nitrogen and phosphorus loads from the Mississippi/Atchafalaya River Basin (Rabalais et al., 2002; Rabalais and Turner, 2019; Robertson et al., 2014; Scavia et al., 2003; Turner and Rabalais, 1991; U.S. Environmental Protection Agency [USEPA], 2007). To reduce the areal extent of the Gulf of Mexico dead zone, the USEPA Science Advisory Board determined that annual nitrogen and phosphorus loadings from the Mississippi/Atchafalaya River Basin needed to be reduced by 45% (USEPA, 2007). As part of the national effort to reduce the Gulf of Mexico dead zone, 12 states within the Mississippi/Atchafalaya River Basin developed plans to reduce the amount of nitrogen and phosphorus discharging to the Gulf of Mexico. Illinois’s effort is referred to as the Illinois Nutrient Loss Reduction Strategy (NLRS) (Illinois Environmental Protection Agency [IEPA] et al., 2015). The Illinois NLRS mirrored the recommendations from the USEPA Science Advisory Board and set a long-term objective of a 45% reduction in total nitrogen and total phosphorus loads originating in Illinois, with interim targets of a 15% decrease in nitrate-nitrogen and a 25% decrease in total phosphorus by 2025. As of 2021, neither the long-term nor the interim targets have been met (IEPA et al., 2023).

In accordance with the Illinois NLRS, the IEPA and the U.S. Geological Survey (USGS) collaborate to monitor, measure, and estimate annual loads and yields of nitrate plus nitrite, as nitrogen (NO3) and total phosphorus (TP) leaving the state through eight major waterways (Hodson, 2023; IEPA et al., 2015;

IEPA et al., 2019). In addition to tracking nutrient loads leaving the state, the numerous USGS streamgages and IEPA ambient water-quality sites (hereafter referred to as water-quality sites) within Illinois provide data to estimate nutrient loads and yields on a finer spatial scale, such as eight-digit hydrologic unit code (HUC8) outlets within Illinois. These HUC8 loads and yields may help to identify critical source areas, meaning locations that deliver a disproportionate amount of nutrients. Detecting and prioritizing management strategies in critical source areas is a key method to improve the effectiveness of nutrient reduction practices (Osmond et al., 2012; Osmond et al., 2019). Because Illinois has not met its nutrient reduction goals, quantifying HUC8 loads and yields helps watershed managers in Illinois identify key areas to target nutrient reductions moving forward.

Average annual HUC8 NO3 and TP loads and yields were previously estimated for the period from 1997 to 2011 in the initial Illinois NRLS (IEPA et al., 2015) and then updated for the period from 2012 to 2017 (McIsaac, 2019; IEPA et al., 2019). For both efforts, NO3 and TP annual loads were estimated at water-quality sites across the state and these water-quality site loads were used to estimate incremental HUC8 loads and yields. Incremental loads and yields represent the nutrient mass originating from specific HUC8s, excluding inputs upstream of the HUC8. In these previous studies, NO3 water-quality site loads were estimated using linear interpolation, and TP loads were estimated using the Weighted Regressions on Time, Discharge, and Season model (WRTDS; Hirsch et al., 2010). Our study incorporates an additional 5 years of NO3 and TP data as well as an improved load estimation method, WRTDS-Kalman (WRTDS-K). WRTDS-K is a post-WRTDS processing procedure that uses a Kalman filter to provide post-hoc adjustments based on autocorrelation of residuals near observed measurements (Lee et al., 2019; Rowland et al., 2021; Zhang and Hirsch, 2019).

The objectives of this study were to (1) quantify recent NO3 and TP loads and yields at the HUC8 level across Illinois through 2022 and (2) evaluate temporal and spatial variation in these loads and yields relative to previous periods. We incorporated the improved WRTDS-K method in the workflow yet maintained computational methods used in previous efforts to estimate HUC8 loads and yields from water-quality site loads (IEPA et al., 2015; IEPA et al., 2019; McIsaac, 2019). In addition to estimating total incremental loads, we also quantified the contributions from point and nonpoint sources. Finally, to provide insight into possible effects on total, point, and nonpoint source loads and yields across Illinois, we computed the percentages of dissolved phosphorus (DP) and particulate phosphorus (PP) relative to TP yields, and the total water yield for each HUC8. This set of watershed-based estimates may help provide a better understanding of NO3 and TP export dynamics across Illinois.

2. Methods

2.1 Study Sites: Illinois Eight-Digit Hydrologic Unit Code (HUC8s)

There are 50 HUC8s in Illinois that drain into the Mississippi River and 2 that drain into Lake Michigan. They range in size from 11 to 2,436 mi^2, with an average size of about 1,080 mi^2. In this study, we estimated loads and yields for 49 of the 52 HUC8s. The two Lake Michigan HUC8s (Little Calument-Gallen and Pike-Root) were omitted because they do not drain to the Mississippi River. The Middle Rock was also omitted because less than 1% of its total area is within Illinois. The remaining 49 HUC8s cover 99% of the land area of Illinois (Figure 1).

These 49 HUC8s include a diverse range of land use and land use intensities (Dewitz, 2019). The northeastern HUC8s include extensive urban areas and high population density associated with the city of Chicago, Cook County, and the surrounding suburbs. The northwestern, north-central, east-central, and southern portions of the state are dominated by sparsely populated row-crop agricultural land. Meanwhile, the extreme southern portion of the state (i.e., the Shawnee National Forest) and the Lower Illinois River Basin are a mix of cultivated and forested land cover.

2.2 Data Compilation

Daily average discharge data from 52 USGS streamgages across Illinois were compiled from the USGS National Water Information System (NWIS) database using the dataRetrieval R package (De Cicco et al., 2024; U.S. Geological Survey, 2024). Gaps in the discharge record of less than 30 consecutive days were estimated using the fillMiss function in the waterData R package (Ryberg and Vecchia, 2017). Five water-quality sites and streamgages were not collocated and point sources were present between the water-quality site and streamgage; discharge values were scaled to better represent flows at the water-quality site.

NO3, TP, and DP concentration datasets were compiled from 1973–2022 using three sources: (1) the Water Quality Portal (WQP; National Water Quality Monitoring Council, 2024), (2) directly from IEPA (Trevor Sample, written commun., 2024), and (3) USEPA's STORET database (https://gaftp.epa.gov/storet/exports/, accessed March 28, 2024). Water-quality data were obtained from 56 monitoring sites in the IEPA's State of Illinois Ambient Water Quality Monitoring Network (AWQMN) and 48 monitoring sites operated by the USGS. In the AWQMN, water samples were collected approximately every 6 weeks, or nine samples per year. The USGS collected water samples monthly, or 12 samples per year. Often, AWQMN and USGS sites were collocated, with USGS-led sampling transitioning to AWQMN-led sampling in the late 1990s. These sites were reconciled to a single water-quality site, which resulted in 52 total water-quality sites. Additional information on discharge and water-quality dataset compilation is included in the supplemental materials with the final datasets used in this study available in Podzorski et al. (2025).

Water-quality site watersheds were delineated to compute drainage areas for the water-quality sites (hereafter, monitored areas) and compute distances among sites, streamgages, and point sources using the web-based application StreamStats (U.S. Geological Survey, 2019). Differences in monitored areas were calculated to scale discharge for non-collocated sites (Podzorski et al., 2025). Monitored areas for these sites are included in Kamrath et al. (2025).

Data for point source facilities were provided by the IEPA (Trevor Sample, written commun., March 15, 2024). This dataset included the latitude and longitude for each facility, their annual loads of total nitrogen (TN) and TP for the years 2011, 2017, and 2018 through 2022 for major municipal point sources. NO3 point source loads were estimated as 90% of the TN point source loads, an assumption in previous NLRS reports (IEPA et al., 2015; IEPA et al., 2019) based on point source data. Point source loads for DP were not available. Each point source was matched with its corresponding monitored area and HUC8 area.

2.3 Eight-Digit Hydrologic Unit Code (HUC8) Loads and Yields Estimates

2.3.1 Annual Water-Quality Site Loads for Nitrate plus Nitrite (NO3), Total Phosphorus (TP), and Dissolved Phosphorus (DP).

Annual loads of NO3, TP, and DP loads at water quality sites were estimated using Weighted Regressions on Time, Discharge, and Season (WRTDS; Hirsch et al., 2010), and particulate phosphorus (PP) loads were calculated as the difference between TP and DP for each water-quality site. Once the WRTDS model was fit, a Kalman filter post-processing procedure was applied (Zhang and Hirsch, 2019). The post-processing procedure uses the serial correlation of the residuals to adjust the regression-based estimates, so they more closely align with the observed values. This entire approach is referred to as WRTDS-K and applied using the 'EGRET' R package (Hirsch et al., 2023). Conceptually, WRTDS-K combines features of regression modeling for estimates far from observed values and interpolation for estimates near observed values. Previous studies have shown this approach outperforms other common load estimation methods (Lee et al., 2019).

WRTDS-K was run separately for every combination of water-quality site and constituent. The fit of the WRTDS models were visually evaluated using plots of residuals, observed, and estimated values. The daily estimates from WRTDS-K were aggregated to water year estimates of NO3, TP, and DP loads and concentrations. A water year is the period from October 1 through September 30 and is designated by the year in which it ends; for example, water year 2022 was from October 1, 2021, to September 30, 2022. Water years were used for parity with previous load computations at the study sites. Annual loads and fitted model information are available in Podzorski et al. (2025).

2.3.2 Extrapolation of Water-Quality Sites to Eight-Digit Hydrologic Unit Codes (HUC8s)

We followed the HUC8 extrapolation approach used in the previous NLRS assessment (IEPA et al., 2019) and described in McIsaac (2019) to estimate nonpoint source, point source, and total HUC8 NO3 and TP loads and yields. This approach estimates the nonpoint source yield upstream from the water-quality site (i.e., the monitored area) by subtracting the sum of the point source loads within the monitored area from the WRTDS-K estimated water-quality site loads and dividing by the monitored drainage area. This estimate of nonpoint source yield was assumed to be representative across the entire HUC8. The HUC8 nonpoint source load was then estimated by multiplying the monitored nonpoint source yield by the HUC8 area. The sum of the point source discharges within each HUC8 was then added to the estimated nonpoint source load to provide an estimate of total NO3 and TP loads from each HUC8 for which there were monitoring data.

Twenty-four HUC8s had water-quality sites that directly represented the HUC8 area with no contributing upstream loads. Ten HUC8s had inputs from upstream HUC8s (e.g., the Lower Sangamon) or out-of-state areas (e.g., Kankakee). Three HUC8s lacked a water-quality site on the river or stream of interest but loads and yields could be reasonably estimated using water-quality sites on tributaries. Nine

HUC8s had little to no river monitoring data within the HUC8. Finally, three HUC8s had corresponding water-quality sites that required unique methods to estimate HUC8 loads and yields.

For the 24 HUC8s with no upstream loads (i.e., no upstream HUC8s), the above steps were applied directly to estimate HUC8 loads and yields (Table 1, "computational method 1"). For the 10 HUC8s with inputs from upstream HUC8s or out-of-state areas, incremental water-quality site loads and point source loads were calculated as the change in load between the downstream and upstream locations (e.g., Sangamon at Oakford (USGS site number 05583000) minus Sangamon at Riverton (USGS site number 05576500) minus Salt Creek at Greenview (USGS site number 05582000) in the Lower Sangamon HUC). The HUC8 nonpoint yields were then estimated using these incremental loads and the incremental area (Table 1, "computation method 2"). For the three HUC8s using tributary water-quality sites, nonpoint source yields for each water-quality site were estimated using the previously described method. The HUC8 nonpoint source yield was then estimated using a weighted average of the water-quality site nonpoint source yields and drainage areas (Table 1, "computational method 3"). For the nine HUC8s with no river monitoring data, nonpoint source yields were estimated as a weighted average of HUC8 nonpoint source yields from neighboring HUC8s and their HUC8 areas (Table 1, "computational method 4"). For the three HUC8s with complex water-quality site relationships, site specific methods were used to estimate HUC8 nonpoint source yields (Table 1, "computational method 5").

The HUC8 extrapolation approach described above was used to compute annual estimates for the 49 HUC8s considered in this study. For these computations, previous efforts applied 2011 point-source loads to all water years between 1997 and 2011 (IEPA et al., 2015) and 2017 point-source loads to all water years between 2012 and 2017 (IEPA et al., 2019; McIsaac, 2019) because limited point-source data were available. For this update, annual point-source loads were available for 2018 through 2022, which were averaged to a single value and then applied to the water years between 2018 and 2022. Using the annual HUC8 estimates computed with the steps above, NO3 and TP total, nonpoint source, and point source incremental loads and yields for the 49 HUC8s in Illinois draining to the Mississippi River were aggregated to three periods: 1997–2011 (baseline), 2012–2017, and 2018–2022 (recent). The baseline and 2012–2017 periods have been used historically by the NLRS to track progress across the State. Datasets of the HUC8 average annual values for these three periods are provided in Kamrath et al. (2025). Note, the HUC8 average annual values reported in Kamrath et al. (2025) and presented here are the *incremental* loads and yields, i.e., the contributions from each HUC8 exclusive of inputs from upstream HUC8s.

To better understand spatial and temporal variation of nutrient point and nonpoint sources, we estimated the percentage of point and nonpoint sources comprising total HUC8 loads. Total HUC8 loads were estimated by adding the sum of the HUC8's point source discharges to the estimated HUC8 nonpoint source load. Using these annual estimates of HUC8 point, nonpoint, and total loads, the percentage of nonpoint and point sources comprising the total NO3 and TP loads were computed. Average annual percentages were then computed for each of the periods. For most HUC8s, these equations resulted in positive values between 0 and 100%. However, a few HUC8s had either negative total loads or had point source values greater than (>) 100%, which complicated the interpretation of these values. The HUC8s with negative total loads were interpreted as nutrient sinks and were removed from the summaries of point and nonpoint source percentages. The HUC8s with point sources greater than (>) 100% were interpreted as HUC8s where point sources dominated the total load, and we set the point source percentage to 100% and the nonpoint source percentage to 0%. These HUC8s likely had a very small amount of nonpoint source nutrients relative to point sources, but in-stream processes (which were assumed to be negligible for all HUC8s) removed more nutrients than nonpoint sources produced resulting in HUC8s with less than (<) 0% nonpoint sources and > 100% point sources.

2.3.3 Dissolved Phosphorus (DP) and Particulate Phosphorus (PP) Percentages

We computed the percentage of DP and PP that comprise the TP load for each HUC8 to characterize changes in DP and PP loads. Point source loads were not available for DP. Therefore, we could only compute the DP and PP percentages of the total TP load and not the point source or nonpoint source components. To estimate total DP loads for each HUC8, we followed an abbreviated version of the computation steps described above, which are also described in the first IEPA NLRS Report (2015). Using the same water-quality sites and HUC8 matches listed in Table 1, the total DP and TP yields computed for the area upstream of the water-quality site were assumed to be equivalent to the DP and TP yields within the entire associated HUC8. This HUC8 yield was multiplied by the Illinois portion of the drainage area to provide the total HUC8 load DP and TP. The total PP loads for each HUC8 were then estimated by subtracting the total DP load from the TP load. Using these annual estimates of HUC8 DP, PP, and TP loads, the percentage of DP and PP comprising the TP load in each HUC8 was computed. These percentages were computed annually and then summarized by HUC8 into average annual percentages for the same three periods: 1997–2011 (baseline), 2012–2017, and 2018–2022 (recent), and are provided in Kamrath et al. (2025).

2.3.4 Water Yields

Water yields were computed for each HUC8 using the modified version of the computation steps for DP and PP percentages described previously. Water yields were computed annually and then summarized by HUC8 into average annual water yields for the same three periods: 1997–2011 (baseline), 2012–2017, and 2018–2022 (recent), and are provided in Kamrath et al. (2025).

2.4 Data Analysis

The average annual NO3 and TP total, nonpoint source, and point source loads and yields, DP percentages, and water yields for 49 Illinois HUC8s compiled in Kamrath et al. (2025) were analyzed to

(1) provide a summary of the recent period (2018–2022) and (2) conduct a change analysis between the historically used baseline (1997–2011) and recent (2018–2022) periods. To summarize temporal changes in HUC8 yields between the baseline and recent periods, we categorized the percentage changes (i.e., 100*(recent yield – baseline yield)/baseline yield) in each HUC8 as stable (+/- 5%), decreasing (< -5%), and increasing (> 5%). Statewide patterns behind the changes in HUC8 NO3 and TP yields were evaluated using a correlation analysis (Pearson's r). The correlation analysis did not include the four HUC8 sites that were found to be nutrient sinks during 2018–2022.

3. Results

3.1 Summary of 2018–2022 Results

3.1.1 Total Loads and Yields

During water years 2018–2022, the average annual HUC8 total NO3 load was 8.4 million pounds per year (lbs/yr) and the yield was 12.1 pounds per acre per year (lbs/acre/yr) (Table 2). The total summed NO3 load across all HUC8s in the state was 410 million lbs/yr. HUC8 NO3 loads and yields varied from minor NO3 sinks (i.e., negative loads and yields) to substantial NO3 sources across the State of Illinois (Table 2, Figures 2 and 3). Three HUC8s were NO3 sinks: Lower Illinois, Lower Illinois-Senachwine Lake, and Middle Kaskaskia. The Lower Illinois and the Lower Illinois-Senachwine Lake HUC8s include low gradient sections of the Illinois River valley with locks and dams and extensive wetlands and lakes, and the Middle Kaskaskia includes a large reservoir (Carlyle Lake), all of which create favorable conditions for larger denitrification rates compared to other HUC8s in the State. Of the HUC8 NO3 loads > zero, the smallest were in the southern portion of the State, while the larger loads (i.e., those > 10 million lbs/yr; Figure 2) commonly occurred in the north and east-central portions of the State. The densely populated Chicago region contained the HUC8s with the largest loads. For example, the Des Plaines HUC8 exported the largest load (27 million lbs). HUC8 NO3 yields (Figure 3) followed a similar spatial pattern to the NO3 loads: low yields in the southern portion of the State and high yields in the Chicago area.

The average annual HUC8 TP load during 2018–2022 was 1.0 million lbs/yr and the yield was 1.5 lbs/acre/yr (Table 2). The summed TP load across all HUC8s was 50 million lbs/yr. HUC8 TP loads and yields also varied from minor TP sinks to major TP sources across Illinois (Table 2, Figures 2 and 3). As with NO3, the Lower Illinois and the Lower Illinois-Senachwine Lake HUC8s were TP sinks. Unlike the NO3 results, the third TP sink was the Lower Sangamon HUC8. Excluding the three sinks, the HUC8s with the smallest TP loads were generally located in the northern portion of the State – excluding the HUC8s in and around the Chicago area. In fact, the Chicago area, along with the western and southern portions of the State had some of the largest TP loads (i.e., those > 1 million lbs/yr in Figure 2). TP yields followed a similar spatial pattern to TP loads, although the larger TP yields were even more concentrated in the southern portion of the State (Figure 3).

3.1.2 Nonpoint Source and Point Source Loads and Yields

Across Illinois, HUC8 NO3 and TP loads and yields were dominated by nonpoint sources (Table 2, Figures 4 and 5). When summed across all HUC8s, nonpoint sources made up 82% of the total NO3 load, while point sources made up the other 18%. For TP, nonpoint sources made up 78% of the TP load, while point sources made up the other 22%. Only 5 of the 49 HUC8s had point sources that accounted for > 25% of the total NO3 loads, and only 6 HUC8s had point sources contributing > 25% to the total TP load. There were 24 HUC8 watersheds with nonpoint source NO3 yields > 10 lbs/acre/yr and only 2 HUC8 watersheds with point source yields > 10 lbs/acre/yr. For TP, 8 HUC8 watersheds had nonpoint source yields > 2 lbs/acre/yr and only 3 HUC8 watersheds had point source yields > 2 lbs/acre/yr. The largest nonpoint source NO3 yields occurred in the Kankakee, Upper Illinois, Vermilion, Pecatonica, and Sugar HUC8s—nearly all of which were in the northern portion of the State (Figure 4a). Conversely, the largest nonpoint source TP yields occurred in The Sny, Cahokia-Joachim, Lower Kaskaskia, Peruque-Piasa, Bear-

Wyaconda, Skillet, Embarras, and Middle Wabash-Busseron HUC8s, which were in the southern portion of the State (Figure 5a).

The HUC8s that were nearly or completely dominated by point sources were often the HUC8s that had the largest NO3 and TP yields (e.g., Chicago, Des Plaines, and Upper Sangamon) (Table 2, Figures 4 and 5). For example, in both the Chicago and Des Plaines HUC8s, point sources comprised 100% of the NO3 yield and over 90% of the TP yield. The distribution of point source NO3 and TP yields showed extreme magnitudes for these HUC8s. For NO3, the average point source yield was 2.5 lbs/acre/yr, while the maximum was 43.3 lbs/acre/yr (Table 2). For TP, the average point source yield was 0.4 lbs/acre/yr, but the maximum was 9.8 lbs/acre/yr (Table 2). The maximum point source yields for both NO3 and TP occurred in the Chicago HUC8. In comparison, the maximum nonpoint source NO3 yield was 28 lbs/acre/yr, and the maximum nonpoint TP yield was 3.8 lbs/acre/yr.

3.1.3 Dissolved Phosphorus (DP) Percentages

DP as a percentage of the TP load ranged from 16.8% at Highland-Pigeon to 82.5% at the Upper Sangamon, with an average of 47.2% across the Illinois. The HUC8s with the greatest percentage of DP were Upper Sangamon and Chicago (Figure 6a). The HUC8s with the lowest percentage of DP were Highland-Pigeon, Saline, Upper Fox, and The Sny. A strong spatial pattern was not evident with these percentages, but the HUC8s with high percentages of DP were also those with large point source TP loads (e.g., Upper Sangamon, Chicago, and Des Plaines). An exception was the Lower Illinois-Senachwine Lake, which had a high DP percentage but a relatively lower point source TP load. The high percentage of DP at the Lower Illinois-Senachwine Lake and the other HUC8 TP sinks may have been due to the settling of PP under the same conditions that caused the HUC8s to be nutrient sinks (i.e., very low gradient sections of river with extensive wetlands and lakes).

3.1.4 Water Yields

During 2018–2022, average annual water yields were lowest across central Illinois with the highest water yields in southern Illinois and the Chicago area (Figure 6). Average annual water yields ranged from 11.2 in/yr in the Lower Illinois HUC8 to 34.5 in/yr from the Des Plaines HUC8 with an average of 16.3 in/yr across all HUC8s. The five HUC8s with the greatest water yields were Des Plaines, Cache, Chicago, Highland-Pigeon, and Saline. The Des Plaines HUC8 water yield (34.5 in/yr) was much larger than other HUC8s (Figure 6b); for example, the Des Plaines HUC8 water yield was 10 in/yr greater than the next largest HUC8 water yield at Cache (24.5 in/yr). Water yield from the Des Plaines HUC8 was substantially larger than elsewhere in the State because it included direct and indirect diversion of water from Lake Michigan through the Chicago Sanitary and Ship Canal including discharge of treated wastewater originating from Lake Michigan and groundwater connected to Lake Michigan (U.S. Army Corps of Engineers, 2023). The HUC8s with the five lowest water yields were the Lower Illinois, Upper Sangamon, Macoupin, Lower Illinois-Senachwine Lake, and The Sny (Figure 6b).

3.2 Changes from Baseline to Recent Period

3.2.1 Changes in Yields

Because of the similarities between the patterns of loads and yields across Illinois, temporal variation results will be focused on changes in nutrient yields in this section to reduce redundancy. In the 49 HUC8s across Illinois, NO3 yields increased for 22 HUC8s between baseline and recent periods, while TP yields increased in 31 HUC8s (Table 3). NO3 yields were stable in the 7 HUC8s compared to 8 for TP. The number of HUC8s with decreasing NO3 yields was 17 compared to 7 for TP. The number of HUC8s with decreasing, increasing, and stable nonpoint yields generally reflected those of the total yields. Point source yields decreased or were stable for both NO3 and TP in all 5 and 4 HUC8s, respectively (Table 3).

Spatially, Illinois HUC8s showed broad patterns of decreasing NO3 yields across the central and northern portion of the State and increasing NO3 yields across the southern portion of the State (Figure 7). For TP, decreasing yields were mainly limited to the northeast portion of the State, with most of the State showing increasing TP yields, including all but two HUC8s in the southern portion of the State (Figure 7). The spatial pattern of temporal changes in nonpoint source yields largely reflect those of the total yield for NO3 (Supplemental Materials, Figure SM1). The temporal changes in nonpoint source TP yields did not show a consistent spatial pattern and were widespread across the State. Some HUC8s that had decreasing total TP yields had corresponding increasing nonpoint source yields. HUC8s with decreasing point source NO3 and TP yields were widespread across the State with the largest decreases in point source yields occurring in the Des Plaines HUC8 for both NO3 and TP (Supplemental Materials, Figure SM2).

Four HUC8s were sinks for NO3 or TP or both during the most recent period: Lower Illinois-Senachwine Lake and Lower Illinois for both NO3 and TP, Middle Kaskaskia for NO3, and Lower Sangamon for TP. Both Lower Illinois HUC8s were sinks for TP during the baseline and recent periods. All three of the HUC8s that were sinks for NO3 loads during the recent period were previously sources during the baseline period. This was also the case for TP in the Lower Sangamon.

Changes in NO3 yields were related to the direction and magnitude of change (Figure 8). All HUC8s with high baseline NO3 yields (>= 17 lbs/acre/yr) had NO3 yield remain stable or decrease by the recent period. Increases in NO3 yield only occurred for HUC8s with yields less than 17 lbs/acre/yr. Improvement in high yield HUC8s was apparent for nonpoint and point source yields. Point source NO3 yields show larger decreases coinciding with higher baseline yields. Changes in TP yields were less correlated to baseline yields due to the overall higher number of HUC8s with increases in TP yield (Figure 8). The two HUC8s with the highest baseline TP yields had decreases in the total yield that were due to decreases in nonpoint and point source yields combined. Similar to NO3 point source yields, higher TP point source yields during the baseline period relate to larger decreases in point source yields over time. However, these decreases were often not enough to offset the nonpoint source TP increases occurring at the same time (Figure 8).

When summed over the entire State, NO3 and TP showed different directions of change in average annual total and nonpoint source loads, whereas point source loads decreased for both constituents. In aggregate, the summed average annual NO3 total load decreased from 451 to 409 million lbs/yr (9% reduction) between the baseline and recent periods, nonpoint source loads decreased from 365 to 334 million lbs/yr (8% reduction) and point source loads decreased from 85 to 75 million lbs/yr (12% reduction). Conversely, the average annual TP total loads increased from 39 to 50 million lbs/yr (25% increase), nonpoint source loads increased from 25 to 39 million lbs/yr (36% increase), while point source loads decreased from 15 to 11 million lbs/yr (27% reduction).

3.2.2 DP percentages

Over the entire State, the average annual DP loads (as a percentage of the TP load) changed minimally between baseline and recent periods (average DP change was <1%). The DP load percentages decreased at 15 HUC8s, were stable at 13 HUC8s, and increased at 21 HUC8s. Spatially, the amount of DP generally increased as a percentage of TP in the southern and eastern portions of the State (Supplemental Materials, Figure SM3). Relative to their respective baseline percentages, the fraction of DP in the TP loads (DP:TP) generally increased in HUC8s with lower baseline DP:TP percentages and remained stable or declined at sites with higher baseline DP:TP percentages, which was similar to the pattern observed for NO3 yields (Supplemental Materials, Figure SM4).

3.2.3 Water yields

The average water yield increased from 13.7 to 16.3 in/yr (19% increase) from 1997–2011 (baseline) to 2018–2022. Water yields were consistently higher across the State during 2018–2022

(Supplemental Materials, Figure SM5). Water yields increased at 39 HUC8s, were stable at 9 HUC8s, and decreased at 1 HUC8 (Supplemental Materials, Figure SM6). Spatially, water yield increases were greater in the most southern and northern portions of the State and smaller in the middle of the State.

3.2.4 Correlation analysis

The correlation analysis among NO3, TP, DP percentages, point source load percentages, and water yield and yield components (total, nonpoint source, and point source), and metrics (baseline values and changes) indicate some potential effects on the observed magnitudes and changes in NO3 and TP loads and yields across Illinois watersheds (Supplemental Materials, Figure SM7). Temporal changes in NO3 and TP yields were strongly correlated with changes in nonpoint source yields ($r = 0.89$ and 0.86, respectively), and weakly correlated with changes in point source yields ($r = 0.22$ and 0.22, respectively), reflecting a substantial effect of changes in nonpoint sources on nutrient yields. Baseline NO3 yields had a moderate negative correlation with changes in NO3 yields ($r = -0.54$), indicating that NO3 yields from critical HUC8s (i.e., those with greater baseline NO3 yields) generally had decreases (or smaller increases) over time while those with lower baseline NO3 yields had greater increases. Changes in yields were also correlated with baseline yields for TP, but this relation was largely driven by a few extreme values (Figure 7). Finally, although almost every HUC8 had water yield increases between baseline and recent periods (Figure SM5), temporal changes in NO3 and TP nonpoint source yield were only weakly correlated with changes in water yield ($r = 0.23$ and 0.38, respectively).

4. Discussion

4.1 Key findings

NO3 yields were higher in central and northern Illinois than southern Illinois, while TP yields showed a reverse pattern, with higher TP yields occurring in southern Illinois. An exception to this spatial distribution was the Chicago area, which had high yields for both NO3 and TP. Nonpoint sources were the main contributor of the NO3 and TP yields for a majority of the HUC8s in Illinois from 2018–2022. Relatively few HUC8s had point source yields that were the main contributor to the total yield; however, where they did occur, these HUC8s had some of the highest NO3 and TP yields in the State (e.g., Chicago, Des Plaines, and Upper Sangamon HUC8s).

Between the baseline (1997–2011) and recent (2018–2022) periods, the spatial pattern of nutrient yields did not vary substantially. Although the NO3 and TP spatial patterns remained stable from the baseline to the recent period, the magnitude of the individual HUC8 loads changed. NO3 loads across the State decreased by 8% from 1997–2011 to 2018–2022 due to reductions in both point and nonpoint sources. NO3 yields declined mainly in the northern and central portion of the State, and much of this decline occurred in HUC8s that had higher NO3 yields (>17 lbs/acre/yr) during the baseline period (1997–2011). For TP, the changes in individual HUC8 loads led to a 25% increase in the sum of all estimated HUC8 TP loads across the State. The HUC8s with increased TP loads and yields were generally located in the southern portion of the State. Although HUC8 TP loads increased, point sources were found to be decreasing statewide for both NO3 and TP, with 12% and 27% reductions in the sum of all estimated HUC8 point source loads for NO3 and TP, respectively.

4.2 Interpretations and Implications

The areas of higher NO3 yields (i.e., north-central Illinois) and TP yields (i.e., southern Illinois) matched the same Major Land Resource Areas (MLRAs) indicated in the initial NLRS 2015 report (IEPA et al., 2015). MLRAs are geographically associated land resource units based on climate, soils, and land use. The 2015 NLRS report found that MLRA 4 (located in north-central Illinois) had the greatest corn and soybean yields in the State, along with widespread tile drainage. Using fertilizer sale and crop yield data, this report found that NO3 yields per row crop acre were greater in this area of Illinois than in southern Illinois, mainly due to tile drainage (McIsaac and Hu, 2004). The associated NO3 load per row crop acre may explain the higher NO3 yields in that portion of the State. Although fertilizer application rates on cropland were relatively similar across the State, MLRAs 5, 6, 8, and 9 in the southern portion of the State had greater TP losses per row crop acre than their northern counterparts, which may explain the high nonpoint source TP yields in the southern portion of the State. The lack of change in this pattern from the baseline to the recent period indicates that elevated NO3 and TP losses in these areas likely remain.

For NO3, decreases in total loads and yields were observed in the HUC8s with higher initial yields. Crawford et al. (2019) also reported a decrease in high NO3 yielding basins within the broader Mississippi River Basin from 1992 to 2012. Spatially, the overall decline in NO3 loads and yields was due to declines in point sources in the Chicago area HUC8s and nonpoint sources in the north-central part of the State. Due to the high percentage of agriculture and nonpoint sources in the north-central part of the State, possible mechanisms for this decline include improved nutrient management, increased nitrogen uptake by new varieties of corn leading to lower nitrogen losses, favorable weather for crop production, or some combination of these (Haegele et al., 2013; Mueller et al., 2019; Ren et al., 2022). Furthermore, this decline occurred during a period of increased water yields, which would have been expected to increase NO3 loads and yields even if concentrations remained stable. Alternatively, increases in NO3 yields were limited to HUC8s with lower baseline NO3 yields (less than 17 lbs/acre/yr) typically located in the southern portion of the State.

For TP, the HUC8s with increased loads and yields were generally located in the southern portion of the State. Increases in TP and NO3 yields in this part of the State were mainly driven by increases in nonpoint sources (Figure 8). One potential explanation for the nonpoint source load increase was the increase in discharge in the southern portion of the State. There was a greater increase in water yields (relative to the north-central portion of the State) (Figure 6) and a widespread increase in peak flows in the southern portion of the state from 1991 to 2020 (Figure 10 in Marti and Over, 2024). In watersheds where nutrient loads are dominated by nonpoint nutrient sources, the nutrient loads are transport limited and directly linked to surface runoff (Moatar et al., 2017). In the case of transport limitation, greater discharge will lead to increases in load, even if nutrient concentrations remained stable. However, water yields also increased in the north-central portion of the State (albeit at a smaller magnitude than the southern portion of the State) and water yield changes were not well correlated with changes in TP or NO3 yields, indicating other factors may be contributing to the increased nutrient yields in the southern portion of the State. Other factors affecting TP yields may include increased tile drainage, reduced till agriculture (reduced incorporation of fertilizer P into soils), and confined animal feeding operations (CAFOs), which have all been shown to increase DP or TP losses (Gentry et al., 2007; Jarvie et al., 2017; King et al., 2015; Ni et al., 2020; Waller et al., 2021). Additionally, precipitation events directly after widespread application of phosphorus fertilizer can also increase DP concentrations, and peak streamflows have been increasing in the winter and spring seasons in Illinois (Gentry et al., 2007; Marti and Over, 2024). The southern HUC8s with increasing TP yields also showed increasing DP:TP ratios supporting these potential mechanisms as well.

A small number of HUC8s were found to be nutrient sinks. These HUC8s were generally positioned the lowest in their respective watersheds where lower gradients would allow time for settling of suspended material to remove TP and biogeochemical processes to remove NO3. However, these sinks were also associated with HUC8s that have large incoming loads, and the incremental loads for these HUC8s are estimated by subtracting upstream water-quality site loads from downstream loads. As such, the small negative total loads relative to the upstream load produced for these HUC8s may be the product of estimation errors, and the true values may range from small sinks to small sources. Nevertheless, these HUC8s may be viewed as areas of low priority for targeted nutrient reduction strategies.

For the Illinois NLRS, our results indicate that reductions occurred in point sources of both NO3 and TP and in nonpoint sources of NO3. However, nonpoint sources of TP were still increasing statewide.

For drivers of these changes, our results indicate that some increases in nutrient loads may be attributed to increases in water yields across the State. But increases in water yield do not account for all the increases observed statewide – especially in the southern portion of the State. Additionally, while the large TP and NO3 loads released via point sources is a concern locally, our results showed that approximately 80% of the NO3 and TP loads leaving Illinois originate as nonpoint sources. Based on our results, the Illinois NLRS may be most successful at reducing nutrient export from the State if the focus remains on reducing nonpoint source losses, particularly in regard to TP loads.

4.3 Limitations and Opportunities for Further Analysis

Study limitations were mainly related to methods. First, estimating loads involves uncertainty that was not quantified in this study. While we used the best method available to estimate loads at water-quality sites (i.e., WRTDS-K), uncertainty is still associated with these loads. This uncertainty could affect the HUC8 loads and yields estimated in the paper, especially those estimated via subtraction from other water-quality sites or averages of yields from neighboring HUC8s. The use of multiple different estimated loads has the potential to propagate errors associated with these loads. Second, the focus on HUC8 loads and yields meant we had to extrapolate water-quality site loads to HUC8 watersheds, and extrapolation has the potential to produce errors in estimation. Third, and perhaps most critically, the baseline period point source data were only available in 2011. These older data were propagated backwards to 1997 to calculate the average annual total HUC8 values according to the previously used method. There is a high potential that the single year of 2011 does not appropriately represent the actual average point source load over this period. If point sources of NO3 and TP had been declining from 1997 to 2011, then our baseline point source loads were likely to be underestimated, which in turn would mean that even greater improvements in point source yields have occurred than what has been shown here. However, it would also have caused an overestimation of the baseline nonpoint source yields, which would have affected the trends in nonpoint sources and potentially change the conclusions presented here. Fourth, converting loads from water-quality sites to HUC8s also assumes a negligible amount of in-stream TN or TP removal by biogeochemical process between the point source discharge and the outlet of the monitoring location or the HUC, which has the potential to overestimate point source and underestimate nonpoint source loads and yields in settings where these processes are substantial. Although the methods were a source of limitations for the study, the sums of estimated incremental NO3 and TP loads across the 49 Illinois HUC8s (410 and 50 million lbs/yr, respectively) between 2018 and 2022 roughly matched the statewide loads from 2017–2021 estimated by Hodson (2023) using USGS continuous monitoring sites and a state-of-the-art Bayesian model (416 and 46 million lbs/yr, respectively). The similar values between our estimates and the published statewide estimates indicate that the methodology used in this report was appropriate enough to make relative comparisons.

Finally, this study did not quantitatively analyze the effects of landscape characteristics (e.g., slope, land cover, reservoirs) on variation in nutrient yields. Future analysis could be conducted using load estimates at river monitoring sites rather than HUC8 estimates, which would remove a source of uncertainty from this approach. Research could focus on the causes of the increased NPS TP yields and reductions in the NO3 yields from sites that had high yields in the baseline period. Additionally, the statistical evaluation of multivariate interactions among influential factors could provide needed causal linkages.

5. Conclusions

In the recent period (2018–2022), NO3 loads and yields were generally largest in the central and northern portion of Illinois, while TP loads and yields were largest in the southern portion of the State – mainly due to high nonpoint sources of both nutrients. An exception to this general spatial pattern was the Chicago area, where both NO3 and TP loads and yields are high due to high point source loads. When HUC8 loads were summed over the entire State, nonpoint sources made up approximately 80% of the total NO3 and TP loads, with point sources dominating in a few urbanized HUC8s. Between the periods of 1997–2011 to 2018–2022, the sum of the 49 Illinois HUC8 NO3 loads decreased 9% despite a 19% increase in water yield. Much of this decline occurred in HUC8s that had NO3 yields > 17 lbs/acre/yr during 1997–2011. During the same period, the TP load summed across all 49 Illinois HUC8s increased 25% despite a 27% reduction in point source discharge. Total TP yields increased in most HUC8s from 1997–2011 to 2018–2022 despite substantial reductions in point source discharge across the State. The percentage of total TP load attributable to point sources decreased from 38% for 1997–-2011 to 22% in 2018–2022. In general, point source yields mostly decreased over time regardless of nutrient type, while nonpoint source yields varied depending on location but reflect the changes in the total yield. Finally, there was a small correlation with water yields, but other factors were likely present to cause the changes observed between 1997–2011 and 2018–2022.

6. Disclaimer

This information product has been peer reviewed and approved for publication as a preprint by the U.S. Geological Survey. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Tables

Table 1: 49 eight-digit hydrologic unit code (HUC8) watersheds and corresponding water-quality sites (U.S. Geological Survey [USGS] and Illinois Environmental Protection Agency [IEPA] site numbers) and USGS streamgages used in this study). Table SM-2 in the Supporting Material contains detailed information about the computation method applied to each HUC8. NA, not applicable.

HUC8	HUC8 Name	USGS Site Number	IEPA site ID	Computational method
05120109	Vermilion	03339000	BP-01	1
05120115	Skillet	03380500	CA-05	1
07110004	The Sny	05512500	KCA-01	1
05140204	Saline	03382100	ATH-05	1
07060005	Apple-Plum	05419000	MN-03	1
07080104	Flint-Henderson	05469000	LD-02	1
07090003	Pecatonica	05435500	PW-08	1
07090006	Kishwaukee	05440000	PQ-12	1
07090007	Green	05447500	PB-04	1
07110001	Bear-Wyaconda	05495500	KI-02	1
05140203	Lower Ohio Bay	03384450	AK-02	1
07120005	Upper Illinois	05542000	DV-04	1
07130002	Vermilion	05555300	DS-07	1
07130004	Mackinaw	05568000	DK-12	1
07130005	Spoon	05570000	DJ-08	1
07130007	South Fork Sangamon	05576000	EO-01, EO-02, EO-3	1
07130009	Salt	05582000	EI-02	1
07130010	La Moine	05585000	DG-01	1
07130012	Macoupin	05587000	DA-06	1
07140101	Cahokia-Joachim	05587900	JQ-05	1
07140106	Big Muddy	05599490	N-12	1
07140108	Cache	03612000	AD-02	1
07140201	Upper Kaskaskia	05592100	O-10	1
07140203	Shoal	05594000	OI-08	1
05120114	Little Wabash	03381500	C-23	2
05120114	Little Wabash	03380500	CA-05	2
07090005	Lower Rock	05446500	P-04	2
07090005	Lower Rock	05437500	P-15	2
07090005	Lower Rock	05440000	PQ-12	2
07120001	Kankakee	05527500	F-01, F-16	2
07120001	Kankakee	05520500	F-02	2
07120001	Kankakee	05526000	FL-02	2
07120002	Iroquois	05526000	FL-02	2
07120002	Iroquois	05525000	FL-04	2
07120006	Upper Fox	05550000	DT-06	2

07120006	Upper Fox	05545750	DT-35	2
07120007	Lower Fox	05552500	DT-01	2
07120007	Lower Fox	05550000	DT-06	2
07130006	Upper Sangamon	05576500	E-26	2
07130006	Upper Sangamon	05576000	EO-01, EO-02, EO-3	2
07130008	Lower Sangamon	05583000	E-25	2
07130008	Lower Sangamon	05576500	E-26	2
07130008	Lower Sangamon	05582000	EI-02	2
07130011	Lower Illinois	05587060	D-01	2
07130011	Lower Illinois	05586100	D-32	2
07130011	Lower Illinois	05587000	DA-06	2
07140202	Middle Kaskaskia	05594100	O-20	2
07140202	Middle Kaskaskia	05592100	O-10	2
05120108	Middle Wabash-Little Vermilion	03339000	BP-01	3
05120108	Middle Wabash-Little Vermilion	03343400	BE-14	3
07120003	Chicago	05536000	HCC-07	3
07120003	Chicago	05536275	HBD-04	3
07140204	Lower Kaskaskia	05595200	OC-04	3
07140204	Lower Kaskaskia	05594800	OD-07	3
05120111	Middle Wabash-Busseron	NA	NA	4
05140202	Highland-Pigeon	NA	NA	4
05140206	Lower Ohio	NA	NA	4
07080101	Copperas-Duck	NA	NA	4
07090004	Sugar	NA	NA	4
07110009	Peruque-Piasa	NA	NA	4
07130003	Lower Illinois-Lake Chautauqua	NA	NA	4
07140105	Upper Mississippi-Cape Girardeau	NA	NA	4
05120113	Lower Wabash	NA	NA	4
05120112	Embarras	03346500	BE-01	5
05120112	Embarras	03345500	NA	5
07120004	Des Plaines	05537980	G-23	5
07120004	Des Plaines	05527800	G-08	5
07120004	Des Plaines	05540500	GB-11	5
07130001	Lower Illinois Senachwine Lake	05568500	D-05	5
07130001	Lower Illinois Senachwine Lake	05543500	D-23	5
07130001	Lower Illinois Senachwine Lake	05552500	DT-01	5
07130001	Lower Illinois Senachwine Lake	05555300	DS-07	5

Table 2: Average and ranges of Illinois eight-digit hydrologic unit code (HUC8) total, nonpoint source (NPS), and point source (PS) loads (million pounds per year [10^6 lbs/yr]), yields (pounds per acre per year [lbs/acre/yr]), and percentages (%) of total load from NPS and PS for 2018–2022. Data from Kamrath et al. (2025).

Nutrient	Estimation Type	Average Loads (range) n=49	Average Yields (range) n=49	Average % of Total Load (range) n=46
		10^6 lbs/yr	lbs/acre/yr	%
NO3	Total	8.4 (-3.1 - 27.0)	12.1 (-2.1 - 42.1)	-
	NPS	6.8 (-6.5 - 24.0)	9.6 (-7.7 - 28.0)	86.9 (-24.2 - 100)[a]
	PS	1.5 (0.0 - 33.5)	2.5 (0.0 - 43.3)	13.1 (0.0 - 124)[a]
TP	Total	1.0 (-0.6 - 3.8)	1.5 (-0.5 - 10.4)	-
	NPS	0.8 (-0.7 - 3.2)	1.1 (-0.6 - 3.8)	86.7 (-0.8 - 100)[a]
	PS	0.2 (0.0 - 3.6)	0.4 (0.0 - 9.8)	13.3 (0.0 - 101)[a]

[a]Three HUC8s were nutrient sinks (total load < 0 10^6 lbs/yr. These were removed from the percentage of the total load.

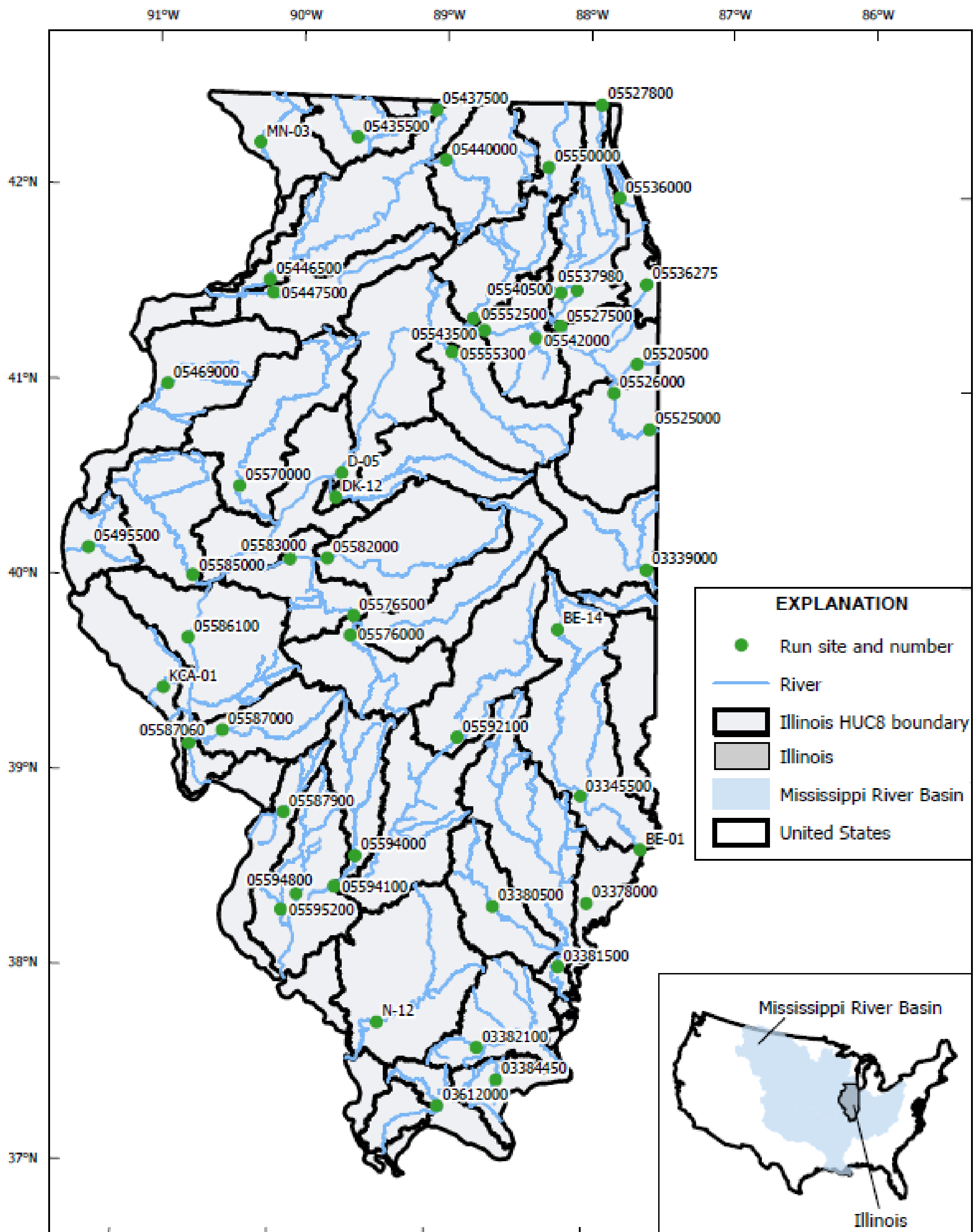
Table 3. Number of Illinois eight-digit hydrologic unit codes (HUC8s; 49 total) by the direction of change in yields between baseline (1997–2011) and recent (2018–2022) periods. Stable, decreasing, and increasing categories are defined as percent changes that are within +/-5%, < -5%, and > 5%, respectively. NO_3, nitrate plus nitrite; NPS, non-point source; PS, point source; TP, total phosphorus. Data from Kamrath et al. (2025)

Nutrient	Type	Decreasing	Increasing	Stable (+/- % 5 change)
NO3	Total[a]	17	22	7
	NPS	15	24	7
	PS	26	5	15
TP	Total[b]	7	31	8
	NPS	9	34	3
	PS	28	4	14

[a]Three HUC8s switched from source (baseline total load > 0 million pounds per year (10^6 lbs/yr) to a sink (recent total load < 0 10^6 lbs/yr).

[b]One HUC8 switched from source (baseline total load > 0 10^6 lbs/yr) to a sink (recent total load < 0 10^6 lbs/yr) and two HUC8s were sinks for both periods (baseline and recent total loads < 0 10^6 lbs/yr).

Figures



Illinois HUC8 boundary from the U.S. Geological Survey, 2023, National Hydrography Dataset (NHD_Illinois_State_GBD), accessed October 2024 at URL http://prd-tnm.s3-website-us-west-2.amazonaws.com/?prefix=StagedProducts/Hydrography/NHD/State/GDB/

Figure 1: Illinois Environmental Protection Agency and U.S. Geological Survey monitoring sites used to estimate water-quality site loads and their associated eight-digit hydrologic unit code boundaries (HUC8).

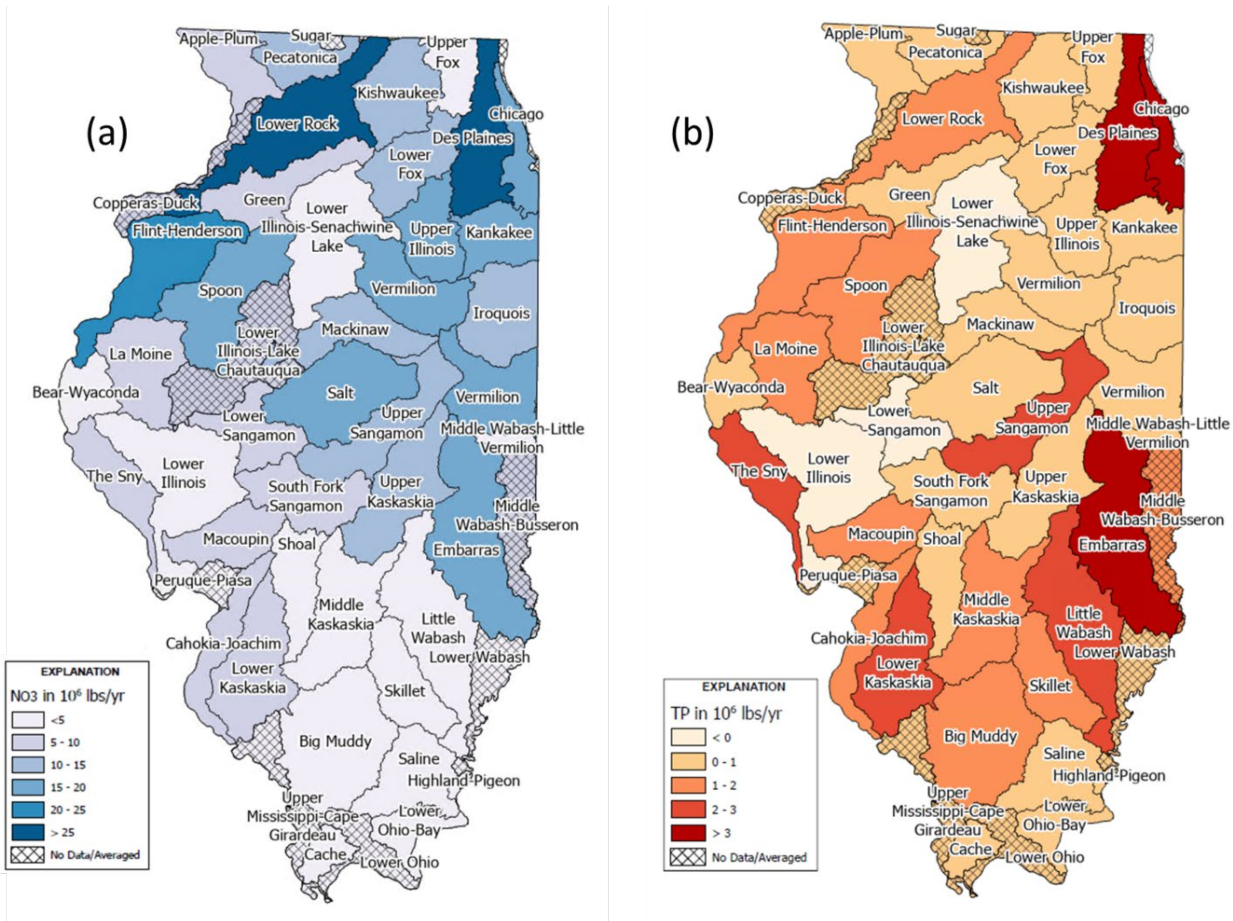


Figure 2: Illinois eight-digit hydrologic unit code (HUC8) average annual (a) nitrate plus nitrite (NO3) and (b) total phosphorus (TP) loads in million pounds per year (10^6 lbs/year) during 2018–2022. Data from Kamrath et al. (2025).

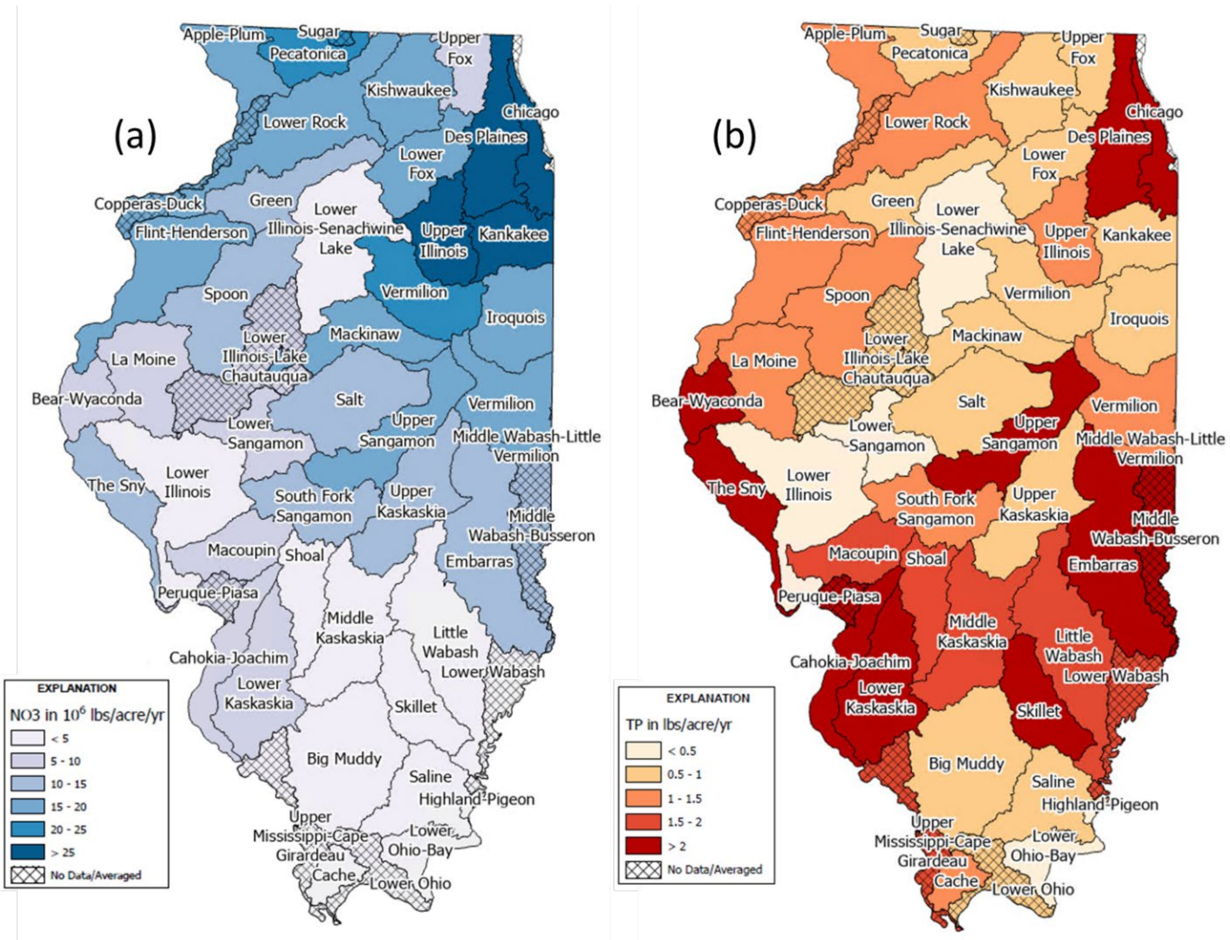


Figure 3: Illinois eight-digit hydrologic unit code (HUC8) average annual (a) nitrate plus nitrite (NO3) and (b) total phosphorus (TP) yields in pounds per acre per year (lbs/acre/yr) during 2018–2022. Data from Kamrath et al. (2025)

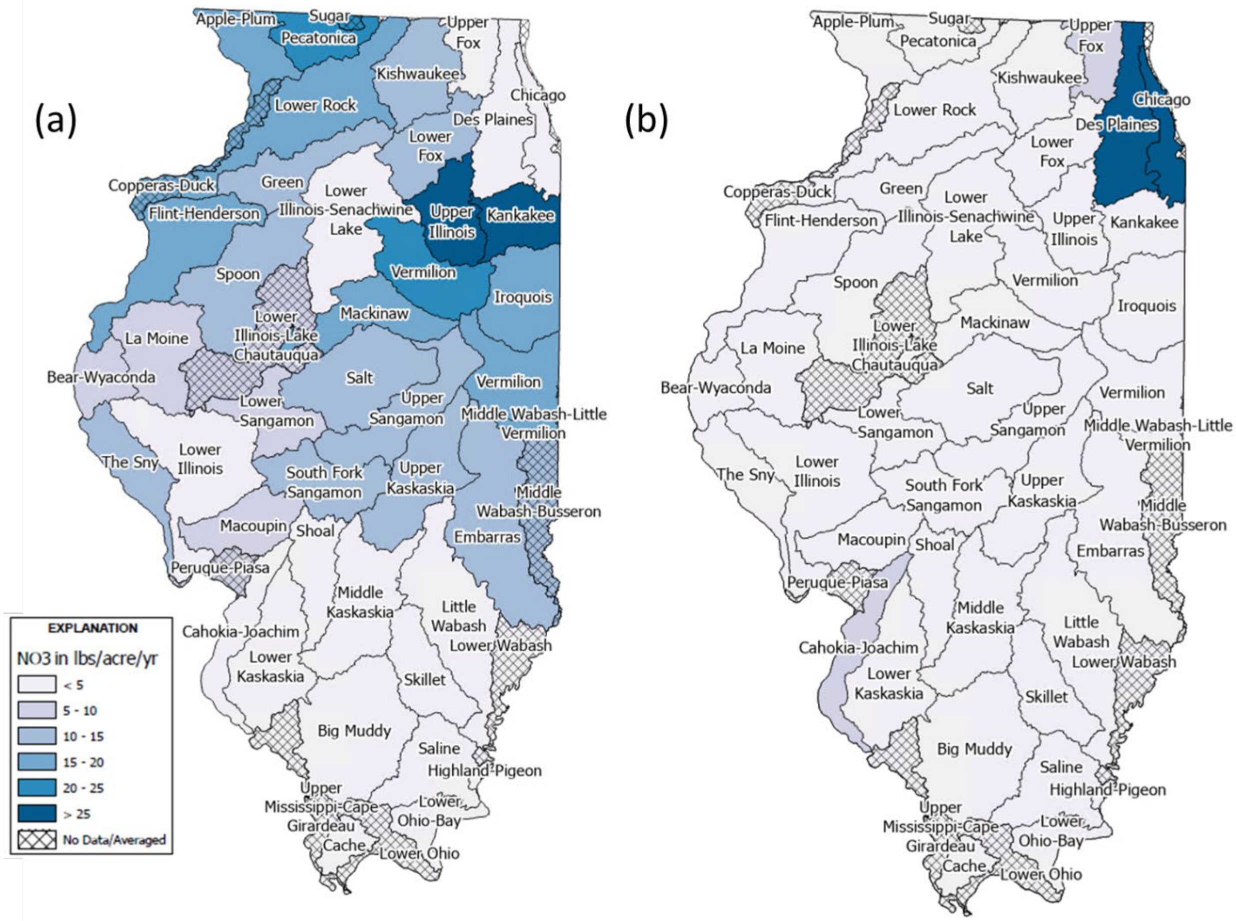


Figure 4: Illinois eight-digit hydrologic unit code (HUC8) estimated average annual (a) nonpoint and (b) point source nitrate and nitrite (NO3) yields in pounds per acre per year (lbs/acre/yr) during 2018–2022. Data from Kamrath et al. (2025).

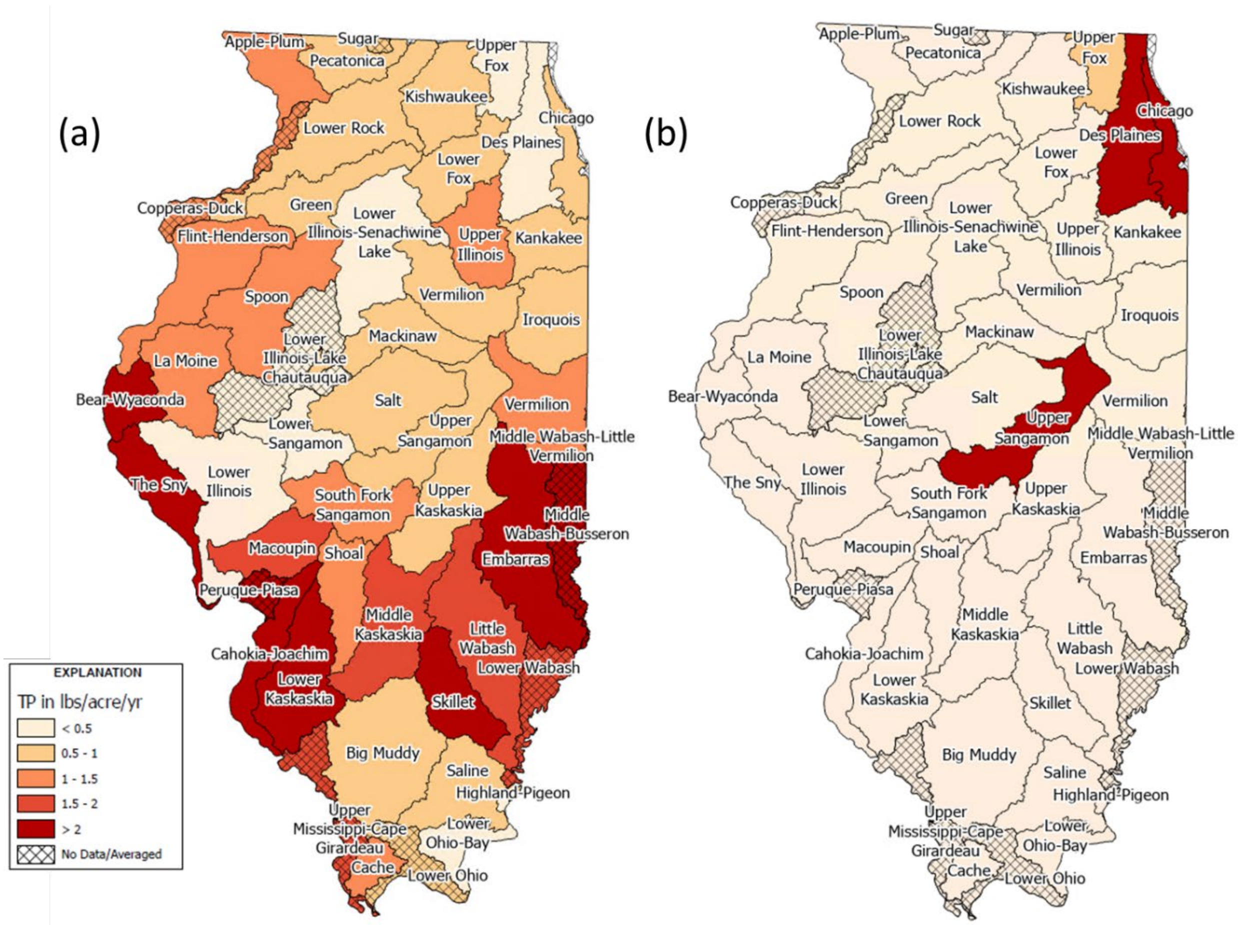


Figure 5: Illinois eight-digit hydrologic unit code (HUC8) average annual estimated (a) nonpoint and (b) point source total phosphorus (TP) yields in pounds per acre per year (lbs/acre/yr) during 2018–2022. Data from Kamrath et al. (2025).

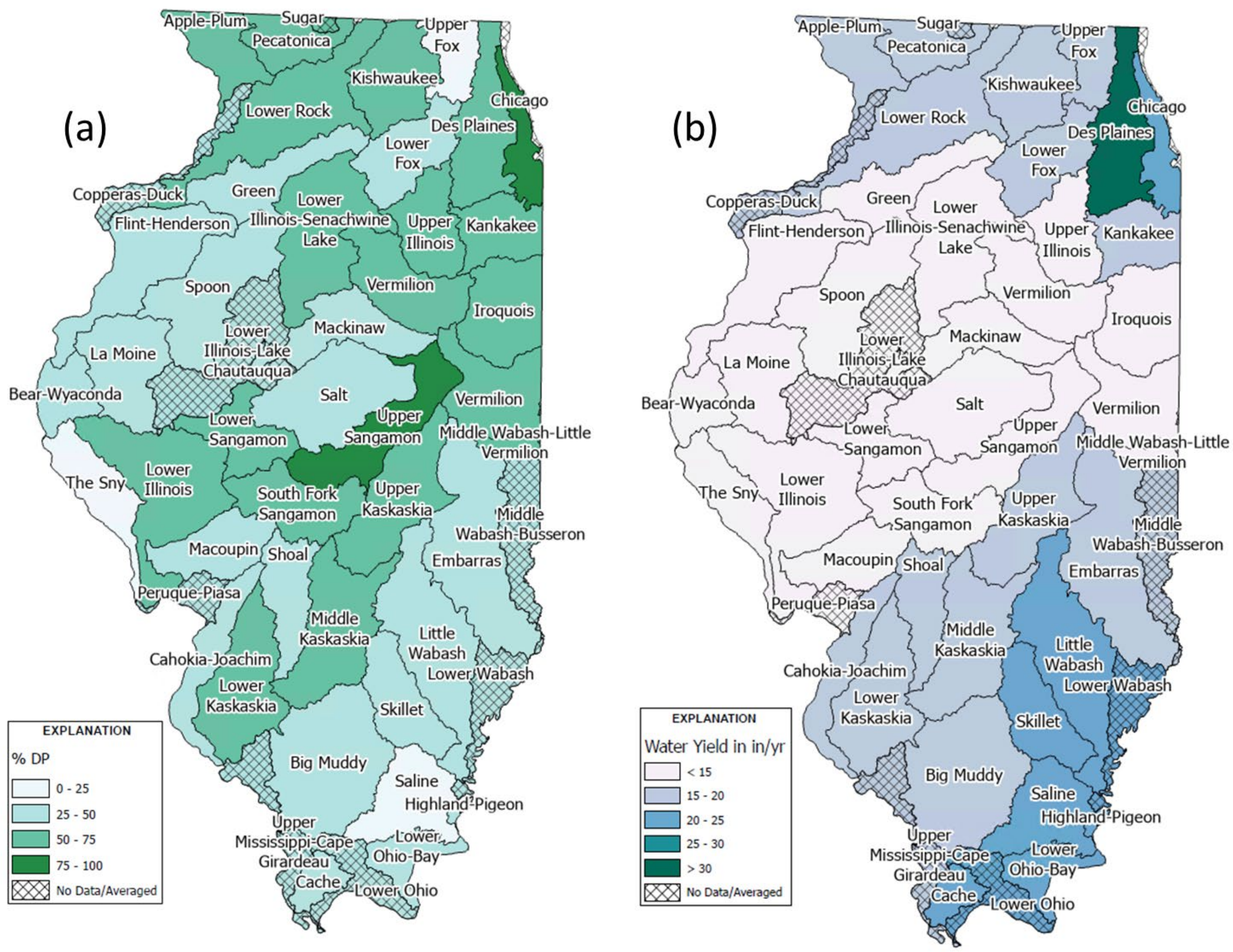


Figure 6: Illinois eight-digit hydrologic unit code (HUC8) estimated average annual (a) dissolved phosphorus (DP) loads in percentage of total phosphorus (TP) loads (% TP) and (b) water yields in inches per year (in/yr) during 2018–2022. Data from Kamrath et al. (2025).

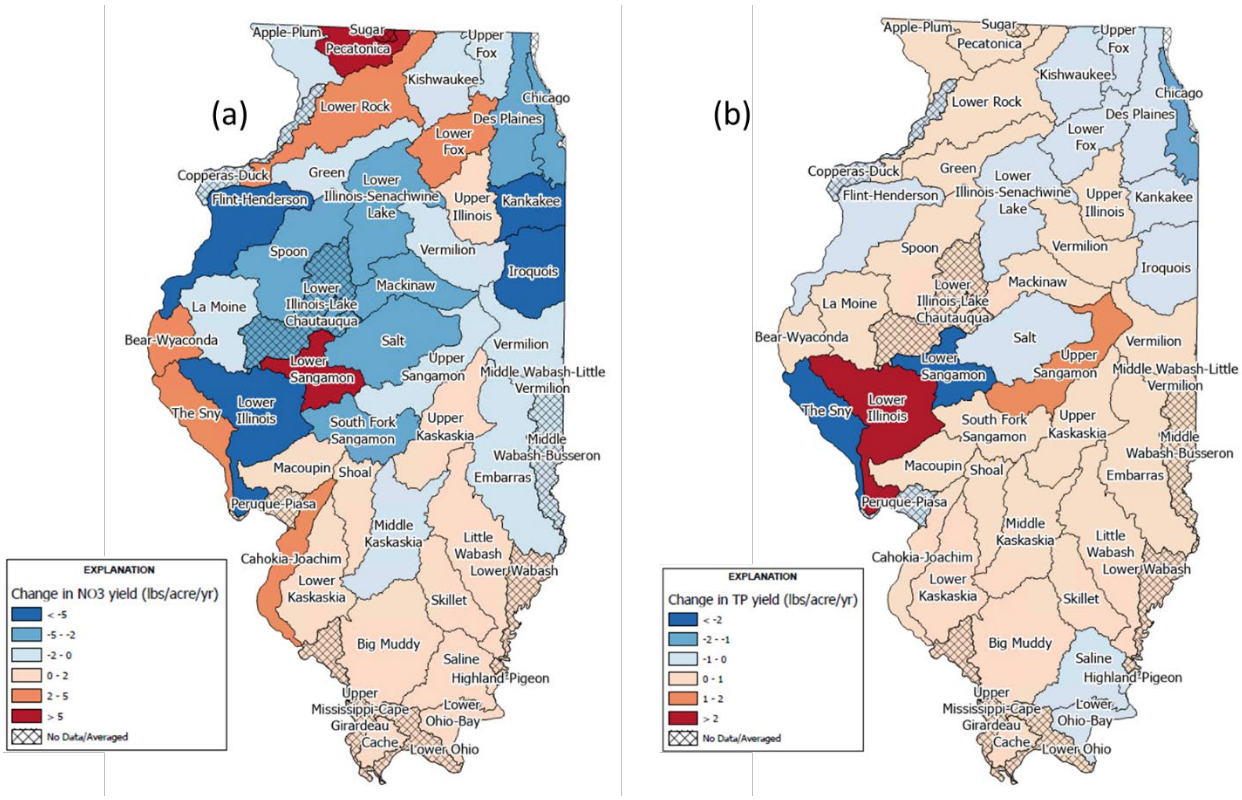


Figure 7: Changes in Illinois eight-digit hydrologic unit code (HUC8) average annual (a) nitrate plus nitrite (NO3) and (b) total phosphorus (TP) yields in pounds per acre per year (lbs/acre/yr) from 1997–2011 to 2018–2022. Data from Kamrath et al. (2025).

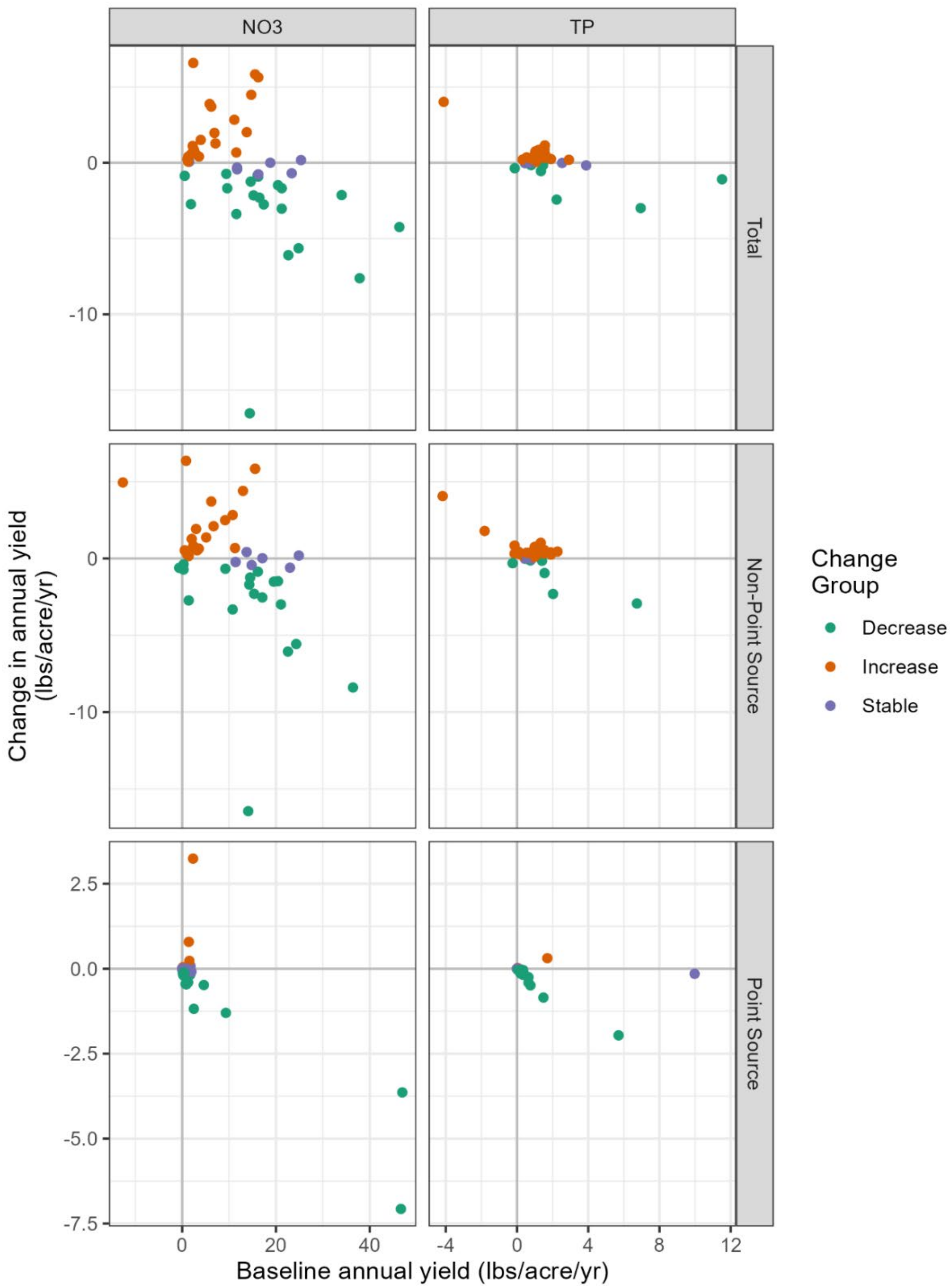


Figure 8. Change between baseline (1997–2011) and recent (2018–2022) in average annual nutrient yields versus baseline (1997–2011) average nitrate plus nitrite (NO3) or total phosphorus (TP) annual yield for all Illinois eight-digit hydrologic unit codes (HUC8s) (except those categorized as sinks), by total, nonpoint source, and point source yields, in pounds per acre per year (lbs/acre/yr). Data from Kamrath et al. (2025).

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Supporting Information

Diverging trends in nitrate and phosphorus loads and yields across Illinois watersheds, 1997–2022

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Water Quality Data Reconciliation and Quality Control

The period of interest for this study was 1997 to 2022. The majority of the data came from the Water Quality Portal (WQP). Data were housed under U.S. Geological Survey (USGS) and Illinois Environmental Protection Agency (IEPA) site numbers in the WQP. Exceptions include sample data from prior to 1999, which were obtained from U.S. Environmental Protection Agency's (USEPA) STORET database, and IEPA sample data not yet uploaded to WQP from 2022, which were obtained directly from IEPA (Trevor Sample, written commun., March 18, 2024). In the WQP, water-quality data for the sites are stored under USGS and IEPA site numbers, often for the same physical location. We reconciled these site numbers within the WQP data and then matched sites from STORET to the reconciled site numbers. With the addition of STORET data, we extended the beginning of the records for 12 sites from 1998 back to 1973 and filled small gaps in the WQP data for 42 sites.

Data from the WQP and IEPA were provided using constituent names, whereas STORET data used USGS parameter codes (p-code). Table SM-1 shows a list of all the constituent names related to nitrate, total phosphorus, and dissolved phosphorous from the WQP, STORET, or IEPA and the priority we assigned these names for use in the compiled dataset. Utilizing this table and the priority ranks allowed us to harmonize constituent names and units while also removing duplicate information. For example, for two samples collected at the same date and time with constituent names of "Phosphate-phosphorus" and "Phosphorus," we prioritized the sample with the constituent name "Phosphorus" and removed the other sample. Data from all three sources were converted to standardized units: milligrams per liter as nitrogen (mg/L as N) or as phosphorus (mg/L as P).

Data from the WQP and IEPA included information on detection limits and if a record was left-censored. The STORET data did not include this information. To identify censored values within the STORET data, we marked all samples with values less than the highest reporting limit as a non-detect (i.e., left-censored). The highest reporting limit was based on the WQP data of each combination of site and constituent. If none of the data were censored in the WQP for a given site and constituent the highest reporting limit for that constituent was derived from the entire dataset.

Missing and zero values, samples identified as field replicates and composites, and duplicated samples were removed from datasets. We also prioritized constituent and method during the duplication resolution process (Table SM-1). Because the data will be used in a load model that runs on a daily time-step, if a constituent was sampled multiple times on the same day at the same site, one randomly selected sample was retained and the remaining dropped. Data from the WQP were always prioritized over STORET data when removing duplicates or selecting a single sample for each day, because WQP contains the most complete record of USGS and IEPA water-quality samples. Finally, the date range was dependent on data availability at each site and constituent (refer to runs table in Podzorski et al. (2025).

Table SM-1. Constituent names and priority rankings. P-Code, parameter code; USGS, U.S. Geological Survey; mg/L, milligrams per liter; N, nitrate, IEPA, Illinois Environmental Protection Agency; P, phosphorus; ug/L, micrograms per liter; PO4, phosphate.

Agency	Original Constituent Name	Standard Name	P-Code	Original Units	Conversion Factor	Priority
USGS	Inorganic nitrogen (nitrate and nitrite)	Nitrate + Nitrite	00630	mg/L as N	1	1
IEPA	Inorganic nitrogen (nitrate and nitrite) ***retired***use Nitrate + Nitrite	Nitrate + Nitrite	NA	mg/L	1	2
IEPA	Inorganic nitrogen (nitrate and nitrite) as N	Nitrate + Nitrite	NA	mg/L	1	1
USGS	Nitrate	Nitrate + Nitrite	00620	mg/L as N	1	2
IEPA	Nitrate + Nitrite	Nitrate + Nitrite	NA	mg/L	1	1
IEPA	Phosphorus	Phosphorus, Dissolved	NA	mg/L	1	1
USGS	Phosphorus	Phosphorus, Dissolved	00666	mg/L as P	1	1
USGS	Phosphate-phosphorus	Phosphorus, Dissolved	00653	mg/L	0.3261*	2
IEPA	Phosphate-phosphorus as P	Phosphorus, Dissolved	NA	mg/L	1	2
IEPA	Phosphate-phosphorus as P	Phosphorus, Dissolved	NA	ug/L	0.001	2
USGS	Phosphorus	Phosphorus, Dissolved	99893	mg/L	1*	2
IEPA	Phosphorus	Phosphorus, Total	NA	mg/L	1	1
USGS	Phosphorus	Phosphorus, Total	00665	mg/L as P	1	1
USGS	Phosphate-phosphorus	Phosphorus, Total	00650	mg/L	0.3261*	2
IEPA	Phosphate-phosphorus as P	Phosphorus, Total	NA	mg/L	1	2
IEPA	Phosphate-phosphorus as P	Phosphorus, Total	NA	ug/L	0.001	2
USGS	Phosphorus	Phosphorus, Total	99891	mg/L	1*	3
USGS	Phosphorus	Phosphorus, Total	71886	mg/L PO4	0.3261	3

* Units included in data source and units associated with p-code did not match. Unit conversion was based on p-code units.

Streamflow Data

Two streamgages (USGS site number 05469000 and 05542000) had more than 30 consecutive days of missing discharge data (U.S. Geological Survey, 2024), and the analysis date ranges were truncated to accommodate. For one water-quality site on the Fox River, two streamgages were used: the discharge record at Fox River at Algonquin, Illinois (05550000), which ended after water year 2009, and discharge at Fox River (Tailwater) at Algonquin, Illinois (05550001), which was used to continue the record (U.S. Geological Survey, 2024). Across the entire dataset, there were 2,363 zero or negative daily values, which equates to 0.3% of the entire discharge dataset. The USGS streamgage with the most zero or negative values (n = 695) was 03378000, which accounted for only 4% of the daily discharge record at this streamgage. Negative values were replaced with zeros in the dataset.

Five water-quality sites and streamgages were not collocated, and point sources were present between the water-quality site and streamgage. For these situations, discharge values were scaled to better represent flows at the water-quality site. For four of the five water-quality sites (BE-01, D-05, DK-12, and KCA-01), daily discharge was scaled by multiplying the ratio of drainage area between the water-quality site and the streamgage. For one site (Illinois River at Hardin, Illinois; 05587060), daily discharge (Q) was estimated by adding the discharge at Illinois River at Valley City, Illinois (05586100) to scaled daily discharges at Macoupin Creek near Kane, Illinois (05587000):

$$Q_{05587060} = Q_{05586100} + (2.24)Q_{05587000} \qquad \text{Equation S1}$$

The scaling value was derived from the difference between Illinois River at Hardin, Illinois, and Illinois River at Valley City, Illinois, drainage area, which is 2.24 times greater than the drainage area of Macoupin Creek near Kane, Illinois (868 sq mi). The processed daily discharge dataset is available in Podzorski et al. (2024).

Weighted Regressions on Time, Discharge, and Season (WRTDS) Model Specifications

Default model specifications were used except for the following: (1) half-window width in the discharge dimension (windowQ) = 1, (2) the minimum number of observations required to run the weighted regression (minNumObs) = 100 if the number of samples was greater than 100, otherwise 0.75 times the number of samples rounded to the nearest whole number was used, and (3) the minimum number of uncensored observations to run the weighted regression (minNumUncen) = 50 if minNumObs was set to 100, otherwise half of the minNumObs.

Extrapolation Metrics

We computed three metrics for each model that indicated the potential for extrapolation issues: flux bias, extrapolation metric, and high discharge metric. The flux bias statistic was estimated by dividing the sum of the estimated flux (here, the flux is equivalent to the load) by the sum of the sampled flux on days with samples. The extrapolation metric was estimated by dividing the maximum estimated concentration by two times the maximum sampled concentration. High discharge was defined as the 85th percentile of the 15-year monthly discharge (refer to Oelsner et al., 2017, page 71). To match WRTDS model windows, 15-year intervals were used. We assumed that any sampling schedule with less than 10% of total samples being collected during high discharges as a sampling schedule that may lead to model extrapolations.

HUC8s with drainage areas outside of Illinois

Following previous Nutrient Loss Reduction Strategy (NLRS) efforts, nutrient loads from areas outside of Illinois were excluded from HUC8 aggregation. Nineteen watersheds with eight-digit hydrologic unit codes (HUC8s) had less than 70% of their drainage areas within Illinois. For seven of these HUC8s, we assumed that point sources from outside of Illinois were minimal within the water-quality site drainage areas. The nonpoint source site yields were calculated by subtracting Illinois point sources within the drainage area from the total estimated load at the site and dividing by the entire site drainage area. There is a potential that our nonpoint source site yields were overestimated due to this assumption. These nonpoint source site yields were then assumed to be the HUC8 nonpoint source yield. This HUC8 nonpoint source yield was multiplied by the HUC8 drainage area within Illinois to obtain the Illinois HUC8 nonpoint source load. The point source loads in Illinois within the HUC8 were then summed and added to the Illinois HUC8 nonpoint source load to estimate the total Illinois HUC8 load. For three of these HUC8s, the load delivered from the portion of the HUC8 outside of the State was subtracted from the portion of the HUC8 inside Illinois's boundaries by identifying a water-quality site near the border and subtracting the load at this site. For example, the Iroquois River HUC8 straddles the border between Illinois and Indiana. To remove the portion of the load originating in Indiana, the water-quality site load from the Iroquois River at Iroquois, Illinois (05525000), which contains the Indiana portion of the HUC8, was subtracted from the water-quality site load at the Iroquois River at Chebanse, Illinois (05526000) as part of the incremental HUC8 load calculation. The final nine HUC8s with areas outside of Illinois were all HUC8s that did not have water-quality sites located in the HUC8 and were therefore estimated by averaging the nonpoint sources yields from nearby Illinois HUC8s.

Computational Methods from Water-Quality Site Loads to Hydrologic Unite Code 8 (HUC8) Loads.

Five different methods were used to convert water-quality site loads to HUC8 loads and yields (Table SM-2). These methods were derived from McIsaac (2019). Methods 1–4 were described in our manuscript. Method 5 details are described below.

Table SM-2. Computation methods for converting water-quality site loads to Hydrologic Unit Code 8 (HUC8) loads and yields.

Computational method	Description	Number of HUC8s
1	Directly computed using a single associated ambient site load divided by the ambient site drainage area.	24
2	Computed by subtracting one or multiple upstream ambient site loads from a single downstream ambient site load and dividing by the incremental area	11
3	Computed using weighted average of multiple associated incremental yields directly computed using method 1.	3
4	No water-quality sites were located within the HUC8. HUC8 loads and yields computed using average of nearby HUC8 loads and yields. List of HUC8s used in averages available in Kamrath et al. (2025).	9
5	Computed using miscellaneous methods	3

Method 5 sites included Embarras (05120112), Lower Illinois-Senachwine Lake (07130001), and Des Plaines (07120004). For Embarras, water-quality data were switched from Embarras at Ste Marie (run site: 03345500) to Embarras at Lawrenceville (run site: BE-01) in 2002. For water years after 2002, water-quality site loads were directly computed using water-quality data from Embarras at Lawrenceville. For water years before 2002, water-quality site loads were predicted from Embarras at Ste Marie water-quality site yields using linear relations between annual water-quality yields between Embarras at Ste Marie and Embarras at Lawrenceville between 2002 and 2017. For Lower Illinois-Senachwine Lake, the HUC8 loads were calculated using a modified method 2 with the water-quality loads from Illinois River at Pekin (WQ site: D-05) and scaled streamflow (using drainage area ratio) from Illinois River at Kingston Mines (05568500) minus water-quality loads from Illinois River at Marseilles (05543500) and the Fox River at Dayton (05552500) and the Vermilion River at Leonore (05555300). For Des Plaines, a modified method 2 was also used with water-quality loads from Des Plaines at Joliet (05537980) minus water-quality loads from Des Plaines at Russell (05527800) plus water-quality loads from DuPage at Shorewood (05540500) minus the load from the Chicago HUC8 (07120003).

Figures

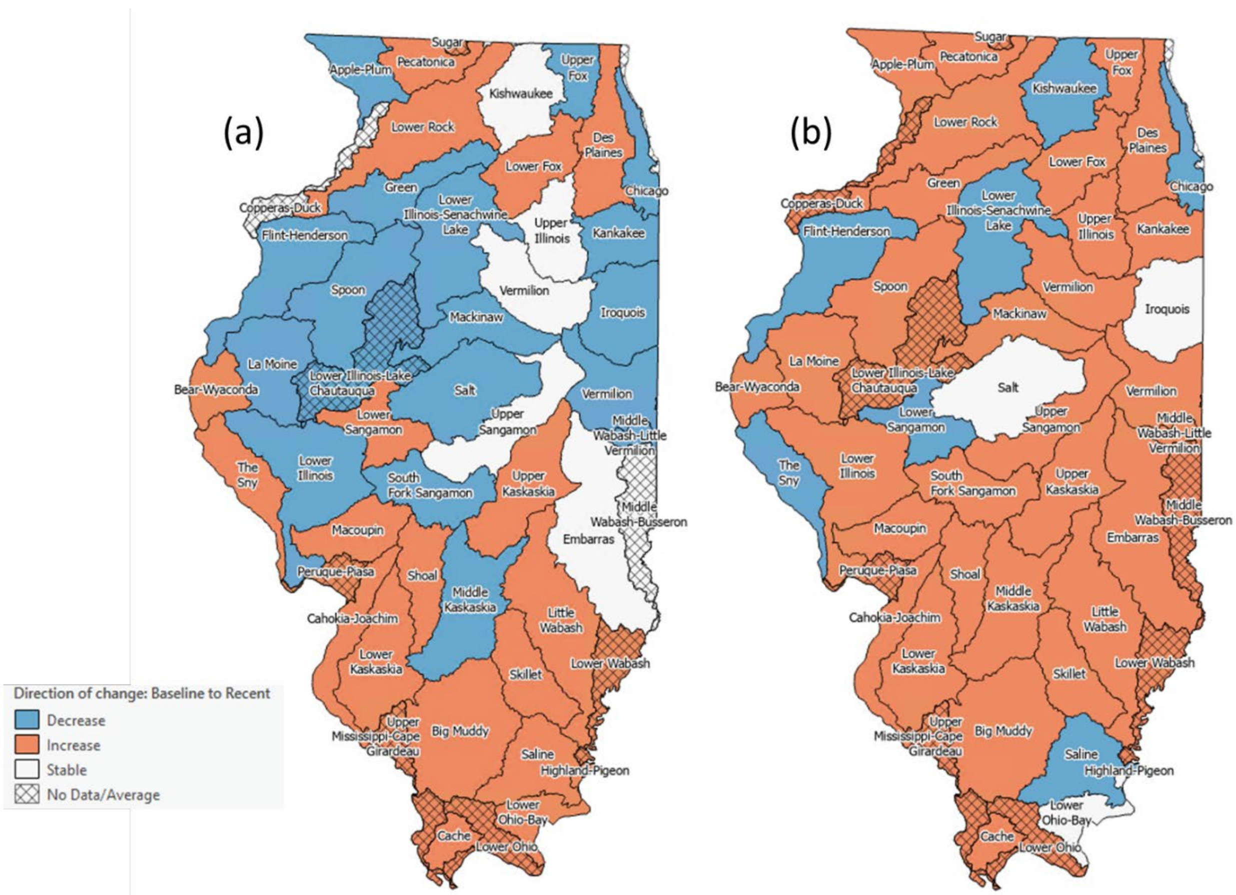

Figure SM1: Changes in Illinois of Hydrologic Unit Code 8 (HUC8) average annual (a) nitrate plus nitrite and (b) total phosphorus nonpoint source yields in pounds per acre per year (lbs/acre/yr) from 1997–2011 to 2018–2022.

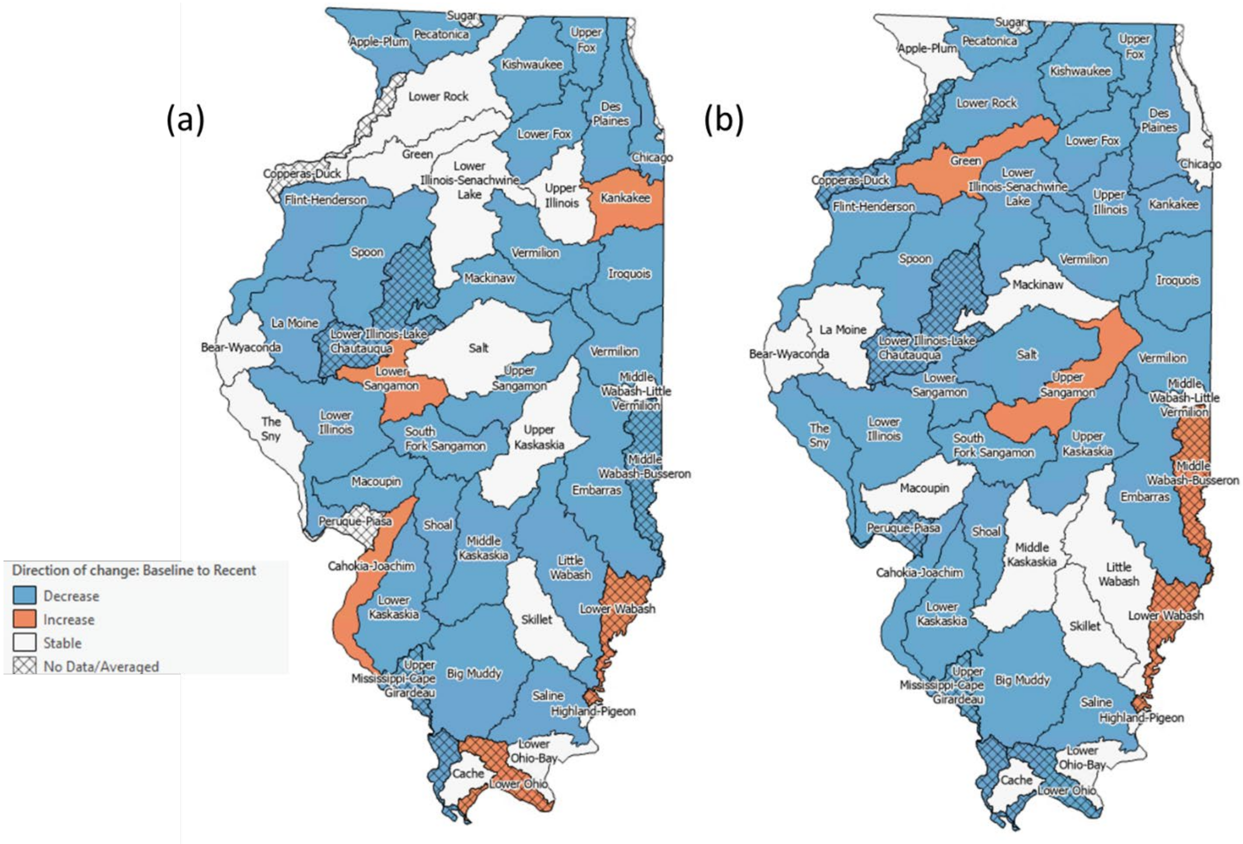

Figure SM2: Changes in Illinois Hydrologic Unit Code 8 (HUC8) average annual (a) nitrate plus nitrite and (b) total phosphorus point source yields in pounds per acre per year (lbs/acre/yr) from 1997–2011 to 2018–2022.

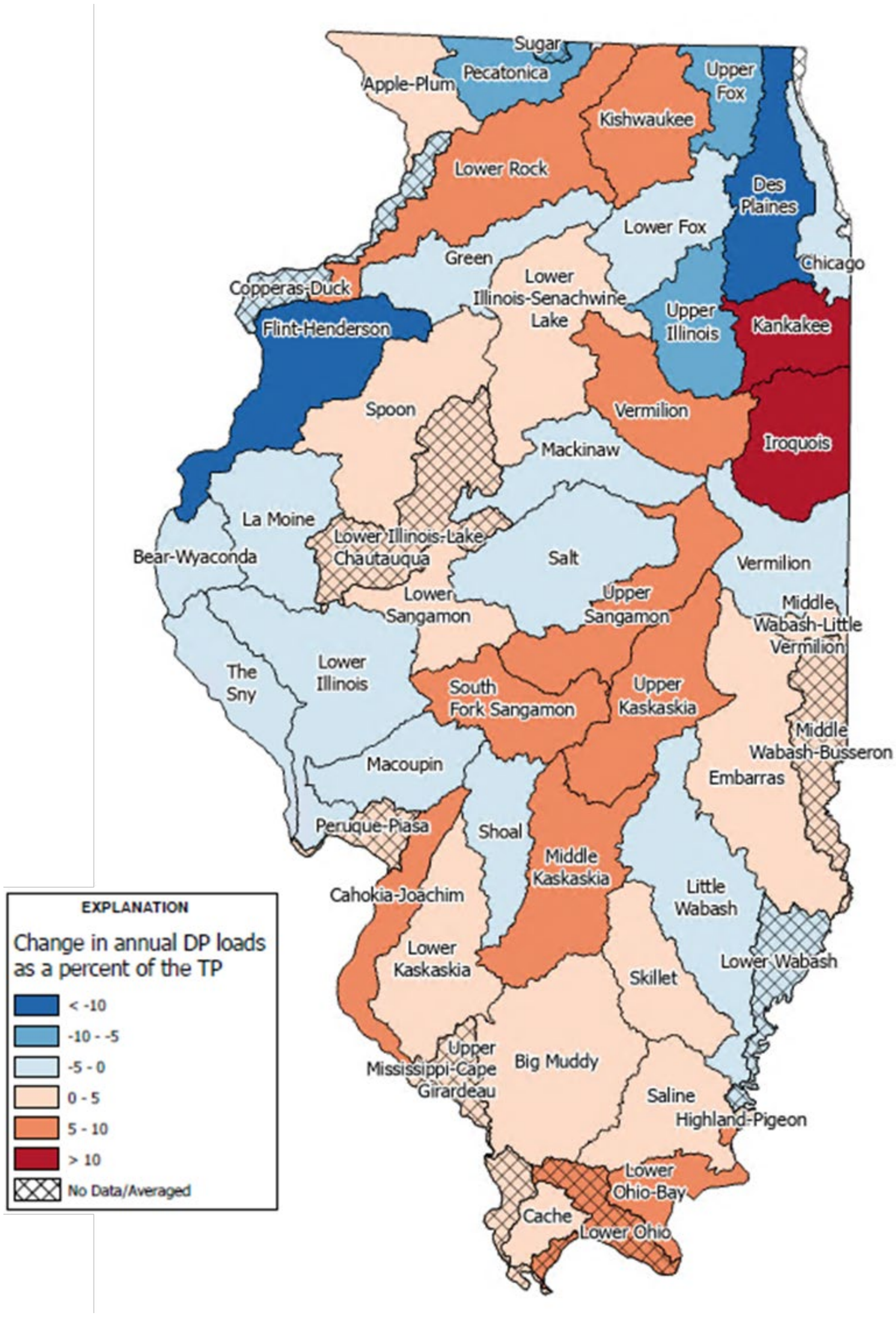

Figure SM3: Changes in Illinois Hydrologic Unit Code 8 (HUC8) average annual dissolved phosphorus (DP) loads as a percentage of the total phosphorus (TP) (%TP/year) from 1997–2011 to 2018–2022.

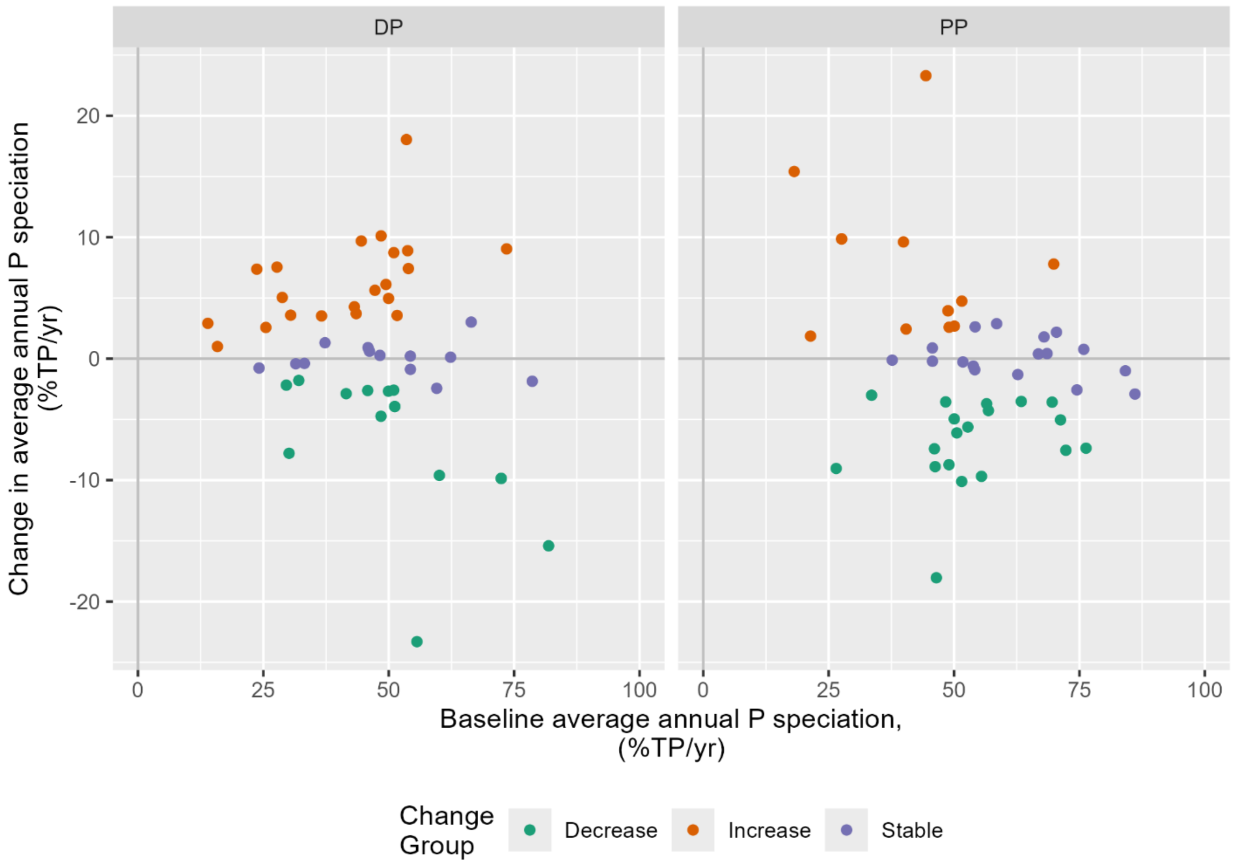

Figure SM4: Changes in average annual dissolved phosphorus:total phosphorus (DP:TP) and particulate phosphorus:total phosphorus (PP:TP) ratios, in percentage of TP per year (%TP/yr) between the baseline (1997–2011) and recent period (2018–2022) versus the average annual DP:TP and PP:TP ratios, in %TP per year, during the baseline period (1997–2011).

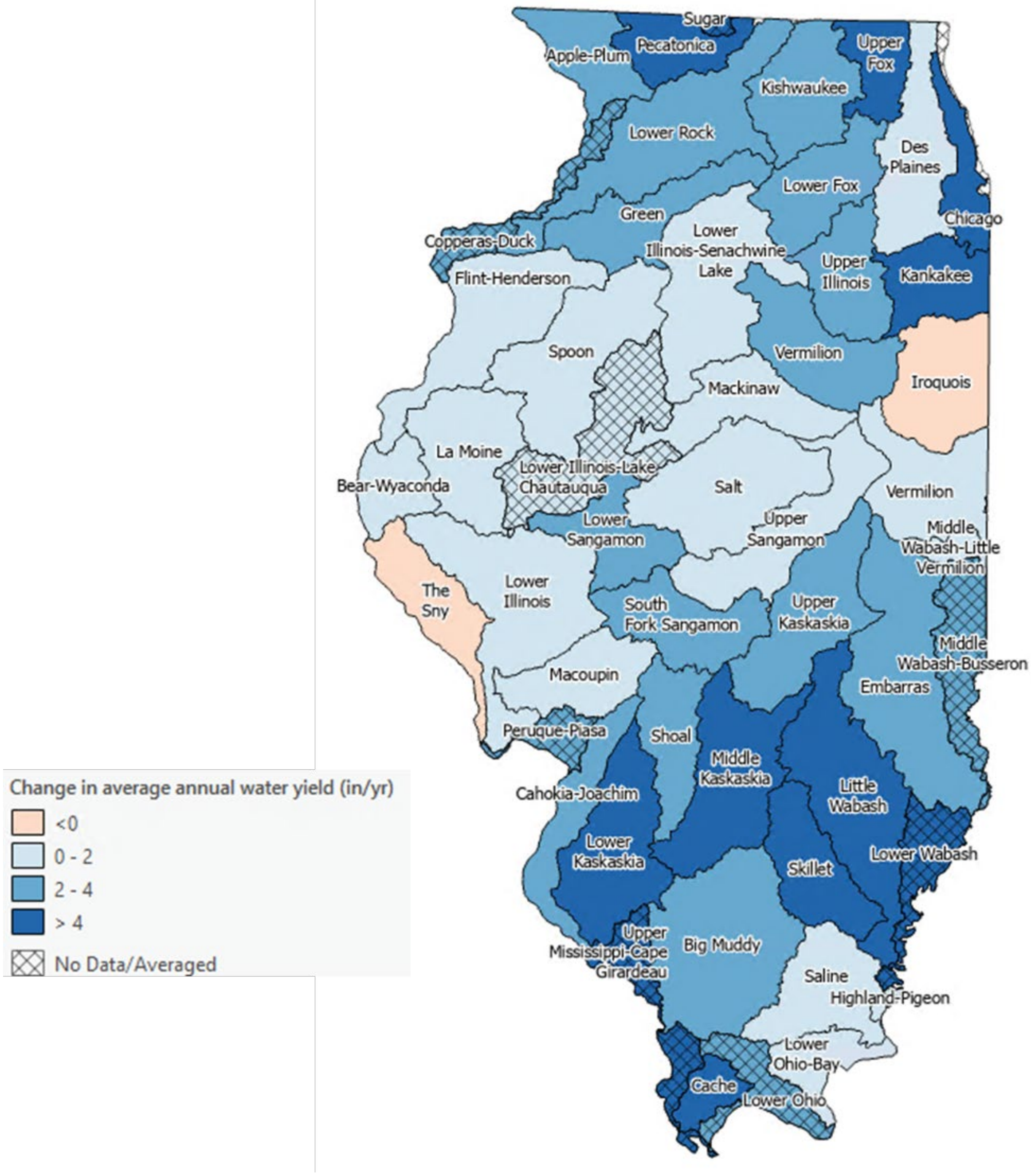

Figure SM5: Changes in Illinois Hydrologic Unit Code 8 (HUC8) average annual water yields in inches per year (in/yr) from 1997–2011 to 2018–2022.

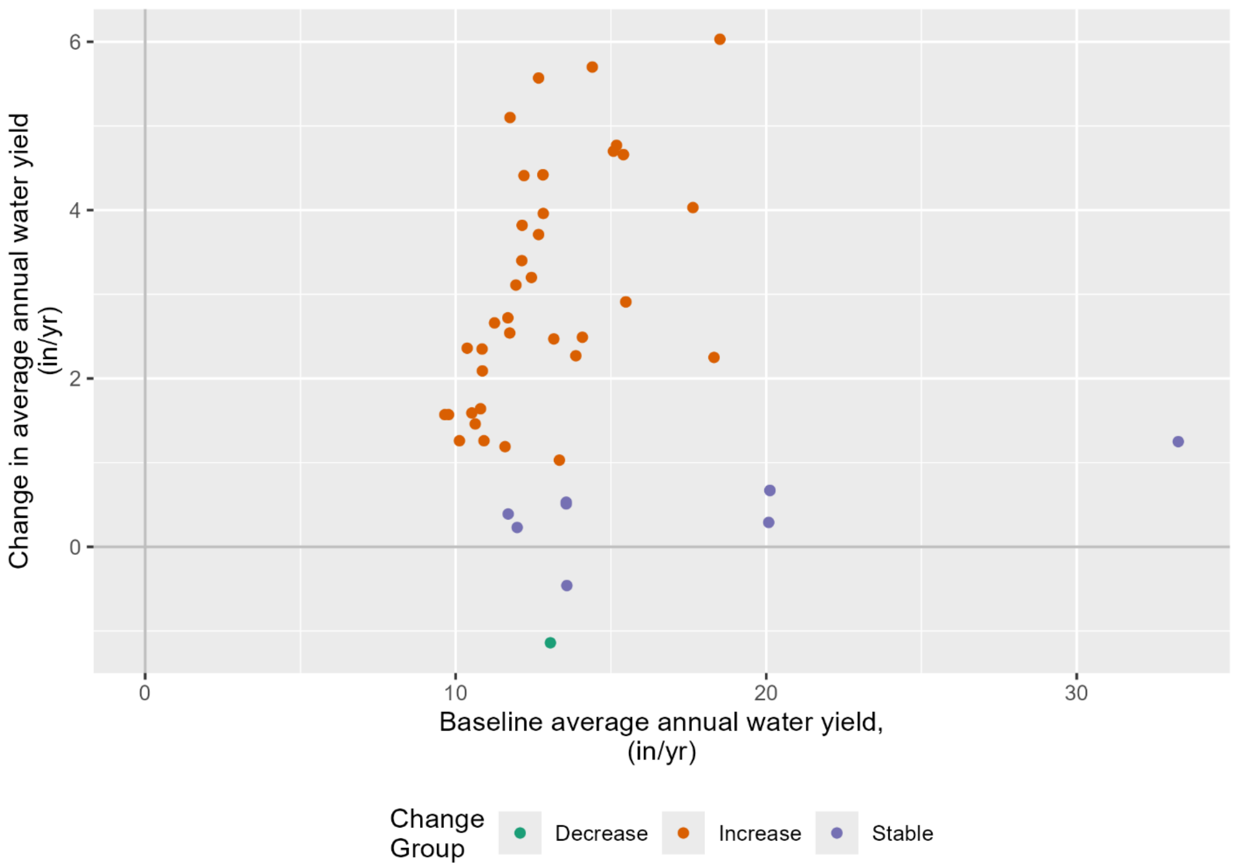

Figure SM6: Changes in average annual water yields, in inches per year (in/yr), between the baseline (1997–2011) and recent period (2018–2022) versus the average annual water yield, in in/yr, during the baseline period (1997–2011).

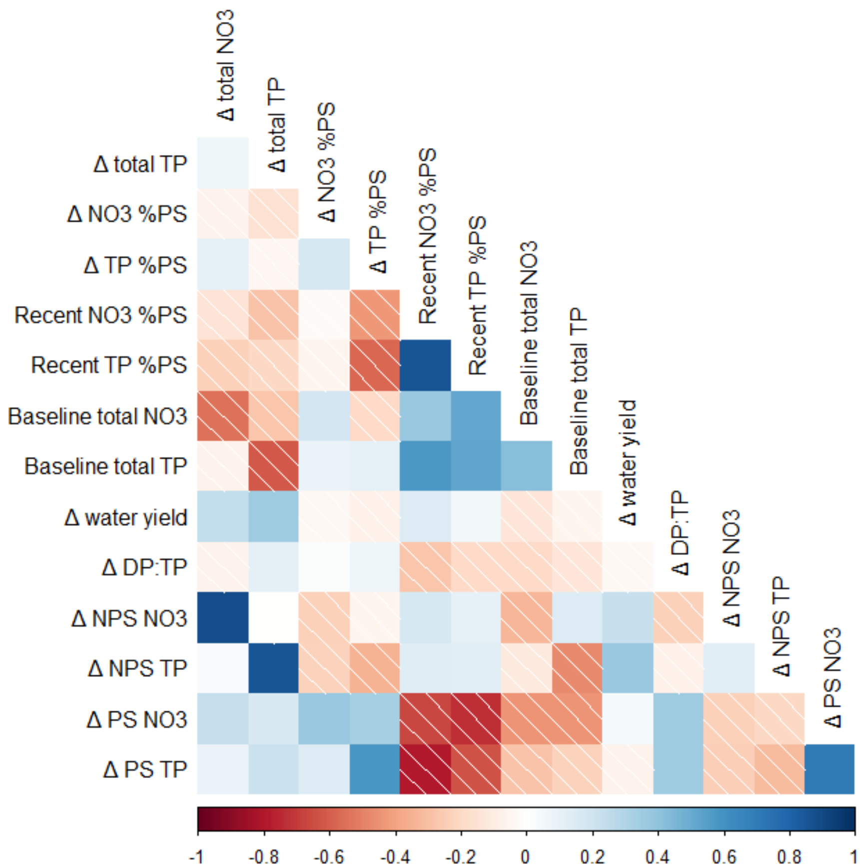

Figure SM7: Correlation matrix of relating changes in annual average Hydrologic Unit Code 8 (HUC8) NO3 and TP yields from 1997–2011 to 2018–2022 to underlaying factors. [Δ, change from baseline to recent period; TP, total phosphorus; NO3, nitrate plus nitrite; PS, point source; NPS, nonpoint source; Baseline, average over period from 1997–2011; Recent, average over period from 2018–2022]

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