Mississippi River/Atchafalaya River Discharge and Nutrients Trends from 2000s and their Drivers/Implications

OCS 4001 12/8/2024

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Abstract

The Mississippi River and the Atchafalaya River are two vital waterways in North America, serving as primary drivers of annual and interannual variations that influence the coastal regions of the Gulf of Mexico. These river systems significantly impact the ecosystem and socioeconomic development in the states within the drainage states, including Louisiana. This research investigates trends in river discharge and nutrient loadings, highlighting their implications for flood management, anthropogenic impact assessment, and aquatic ecosystem health.

We hypothesize that increased anthropogenic activities have elevated nutrient loading and water demand, with consequential effects on water quality and ecosystem resilience (Cao, et al., 2018; David, et al., 2010, Robertson, et al., 2019). Analyzing discharge trends helps elucidate temporal variations and offers predictive insights for future development scenarios. Nutrient transport from agricultural and urban sources provides a lens through which to evaluate the relative importance of human activities and economic development and contributions on water quality.

Both river discharge and nutrient dynamics are critical to aquatic environments, influencing river pathways, coastal regions, and even the open ocean. Coastal hypoxia in the Gulf of Mexico, for instance, is tightly linked to nutrient inputs from the Mississippi and Atchafalaya Rivers, characterized by annual and interannual variations. Examining discharge and nutrient trends in the last 20 years offers valuable insights into ecological health, water quality management, and the broader impacts of human activity. The findings of this study aim to inform and enhance environmental policies and practices in Louisiana and beyond.

Introduction

The Mississippi River and the Atchafalaya River system form the longest and largest river network in North America, creating a vast drainage basin that spans over 1.2 million square miles, which is equally the size of India. After the 1950s, industrialization, urbanization, and agricultural activities within this basin have raised significant concerns about water quality and ecosystem health. Long-term in-situ observations of discharge and nutrient loading in the Mississippi River, as shown by Turner and Rabalais (2019) and Turner (2023), provide valuable insights into these challenges. This research aims to analyze the temporal trends in both the quantity and quality of river discharge since the 2000s, utilizing observational data from the U.S. Geological Survey (USGS) and insights from published literature. This study seeks to provide a deeper understanding of the important sources of nutrients in the Mississippi River and Atchafalaya River system. The quantitative estimate of wastewater, agricultural fertilizer, and atmospheric input within the river basin are conducted during 2000 and 2020.

Method

USGS monitors time-series observations of nutrient loads (such as total nitrogen and total phosphorus) and discharge for the Mississippi River and the Atchafalaya River Basin, which are widely applied to understand nutrient fluxes, sediment transport, and the roles on downstream systems like the Gulf of Mexico. In this study, several datasets are selected for investigating the temporal trends of nutrients and discharge. The observations between 2000 and 2021 are analyzed from Mississippi River near St. Francisville, LA (USGS site No. 07373420) and Lower Atchafalaya River at Morgan City, LA (USGS site No. 07381600). Besides, the nutrient trends are studied within the subbasins, including Illinois River (USGS site No. 05586100), Arkansas River (USGS site No. 07263620), Ohio River (USGS site No. 03612600), Tennessee River (USGS site No. 03609750), upper Mississippi River (USGS site No. 05331580), lower Mississippi River (USGS site No. 07374525, 07374000) and Atchafalaya River (USGS site No. 07381590). The various nutrient species, including Nitrate and Nitrite (NO_3^- and NO_2^-), Total Nitrogen (TN), Total Phosphorus (TP), Ammonium (NH_4^+), Dissolved Organic Carbon (DOC), are in different concentration levels in discharge. The TN and TP are the most concerning nutrients for coastal region and shell. The discharge-weighted monthly nutrient concentration is calculated to account for temporal variations and discrepancies in river discharge and nutrient loading over time. The formula is:

$$Q_m = \frac{\sum (Q_t \cdot C_t)}{\sum Q_t}$$

Where:

Q_m: discharge-weighted monthly nutrient concentration (mg/L).
Qt : Discharge (m^3/s) at time .
Ct : Nutrient concentration (mg/L) at time .

The Point-Source Nutrient Loads to Streams of the Conterminous United States (1999-2020) dataset provides crucial information on nutrient loads (primarily nitrogen and phosphorus) contributed by point sources, such as wastewater treatment plants and industrial facilities. Herein, this dataset is applied to calculate nutrient transport from industrial and urban sources into the river basin to better understand their importance on water quality. The dataset is determined by source points, which are more reliable for quantifying compared with the agricultural nutrient dataset and atmospheric deposition observation.

The EPA provides data on fertilizer purchases and utilization to significantly reduce fertilizer nitrogen and phosphorus use and runoff. This dataset is collected based on state level instead of fine spatial grid. As to constrain the reasonable budget on runoff nutrient, only 20 out of 31 states are targeted to avoid the overestimate on nutrient input to Mississippi River and Atchafalaya River Basin. These 20 states are mostly covered within the boundaries of the basin, namely Arkansas, Illinois, Indiana, Iowa, Kansas, Kentucky, Louisiana, Minnesota, Mississippi, Missouri, Montana, Nebraska, North Dakota, Ohio, Oklahoma, South Dakota, Tennessee, Texas, Wisconsin, and Wyoming. Agricultural fertilizer is shown as the amounts of nitrogen and phosphorus by states in the years 2003, 2005, 2007, 2009, 2011, 2016, and 2017.

Atmospheric deposition of nitrogen and phosphorus is a significant contributor to nutrient inputs in ecosystems, including runoff nutrients in rivers and streams. Understanding its contribution to nutrient loading in the Mississippi River and Atchafalaya River Basin is necessary to track the nutrient pathway and estimate its contribution. The National Atmospheric Deposition Program (NADP) is a long-term monitoring program that provides comprehensive data on atmospheric deposition of nitrogen, phosphorus, sulfur, and other compounds across the United States. The atmospheric deposition is the main component of runoff nutrient cycle. We study the spatial distribution and temporal variation of Nitrogen and Phosphorus deposition from 2000 to 2020.

Results

Total Nitrogen (TN) and Total Phosphorus (TP) are critical indicators in water quality and biogeochemistry. Their levels and dynamics influence aquatic ecosystems, water quality, and broader biogeochemical cycles. The 20-year trends of TN and TP in the different subregions within the river basin have both intra-annual and inter-annual variations. The mean TN concentrations in various stations have similar statistical patterns and range from 0.51 to 0.61 mg/L, except Arkansas River and Upper Mississippi River (Fig 1). The climatological mean of TN concentration in the mainstream of Mississippi River does not differ a lot with the branches, including Ohio, Illinois, and Tennessee River. However, the correlations between the TN concentration in several branches do not agree well with each other, which means the great spatial variations in the TN distribution along the pathway of Mississippi River. The inter-annual and seasonal fluctuations in the TN concentration at different hydrological stations could vary a lot due to natural forcing and inhomogeneities of emission activity. The TP concentration has an obvious spatial pattern along the pathway of the branches and mainstream. The observed TP concentration within the pathway has a similar pattern with TN, but more distinctive differences between upper and lower parts of the Mississippi River (the outlet near St. Francisville). The TP level in the streamflow can be categorized as low concentration within the Upper Mississippi River and its branches, including Arkansas River, Ohio River, Illinois River, and Tennessee River. TN concentration ranges from 0.26 to 0.45 mg/L in the subbasin region. However, TN concentration excesses 0.45 mg/L in the Lower Mississippi River and is recorded the peak value about 0.51 mg/L at the station near St. Francisville and Baton Rouge (Fig 2).

To better understand and estimate the nutrition load of Mississippi River and Atchafalaya River within the last 20 years, the observation from USGS station near St. Francisville is selected for the further investigation because of its temporal coverage from 2000 to 2020 and nice location. The annual mean discharge record from 2000 to 2020 at the station near St. Francisville exhibits a steady upgoing trend (Fig 3 black dash line). Over the two decades, the maximum and minimum of annual discharge fluctuate, dominated by changes in hydrological patterns or water resource management. The annual mean TN and TP concentration level have the opposite tendency compared with the discharge, which in result leads to increased nutrient load in TN and TP. The increases in TN and TP load in Mississippi River are primarily driven by the discharge even though the concentration levels have downward trend from 2020.

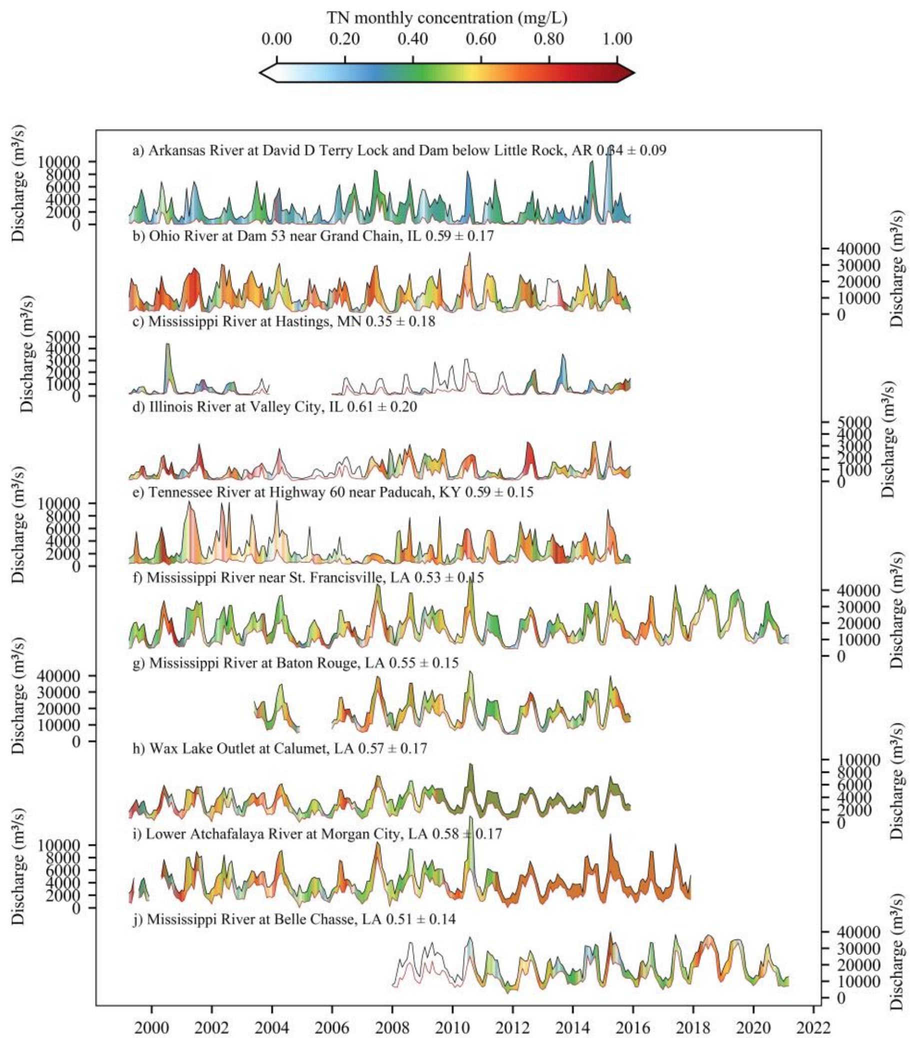


Fig 1. Monthly TN concentration (colormap) and discharge (upper line and lower line) during 2000 to 2020 at the USGS stations: Mississippi River near St. Francisville, LA (USGS site No. 07373420) and Lower Atchafalaya River at Morgan City, LA (USGS site No. 07381600). Besides, the nutrient trends are studied within the subbasins, including Illinois River (USGS site No. 05586100), Arkansas River (USGS site No. 07263620), Ohio River (USGS site No. 03612600), Tennessee River (USGS site No. 03609750), upper Mississippi River (USGS site No. 05331580), lower Mississippi River (USGS site No. 07374525, 07374000) and Atchafalaya River (USGS site No. 07381590)

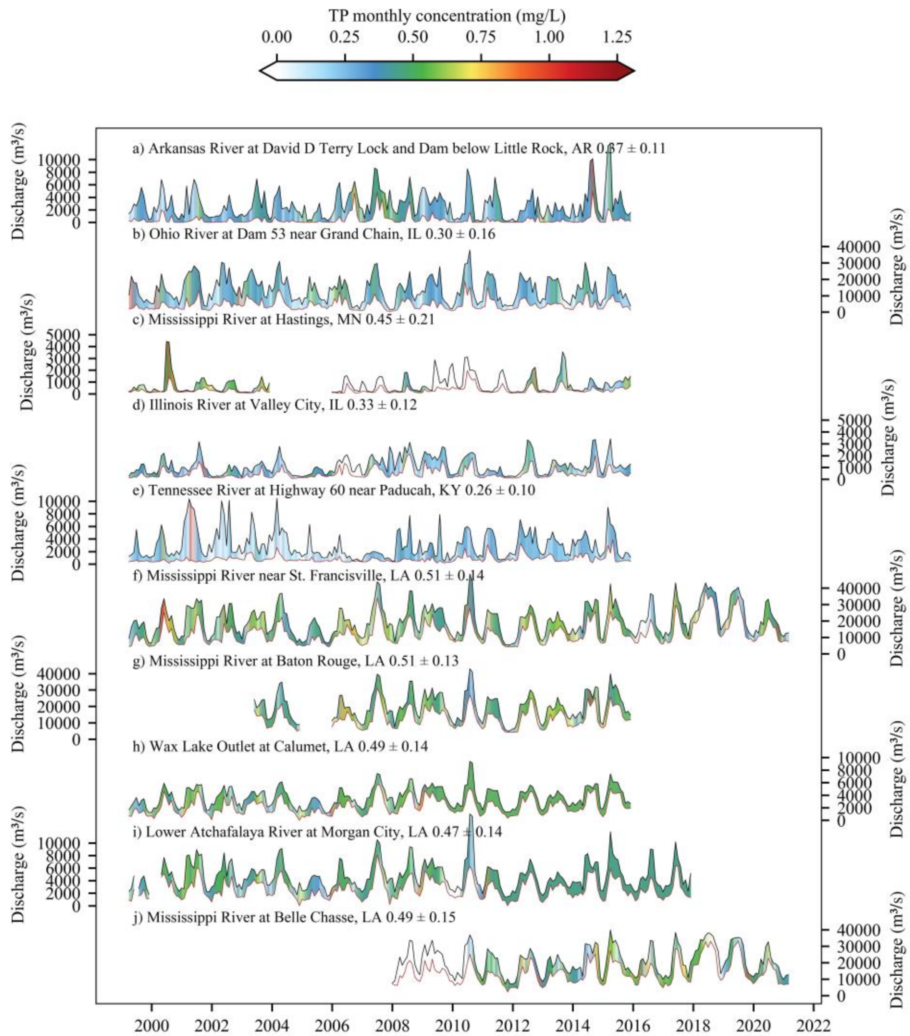


Fig 2. Same with Fig 1., but for monthly TP concentration.

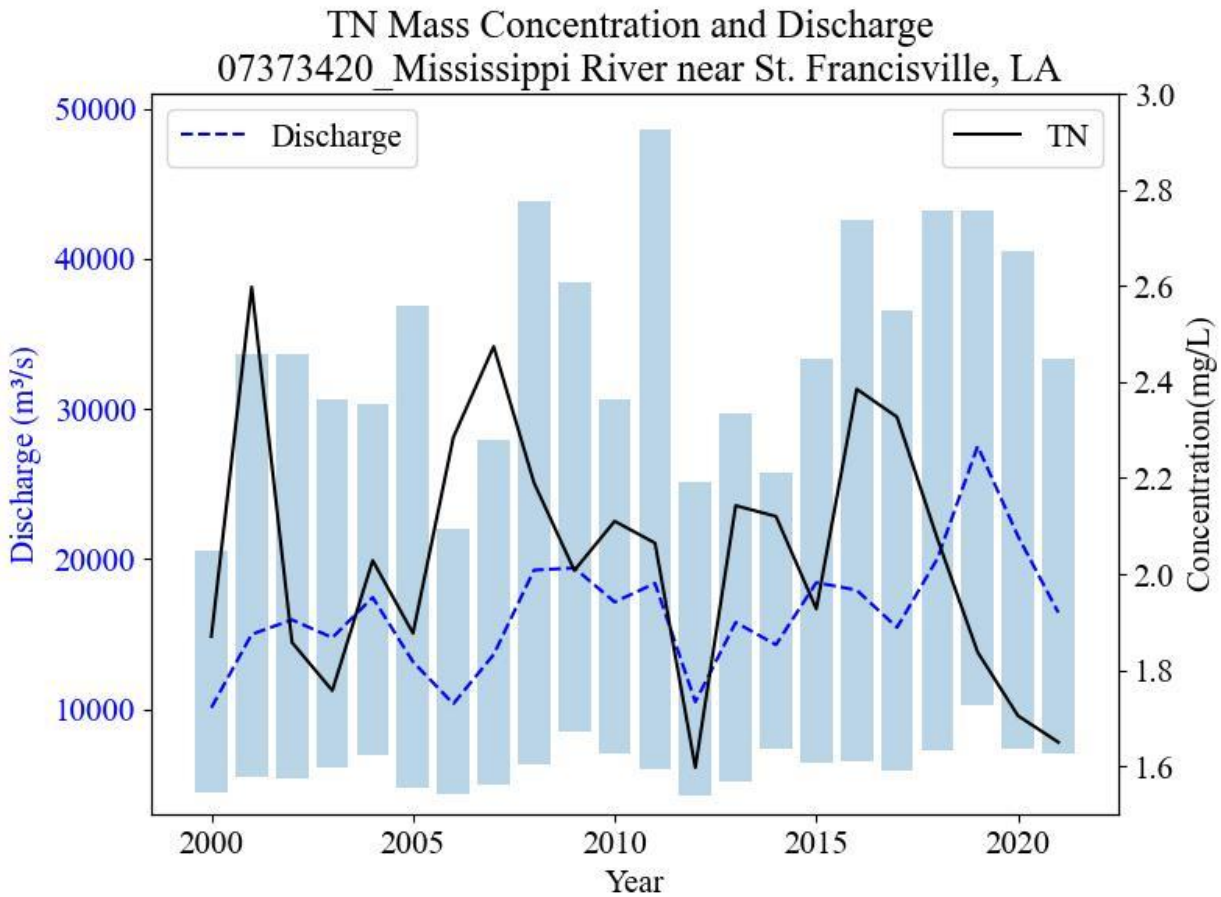


Fig 3. Annual TN concentration (black line), mean discharge (blue line), and maximum and minimum (upper and lower limit of blue bar) during 2000 and 2020.

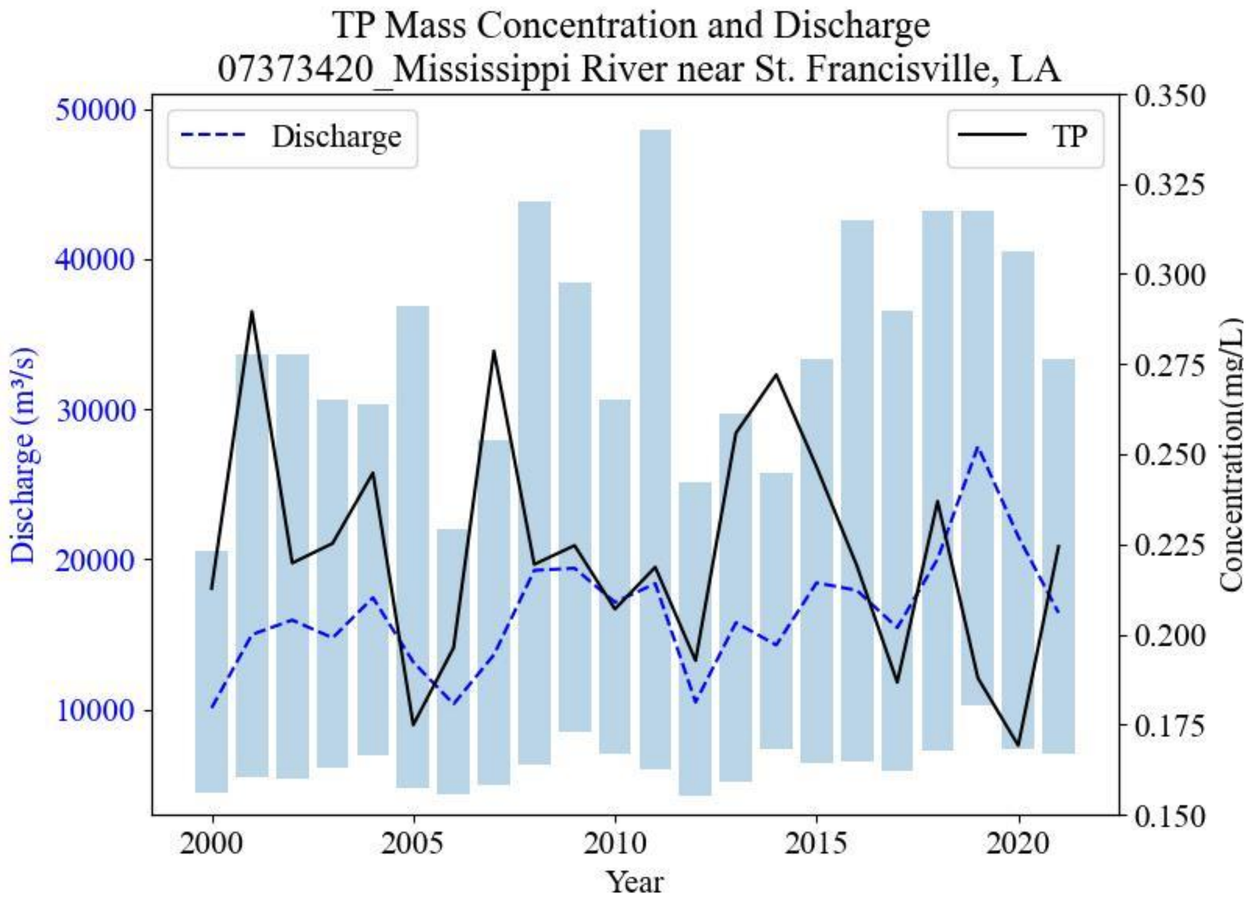
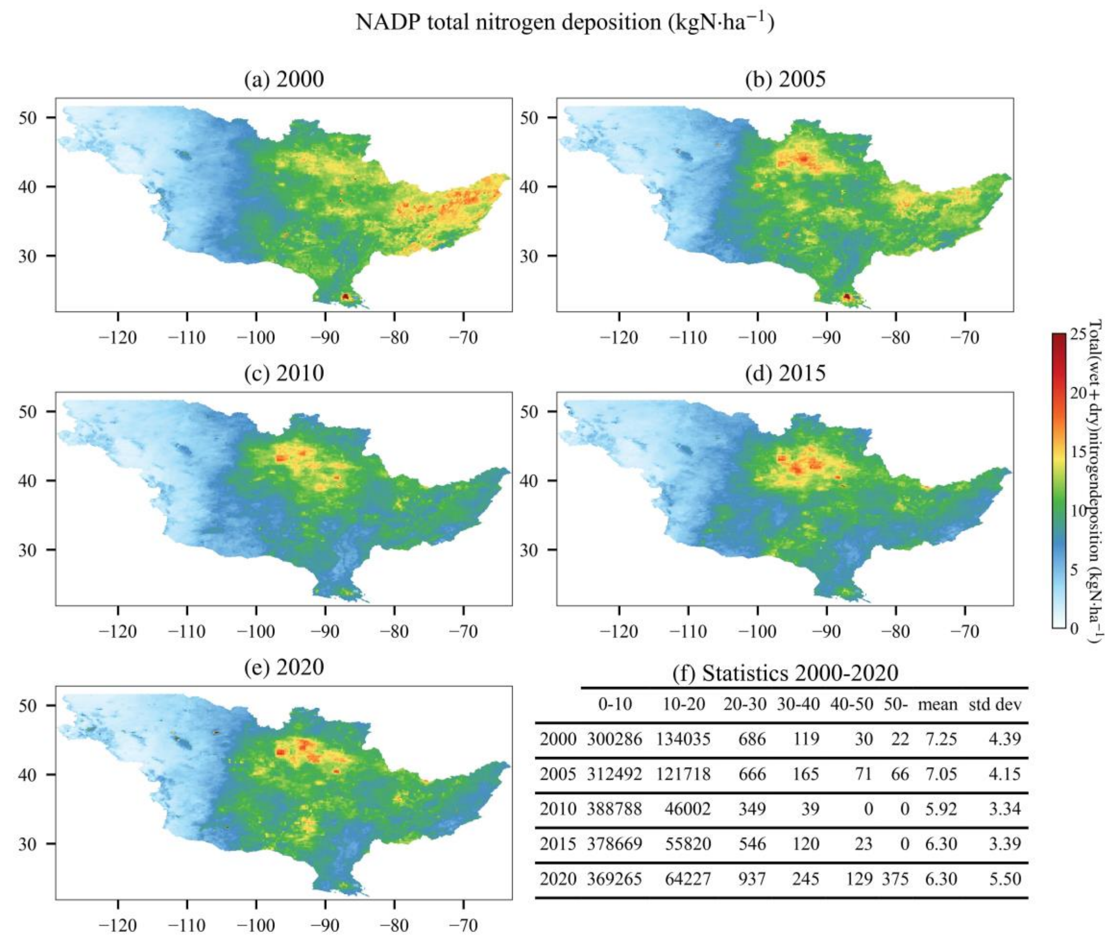


Fig 4. Annual TP concentration (black line), mean discharge (blue line), and maximum and minimum (upper and lower limit of blue bar) during 2000 and 2020.

The nutrient load is going upward since 2000 with gradual decline in nutrient concentration during the same period, which has been an important concern to investigate geochemical processes in the Gulf of Mexico. To understand the relative importance of different source of nutrients and quantify the contribution of various sources, it is necessary to analyze the potential contribution of nutrients from combination of natural and anthropogenic sources, including agricultural activities, wastewater treatment and atmospheric deposition. Agricultural activities are a major contributor, as fertilizers, animal manure, and crop residues release nitrogen and phosphorus into the soil, which can then be transported by rainwater into nearby water bodies and get involved within the hydrological cycle. The wastewater from urban areas and industrial section also contributes through stream water. Natural sources, such as the decomposition of organic matter, add to the nutrient load via soil and precipitation.

In this study, atmospheric deposition, wastewater, and agricultural fertilizer are analyzed individually as independent sources within Mississippi River and the Atchafalaya River basin (MARB), which means the interactions between each other neglected, like the wastewater containing the N or P fertilizer from farmland transported into the runoff.



	0-10	10-20	20-30	30-40	40-50	50-	mean	std dev
2000	300286	134035	686	119	30	22	7.25	4.39
2005	312492	121718	666	165	71	66	7.05	4.15
2010	388788	46002	349	39	0	0	5.92	3.34
2015	378669	55820	546	120	23	0	6.30	3.39
2020	369265	64227	937	245	129	375	6.30	5.50

Fig 5. Annual TN deposition (a-e) and statistics for the grid within 0-10, 10-20, 20-30, 30-40, 40-50, greater than 50 and spatial mean and standard deviation during 2000 and 2020 (unit: kg N/ha).

Annual TN deposition in 2000, 2005, 2010, 2015 and 2020 shows the hotspot in the Upper Mississippi River and Ohio River with deposition amount up to 15 – 20 kg N/ha (Fig 5). The western part of the MARB is much lower than most of the basin. The spatial pattern of TN deposition varies from 2000 to 2020, when mean annual deposition is up to 7.25 kg N/ha in 2000 and goes down to 5.92 kg N/ha in 2010, then maintains 6.30 kg N/ha in 2015 and 2020. The TN deposition within the Ohio River shows sharp decreases from 2000 to

2010, which can account for the lowest deposition level in 2010 within the MARB. Since 2010, the new spreading of higher TN deposition in the southern MARB explains the increments in TN deposition well. The variations in deposition from 10 to 20 kg N/ha well match with the annual mean deposition amount with whole MARB. The shift of spatial pattern reveals the hotspot of industrial emission and agricultural activities in each year.

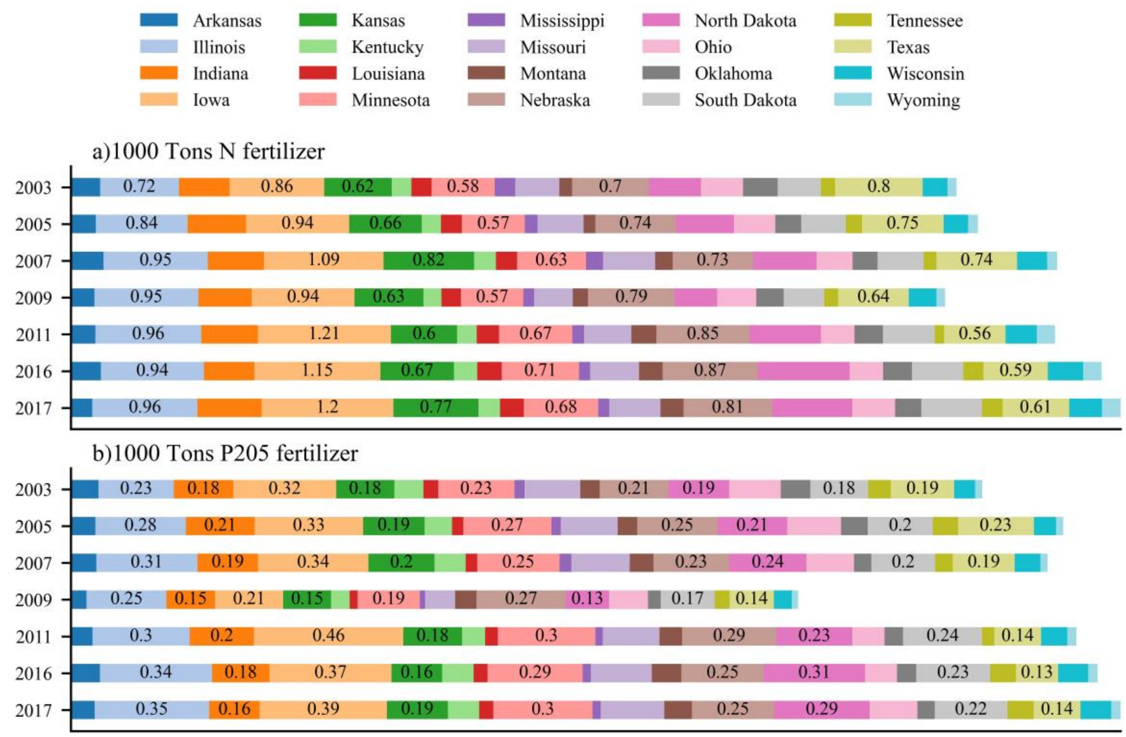
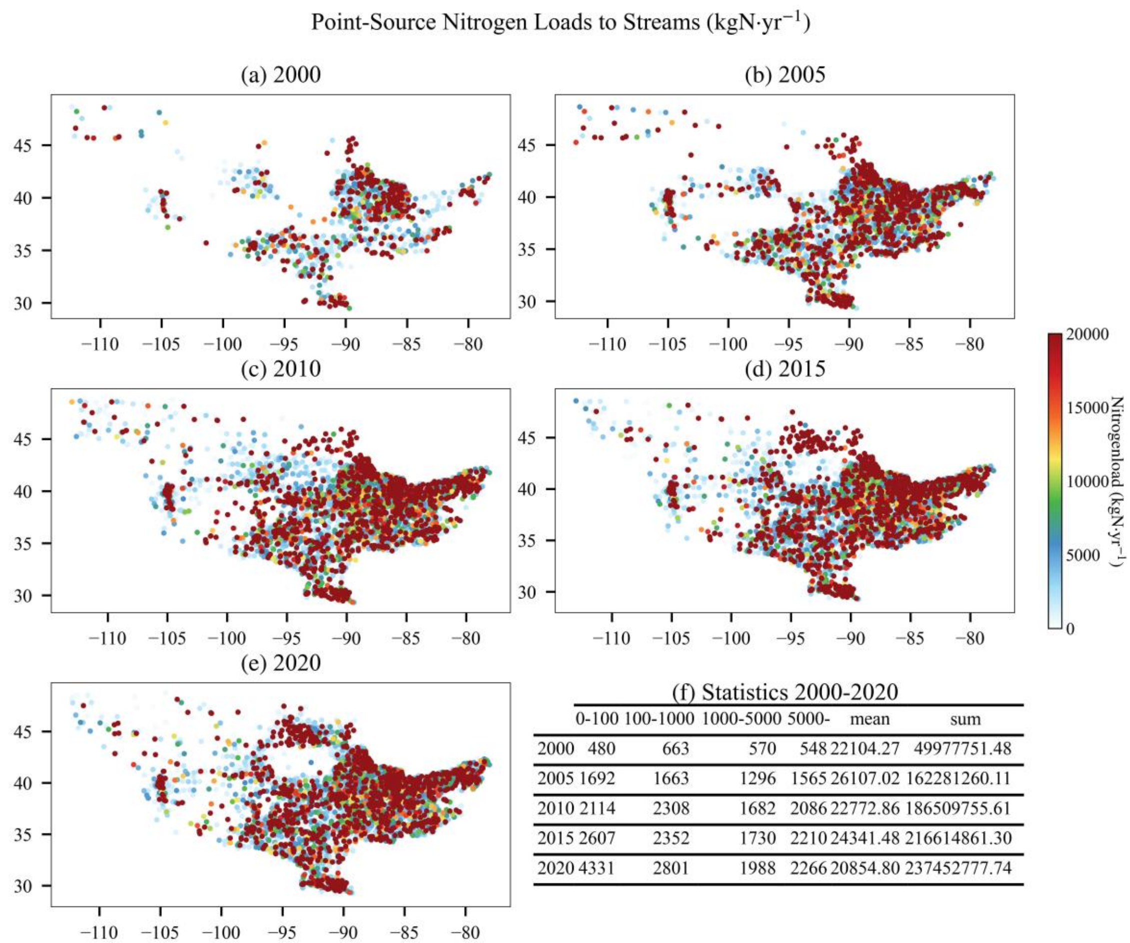


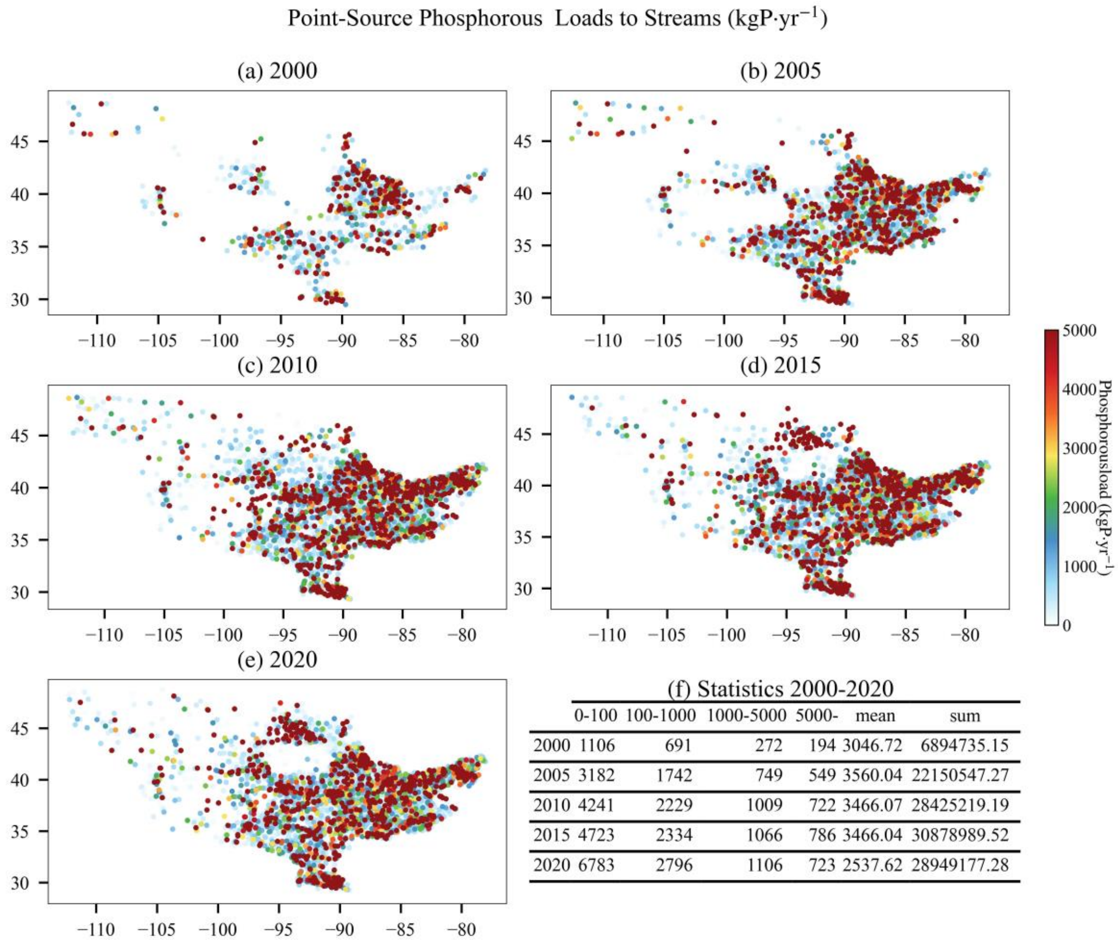
Fig 6. Annual N and P2O5 fertilizer labeled by state in the year 2003, 2005, 2007, 2009, 2011, 2016 and 2017 (unit: 1000 ton).

The agricultural fertilizer is a good indicator of the agricultural activities within MARB, because it can imply the intensity of agricultural activity. The EPA dataset provides the N and P2O5 fertilizer consumed in the year 2003, 2005, 2007, 2009, 2011, 2016 and 2017. The statistics are analyzed according to the state in the US. There are 31 states in the US partly or entirely located in the MARB. In this study, 20 out of 31 states are included because of over half of their continent within the MARB. As shown in Figure 6, the gross trend in agricultural fertilizer use has increased both for P and N fertilizer since 2003, but in 2009 is marked by a temporary interruption in the growth. The N fertilizer used in Iowa, Kansas, Arkansas, Minnesota, Nebraska, and Tennessee contributes to the total consumption during 2000 to 2020. The increasing trend in N fertilizer can be seen in these states, except Tennessee with gradual decline since 2003. The P2O5 fertilizer has a similar increasing trend since 2003, but a more significant decline in 2009 compared with N fertilizer (Fig 6). The P2O5 fertilizer consumption is from Iowa, Kansas, Minnesota, Arkansas, Tennessee, Nebraska, and North Dokata. In all, Despite the pause in 2009, the overall use of agricultural fertilizer rises during 2000 to 2020.



	0-100	100-1000	1000-5000	5000-	mean	sum
2000	480	663	570	548	22104.27	49977751.48
2005	1692	1663	1296	1565	26107.02	162281260.11
2010	2114	2308	1682	2086	22772.86	186509755.61
2015	2607	2352	1730	2210	24341.48	216614861.30
2020	4331	2801	1988	2266	20854.80	237452777.74

Fig 7. Annual N load distribution and statistics for the point-source emission rate with 0-100, 100-1000, 1000-5000, greater than 5000, and mean and total N load originated from wastewater during 2000 and 2020 (unit: kg N/yr).



	0-100	100-1000	1000-5000	5000-	mean	sum
2000	1106	691	272	194	3046.72	6894735.15
2005	3182	1742	749	549	3560.04	22150547.27
2010	4241	2229	1009	722	3466.07	28425219.19
2015	4723	2334	1066	786	3466.04	30878989.52
2020	6783	2796	1106	723	2537.62	28949177.28

Fig 8. Annual P load distribution and statistics for the point-source emission rate with 0-100, 100-1000, 1000-5000, greater than 5000, and mean and total P load originated from wastewater during 2000 and 2020 (unit: kg P/yr).

Wastewater is exceedingly produced as the development of urbanization and industrialization within the MARB and directly contributes to the nutrient balance in the runoff compared to the contribution from agriculture and atmospheric deposition. It is important to monitor the wastewater into the Mississippi River and Atchafalaya River, particularly in the wastewater volume and nutrient concentration of nitrogen and phosphorus. As shown in Fig 7 and 8, the wastewater source and its emission rate are increasingly developing from 2000 to 2020, and the hotspots are concentrated in the eastern and southern MARB. The uneven pattern of spatial distribution of wastewater emission rate is due to the urbanization and industrialization and explains the spatial discrepancies of nutrient concentrations in the streamflow and branches of Mississippi

River and Atchafalaya River. The mean Nitrogen and Phosphorus emission rates are about 20000 kg/yr and 3000 kg/yr within 2000 to 2020. The temporal variations of N load from wastewater within MARB have distinctive characteristics in terms of total value and mean value. The mean N load emitted from wastewater has fluctuations from 2000 to 2020, but total N load continues to go upward from 50 Gg to 238 Gg during the same period. The temporal changes in P load differ from those in N load, which is characterized as peak values in mean and total N load in 2015 and followed by decline in 2020.

Discussion

The nutrient load in Mississippi River and Atchafalaya River is the essential source of nutrient substances in coastal regions of northern Guld of Mexico. Nutrient load is modulated by the natural forcings, including precipitation, runoff, and atmospheric transport, and anthropogenic activities, including industrialization and agriculture, respectively. In this study, the spatial distribution, and temporal trend of nitrogen and phosphorus from atmospheric deposition, agricultural fertilizer use, and wastewater are examined to determine the relative importance of each source. The interplay between nutrient sources reshapes the spatial and temporal distribution of nutrient load in the Mississippi River and Atchafalaya River.

To determine the potential impact and contribution of atmospheric deposition, agricultural fertilizer use, and wastewater on nutrient load in nutrient load in the Mississippi River and Atchafalaya River. The multi-year average of TN and TP in Mississippi River and Atchafalaya River are compared, with the annual estimate of nutrient load from atmospheric deposition, agricultural fertilizer use, and wastewater within 2000 and 2020, to determine their relative importance. The nutrient load transported by the Mississippi River and Atchafalaya River into the Gulf of Mexico has shown a significant increase from 2000 to 2020, with multi-year mean TN load reaching approximately 1450 Gg and TP load approximately 177 Gg. Between 2000 and 2020, atmospheric nitrogen deposition rates have fluctuated within MARB, and annual nitrogen deposition within the basin ranges from 1833 Gg to 2253 Gg, which is about 1.26 to 1.55 time of multi-year mean TN load. Agricultural fertilizer use in 20 states, which are mostly located in the MARB, has been increasing since 2003 to 2017. Nitrogen in the fertilizer increases from 8000 Gg in 2009 to 9500 Gg in 2017, approximately 18.8% increase over the period. Phosphorus in the fertilizer is estimated to increase by 45.5% from 2200 Gg in 2009 to 3200 Gg in 2017. The annual nitrogen load into the MARB from N fertilizer is 5.5 to 6.5 times multi-year mean TN load, while annual phosphorus load from P2O5 fertilizer is 5.9 to 8.0 times multi-year mean TP load. Agricultural activity is the most important source of nutrient load in the runoff within MARB, which is coincided with the findings in recent year observations and estimates (Turner and Rabalais, 2019, Turner, 2023). As to wastewater, it provides limited nutrient input but plays a key role in the short-term variations of nutrient load in MARB for its direct role in the nutrient cycle driven by hydrological process. In 2020, nitrogen in wastewater accounted for 16% of the multi-year mean TN load, while phosphorus in wastewater represented 16% of multi-year mean TP load. The ratio is only 3.4% for nitrogen in wastewater in 2000 and 3.3% for phosphorus with respect to TN and TP load in 2000. These notable trends highlight the growing role of urbanization and industrialization in nutrient pollution. It is necessary to improve wastewater treatment and reschedule management strategies to mitigate the environmental impact of wastewater, especially nitrogen and phosphorus.

The time scales of nutrient input into nutrient load in the runoff from various sources—atmospheric deposition, agricultural fertilizers, and wastewater emissions—vary in their impacts depending on their pathways through the environment (Stackpoole et al., 2021). Firstly, wastewater from industrial facilities and urban areas can lead to direct increases in nitrogen and phosphorus loads in the local and downstream waters. Increasing nutrient load in the wastewater is related to developing urbanization and industrial productivity within MARB. When fertilizers are used, they are directly emitted into the soil and gradually suspended in the nutrient transport into nearby aquatic environment, which is modulated by various time-scale dynamical processes, such as leaching into groundwater and soil retention. In turn, the nutrient contribution from agricultural fertilizer will have a long-term impact on the nutrient load in the Mississippi River and Atchafalaya River. These complex processes are the physical transport and chemical reaction of nutrient in soil, discharge, and sediment. Atmospheric deposition is considered a key role in nutrient transport from other basins into MARB and redistribution of nutrient load within MARB. The spatial distribution of nitrogen atmospheric deposition also reveals the intensity of industrial emissions and farming activities, including the Upper Mississippi River, Ohio River, and Lower Mississippi River and Atchafalaya River.

The overwhelming nutrient load, especially nitrogen and phosphorus, is the primary driver for the eutrophication in the Gulf of Mexico. However, the fast-increasing phosphorus in the Mississippi River and Atchafalaya River is significantly altering the N:P ratio. This ratio will determine the favored species of algae and microorganisms and potentially lead to algal blooms (Lane et al., 2014). Nutrient load in Mississippi River and Atchafalaya River is not only concerned with water quality but also affects the marine environment.

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Code Example

https://github.com/chsharrison/Sci_comp_F24/blob/main/Bentao_Li/NADP%20Total%20Deposition%20N%20P.py

```
vmin, vmax = 0, 40  # Custom value range
norm = mcolors.Normalize(vmin=vmin, vmax=vmax)  # Normalization
cmap = colorbar_plt # Colormap

ax = plt.subplot(3, 2, year_index + 1)
ax.spines['bottom'].set_linewidth(1 * dpi / 72)
```

```
ax.spines['top'].set_linewidth(1 * dpi / 72)
ax.spines['left'].set_linewidth(1 * dpi / 72)
ax.spines['right'].set_linewidth(1 * dpi / 72)

ax1 = ax.imshow(out_image[0], cmap=colorbar_plt, extent = [bounds[0], bounds[2],
bounds[1], bounds[3]], norm= norm)  # Set extent to match lon/lat bounds
sub_title = '$\mathrm{(}$' + '$\mathrm{0}$'.format(
  str('{') + order_subplot[(year_index + 1)] + str(
    '}')) + '$\mathrm{)}$' + ' ' + year
ax.text(0.50, 1.08, sub_title, horizontalalignment='center', verticalalignment='center',
    transform=ax.transAxes,
    fontsize=9, fontproperties='Times New Roman', math_fontfamily='stix')
```

https://github.com/chsharrison/Sci_comp_F24/blob/main/Bentao_Li/Point-Source%20Nutrient%20Loads%20wastewater%20nutrient.py

```
for lower, upper in ranges:
  range_index = ranges.index((lower, upper))
  # Filter data within the current range
  in_range = TP_dataset_subset_year_loc[(TP_dataset_subset_year_loc['loadTP'] > lower)
& (TP_dataset_subset_year_loc['loadTP'] <= upper)]
  mean = np.mean(TP_dataset_subset_year_loc['loadTP'])
  sum = np.sum(TP_dataset_subset_year_loc['loadTP'])
  quantile_25 = TP_dataset_subset_year_loc['loadTP'].quantile(0.25)
  quantile_75 = TP_dataset_subset_year_loc['loadTP'].quantile(0.75)

  print(mean, quantile_25,quantile_75 )
  # Calculate statistics
  count = in_range.shape[0]
  # print(count)
  table.loc[year][range_index] = count
  table.loc[year]['mean'] = '%1.2f' % mean
  table.loc[year]['sum'] = '%1.2f' % sum
  # print(table)

ax = plt.subplot(3, 2, year_index + 1)
```

```
print(year_index)
ax.spines['bottom'].set_linewidth(1 * dpi / 72)
ax.spines['top'].set_linewidth(1 * dpi / 72)
ax.spines['left'].set_linewidth(1 * dpi / 72)
ax.spines['right'].set_linewidth(1 * dpi / 72)
vmin, vmax = 0, 5000  # Custom value range
norm = mcolors.Normalize(vmin=vmin, vmax=vmax)
TP_dataset_subset_year_loc = TP_dataset_subset_year_loc.sort_values(by='loadTP',
ascending=True)
ax1 = plt.scatter(TP_dataset_subset_year_loc['Longitude'],
TP_dataset_subset_year_loc['Latitude'], c = TP_dataset_subset_year_loc['loadTP'], s=1,
norm = norm, cmap=colorbar_plt)
sub_title = '$\mathrm{(}$' + '$\mathrm{0}$'.format(
  str('{') + order_subplot[(year_index + 1)] + str(
    '}')) + '$\mathrm{)}$' + ' ' + str(year)
ax.text(0.50, 1.08, sub_title, horizontalalignment='center', verticalalignment='center',
    transform=ax.transAxes,
    fontsize=9, fontproperties='Times New Roman', math_fontfamily='stix')
```