Supporting Information for:
India’s Riverine Nitrogen Runoff Strongly Impacted by Monsoon Variability

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Consisting of 2 sections, 6 figures, and 7 tables within 17 pages
**S1. Application of WRTDS approach**

The WRTDS method is a commonly used approach for estimating nutrient loading in the absence of daily concentration measurements. In the current application, the $R^2$ between observed and WRTDS estimated DIN load ranges from 0.31 to 0.87 (filled triangles in Fig. S6A) across the examined basins, which is comparable to the $R^2$ observed for rivers in the United States and ranges from 0.43 to 0.9 (filled triangles in Fig. S6B). The relationship between observed and WRTDS estimated natural log concentrations is slightly weaker ($R^2$ of 0.04 to 0.045; Fig. S5 and filled circles in Fig. S6A) relative to that observed for rivers in the United States ($R^2$ of 0.06 to 0.54; filled circles in Fig. S6B).

The number for the United States are based on an application of the WRTDS method to eight river basins with drainage areas comparable to the CWC basins in India. Water quality measurements and discharge data were obtained from the USGS National Water Information System (NWIS) \(^1\). The eight basins along with the number of water quality samples used for WRTDS, number of years of continuous daily discharge measurement, and drainage area are: 1) Susquehanna river basin (1050 samples, and 38 years, 70,189 km\(^2\)); 2) Mississippi river basin at Clinton, IA (400 samples, 38 years, 221,703 km\(^2\)); 3) Missouri river basin at Omaha, NE (289 samples, 37 years, 836,049 km\(^2\)); 4) Missouri river basin at Hermann, MO (513 samples, 38 years, 1,353,270 km\(^2\)); 5) Mississippi river basin at Thebes, IL (444 samples, 37 years, 1,847,181 km\(^2\)); 6) Ohio river basin at Cannelton, IN (315 samples, 37 years, 251,229 km\(^2\)); 7) Mississippi river basin at Francisville, LA (349 samples, 32 years, 2,914,516 km\(^2\)); and 8) Lower Atchafalaya river basin at Melville, LA (333 samples, 32 years, 241,688 km\(^2\)). The WRTDS methodology for estimating daily DIN load was same as described in the Methods section.

For rivers both in India and in the United States, we observe a higher correlation between estimated DIN load and discharge ($R^2$ of 0.44 – 0.96 for India and $R^2$ of 0.56 – 0.97 for the United States; filled squares in Fig. S6A and S6B, respectively) relative to between observed DIN load and discharge ($R^2$ of 0.31-0.85 for India and $R^2$ of 0.31 – 0.88 for the United States; filled diamonds in Fig. S6A and S6B, respectively). This implies that WRTDS estimates of DIN load have somewhat less variability compared to the observed, as expected given that variability in concentration cannot be fully captured. The application in India and the United States, where the usefulness of the WRTDS approach has been well documented\(^2\) are therefore very similar, further supporting the applicability of WRTDS within the context of the current analysis.

**S2. Sensitivity analyses for individual basins**

We find that climatic variables and nitrogen inputs explain much of the interannual variability in DIN fluxes for the Godavari, Subernarekha, Mahanadi, and Narmada basins (64-91%). Among the precipitation variables, annual precipitation provides the highest explanatory power for the Godavari basin, while basin seasonal precipitation for the months of June, July, August, and September (JJAS) provides the highest explanatory power for the Subernarekha, Mahanadi, and Narmada basins. However, we find that replacing JJAS seasonal precipitation with annual precipitation and vice-versa
results in only a slight loss of explanatory power for these basins, with 58% to 86% of the variability explained, due to the strong covariability between these two precipitation variables.

For the Brahmani and Baitarni, Cauvery, and Krishna basins, the examined climatic factors and nitrogen inputs explain less than half of the interannual variability in DIN fluxes (38-40%), and we find that there is also a greater loss of explanatory power for these basins when precipitation variables selected for other basins are substituted, with only 20% to 32% of the variability explained.

Overall, for all seven basins, annual, seasonal, or extreme seasonal precipitation is one of the primary drivers of the interannual variability in DIN flux. Time-varying total live storage capacity of dams within each basin was also tested as a predictor variable but was not found to explain variability in any of the basins.

We performed two additional sensitivity tests using climatic variables and NO\textsubscript{x} deposition estimates from different sources in order to evaluate the robustness of the selected variables in explaining the observed interannual variability in DIN fluxes. In the first sensitivity test, we replaced precipitation and temperature data from the India Meteorological Department \cite{3} with precipitation from the Climate Prediction Center dataset (https://psl.noaa.gov/data/gridded/data.cpc.globalprecip.html) and temperature based on Climatic Research Unit dataset \cite{4} (see Materials and Methods). Consistent with our base case results, we found precipitation variables to be one of the primary drivers of DIN flux for all river basins (results not shown), and the final selected precipitation variables for most river basins were similar to the ones selected in our base case. In the second sensitivity test, we replaced NO\textsubscript{x} deposition data from Lamarque et al. \cite{5} with those from Geddes and Martin \cite{6} for 1996 to 2014 and kept the Lamarque et al., \cite{5} estimates for 1980 to 1995 (scaled based on the average ratio between annual deposition from Geddes and Martin \cite{6} and Lamarque et al. \cite{5} during 1996-2014). This sensitivity test again yielded qualitatively consistent results, with similar predictor variables being selected for most basins, with the exception of nitrogen input variables selected for the Narmada and the Mahanadi basins. For the Narmada basin, the NO\textsubscript{x} deposition plus nitrogen fertilizer variable was replaced with nitrogen fertilizer variable ($R^2$ lowered from 0.75 to 0.74) while for the Mahanadi basin the NO\textsubscript{x} deposition plus nitrogen fertilizer variable was replaced with only the nitrogen fertilizer variable ($R^2$ unchanged).
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**Fig. S1.** Contribution of predictor variables to modeled dissolved inorganic nitrogen fluxes ($Q_{\text{DIN}}$) for the seven examined basins. Fluxes (red dots, same values as Fig. 3) were modeled using the variables presented in Table S5 (black). The contribution of each variable is presented as a stacked polygon plot, with variables as defined in Table S5. The values of the predictor variables are minimum-deviated to help visualization, and the intercept was added to $P_{p>0.90}$, $P_{\text{JAS}}$, $N_{\text{Fert,Dep}}$, $N_{\text{Fert,Dep}}$, $T_{\text{JAS}}$, $n_{P>10\text{mm}}$, and $T_{\text{JAS}}$ for panels a-g, respectively.
Fig. S2. Fertilizer application rate for Indian river basins for 1980-2015 based on statewide fertilizer application rate data provided by the Directorate of Economics and Statistics, Department of Agriculture, Cooperation, and Farmers Welfare, Ministry of Agriculture and Farmers Welfare, Government of India. The decline in fertilizer application rate between 2011 and 2015 was due to a sharp increase in the price of nitrogen fertilizers during this period.
**Fig. S3.** NO$_x$ deposition rates for Indian river basins for 1980-2015 based on Lamarque et al.,$^5$. 

![Graph showing NO$_x$ deposition rates for Indian river basins from 1980 to 2015](image-url)

**Legend:**
- Blue: Brahmani and Baitarni
- Purple: Subernarekha
- Cyan: Narmada
- Green: Mahanadi
- Teal: Godavari
- Light Green: Cauvery
- Orange: Krishna

**Graph Description:** The graph shows the trend of NO$_x$ deposition (kg N km$^{-2}$ yr$^{-1}$) for different river basins in India from 1980 to 2015. The deposition rates are represented by different colored lines for each river basin: Brahmani and Baitarni, Subernarekha, Narmada, Mahanadi, Godavari, Cauvery, and Krishna. The x-axis represents the years from 1980 to 2015, and the y-axis represents the NO$_x$ deposition rates.
Fig. S4. Mann-Kendall trend test on flow-normalized concentration (A, C) and flow-normalized load (B, D) for the Narmada (A, B) and Mahanadi (C, D) basins. Significant increasing trends are observed in flow-normalized concentration and load for both basins.
Fig. S5. Observed vs. WRTDS-estimated natural log of DIN concentration across the seven examined basins.
Fig. S6. Comparison of $R^2$ values between observed vs. WRTDS-estimated natural log of DIN concentration, observed vs. WRTDS-estimated DIN concentration, observed vs. WRTDS-estimated DIN load, observed DIN load vs. observed discharge, and WRTDS-estimated DIN load vs. observed discharge for sampled days and all days for the seven examined basins for CWC basins (A) and river basins in United States (B).
### Supporting Tables

**Table S1.** Estimates of annual dissolved inorganic nitrogen flux ($Q_{DIN}$) [kg N km$^{-2}$ yr$^{-1}$] for major river basins as reported here and in earlier studies (see Source column). Estimates for Lambs et al. $^9$ and Subramanian et al. $^10$ were obtained by multiplying the reported concentration and discharge to obtain estimates of flux. Subramanian et al. $^10$ only report observed extreme concentration values, such that these estimates are not expected to be broadly representative. Dashes denote years and basins for which estimates are not reported in the cited studies. For each basin and year covered by earlier studies, we present corresponding estimates from the current study, based on results in Fig. 3. Dashes represent years for which fewer than six dissolved inorganic nitrogen measurements were available for a particular basin, and no estimate of flux is therefore presented in the current study. For context, we also present the mean and range of flux estimates from the current study for the period 1981-2014.

| Year | Basin            | Source                                      |
|------|------------------|---------------------------------------------|
|      | Brahmani & Baitarni | Subemarekha | Narmada | Mahanadi | Godavari | Cauvery | Krishna |
| 1998 | 5,302            | 598            | -       | 3,165    | 7,124    | 445     |          | Subramanian et al. (2008) |
|      | 827              | 608            | 239     | 207      | 163      | 249     | 101      | This study |
| 2000 | 730              | -              | -       | 606      | 404      | 223     | 206      | Seitzinger et al. (2014) |
|      | -                | 428            | 146     | -        | 167      | 340     | 18       | This study |
| 2001 | -                | -              | 252     | 227      | 82       | 4       | 52       | Lambs et al. (2005) |
|      | 1,470            | 916            | 256     | 417      | 166      | 244     | 5        | This study |
| 2011 | -                | 65             | 488     | 55       | 254      | 18      | 36       | Krishna et al. (2016) |
|      | 747              | 954            | 1,164   | -        | 172      | -       | -        | This study |
| 1981-2014 (mean) | 679              | 644            | 423     | 264      | 218      | 214     | 43       | This study |
| 1981-2014 (range) | (168,1470)       | (199,1161)     | (88,1778) | (142,547) | (74,441) | (24,690) | (1,138) | This study |

Note: Estimates from earlier studies are reported as averages over whole river basins, while results from this study represent average fluxes over 49% to 98% of the area of the seven examined basins, based on the area upstream of the stations used in the analysis (Table S2). The effect of this discrepancy is expected to be minor on a per unit area basis, but some differences are possible due to heterogeneity within basins and additional in-stream nitrogen losses between the measurement stations and the final ocean discharge point.
Table S2. Discharge and dissolved inorganic nitrogen (DIN) observations used for quantifying annual fluxes and characteristics of monthly DIN fluxes for each of the seven examined basins. The years of discharge observations used were selected based on availability of discharge throughout the entire year. Monthly DIN fluxes include the maximum observed monthly flux, the month with the highest average flux, the average seasonal flux from June to October, and the percentage of total annual fluxes occurring in June to October.

| Basin characteristics | Available observations | Dissolved inorganic nitrogen flux statistics |
|-----------------------|------------------------|---------------------------------------------|
|                       | Baseline area [km²]    | % Basin area upstream of station | Years of discharge observation used | Number of DIN observations during listed period | Maximum observed monthly DIN flux [kg N km⁻² month⁻¹] | Month with highest average DIN flux | Average monthly DIN flux in JJASO [kg N km⁻² month⁻¹] | Percent of annual DIN flux occurring in JJASO |
| Brahmani & Baitarni   | Brahmani               | Jenapur                          | 33,955                             | 65% | 1990-2013 | 269 | 720 | August | 108 | 79% |
| Subernarekha          | Ghatsila               |                                 | 14,176                             | 49% | 1990-2013 | 244 | 496 | August | 111 | 86% |
| Narmada               | Mandleshwar            |                                 | 72,809                             | 74% | 1987-2014 | 327 | 952 | August | 74  | 88% |
| Mahanadi              | Tikarapara             |                                 | 124,450                            | 88% | 1990-2006* | 167* | 226 | August | 46  | 87% |
| Godavari              | Polavaram              |                                 | 307,800                            | 98% | 1980-2013 | 609 | 204 | August | 41  | 94% |
| Cauvery               | Urachikottai          |                                 | 44,100                             | 54% | 1989-2011 | 220 | 246 | October | 29  | 68% |
| Krishna               | Vijayawada             |                                 | 251,360                            | 97% | 1981-2011 | 506 | 70  | August | 8   | 88% |

* Tikarapara station falls short of WRTDS application criteria, of more than 200 concentration measurements and more than 20 years of daily discharge values, but still has sufficient measurements for reliable flux estimate.11
**Table S3**: Characteristics of the river basins including population, annual rainfall, maximum and minimum temperature, and land use.

| Basin               | Population (2001 Census) | Mean annual rainfall (mm) | Mean Maximum Temperature (°C) | Mean Minimum Temperature (°C) | Built Up Land | Agricultural | Forest | Wasteland | Waterbodies |
|---------------------|--------------------------|---------------------------|-------------------------------|------------------------------|---------------|--------------|--------|-----------|-------------|
| Brahmani & Baitarni | 11,039,276               | 1395                      | 31.67                         | 20.32                        | 4.62          | 52.04        | 34.37  | 6.02      | 2.95        |
| Subernarekha        | 7,426,016                | 1459                      | 31.46                         | 20.5                         | 8.32          | 53.76        | 28.75  | 6.77      | 2.39        |
| Narmada             | 16,245,666               | 1042                      | 40.58                         | 10.87                        | 1.13          | 56.9         | 32.88  | 6.13      | 2.95        |
| Mahanadi            | 28,322,294               | 1292                      | 39.56                         | 20.01                        | 3.3           | 54.27        | 32.74  | 5.24      | 4.45        |
| Godavari            | 60,489,310               | 1093                      | 33.04                         | 20.63                        | 1.66          | 59.57        | 29.78  | 5.36      | 3.6         |
| Cauvery             | 31,889,280               | 1075                      | 34.31                         | 17.15                        | 4.01          | 66.21        | 20.5   | 3.86      | 4.09        |
| Krishna             | 66,341,683               | 859                       | 32.14                         | 20.52                        | 2.29          | 75.86        | 10.04  | 7.64      | 4.07        |
Table S4. Comparison of $R^2$ between WRTDS-estimated annual dissolved inorganic nitrogen flux ($Q_{DIN}$) and observed annual discharge ($Q$) and between $Q_{DIN}$ and total annual precipitation ($P_{Annual}$), where $P_{Annual}$ is based either on Indian Meteorological Department (IMD) data and Climate Prediction Center (CPC) data (https://psl.noaa.gov/data/gridded/data.cpc.globalprecip.html).

| Basin              | Number of years | $R^2$ | $Q$ | $P_{Annual}$ (IMD) | $P_{Annual}$ (CPC) |
|--------------------|----------------|-------|-----|-------------------|--------------------|
| Brahmani & Baitarni| 23             | 0.59  | 0.30| 0.22              |
| Subernarekha       | 22             | 0.83  | 0.58| 0.59              |
| Narmada            | 28             | 0.33  | 0.20| 0.40              |
| Mahanadi           | 15             | 0.82  | 0.80| 0.54              |
| Godavari           | 33             | 0.91  | 0.81| 0.51              |
| Cauvery            | 19             | 0.18  | 0.20| 0.30              |
| Krishna            | 23             | 0.96  | 0.20| 0.18              |
| All basins         | 163            | 0.65  | 0.52| 0.57              |
| Category                        | Variables considered                      | Variable description                                                                 | Considered | Allowed |
|--------------------------------|------------------------------------------|---------------------------------------------------------------------------------------|------------|---------|
| Nitrogen inputs                | $N_{\text{Fert}}$, ln($N_{\text{Fert}}$) | Fertilizer application rate [kg N km$^{-2}$ yr$^{-1}$] and natural log transformed fertilizer application rate | 2          | 1       |
|                               | $N_{\text{Fert, Dep}}$, ln($N_{\text{Fert, Dep}}$) | Fertilizer and NO$_x$ deposition and natural log transformed fertilizer and NO$_x$ deposition | 2          |         |
| Annual precipitation           | $P_{\text{Annual}}$                      | Total annual precipitation [mm]                                                       | 1          | 1       |
| Seasonal precipitation         | $P_{\text{JJAS}}$, $P_{\text{JAS}}$, $P_{\text{JASO}}$, $P_{\text{ASO}}$ | Total precipitation [mm] in June, July, August, and September (JJAS), in July, August, and September (JAS), in July, August, September, and October (JASO), and in August, September, and October (ASO) | 4          | 1       |
|                                | $n_{P>10\text{mm}}$, $n_{P>20\text{mm}}$ | Number of days with precipitation greater than 10 or 20 mm [days]                     | 2          |         |
|                                | $P_{p>0.90}$, $P_{p>0.95}$, $P_{p>0.99}$ | Total precipitation on days with precipitation above the 90th, 95th or 99th percentile (calculated based on 35 years of daily precipitation amounts for 1981-2015) [mm] | 3          |         |
|                                | $n_{\text{JJAS, P>10mm}}$, $n_{\text{JJAS, P>20mm}}$, $n_{\text{JAS, P>10mm}}$, $n_{\text{JAS, P>20mm}}$, $n_{\text{JASO, P>10mm}}$, $n_{\text{JASO, P>20mm}}$, $n_{\text{ASO, P>10mm}}$, $n_{\text{ASO, P>20mm}}$ | Number of days in JJAS, JAS, JASO, and ASO with precipitation greater than 10 or 20 mm [days] | 8          | 1       |
| Extreme precipitation          | $P_{\text{JJAS, p>0.90}}$, $P_{\text{JJAS, p>0.95}}$, $P_{\text{JJAS, p>0.99}}$, $P_{\text{JAS, p>0.90}}$, $P_{\text{JAS, p>0.95}}$, $P_{\text{JAS, p>0.99}}$, $P_{\text{JASO, p>0.90}}$, $P_{\text{JASO, p>0.95}}$, $P_{\text{JASO, p>0.99}}$, $P_{\text{ASO, p>0.90}}$, $P_{\text{ASO, p>0.95}}$, $P_{\text{ASO, p>0.99}}$ | Total precipitation [mm] in JJAS, JAS, JASO, and ASO on days with precipitation greater than 90th, 95th or 99th percentile (calculated based on 35 years of daily precipitation for 1981-2015) | 12         | 1       |
|                                | $P_{\text{JJAS, p(JJAS)>0.90}}$, $P_{\text{JJAS, p(JJAS)>0.95}}$, $P_{\text{JJAS, p(JJAS)>0.99}}$, $P_{\text{JAS, p(JAS)>0.90}}$, $P_{\text{JAS, p(JAS)>0.95}}$, $P_{\text{JAS, p(JAS)>0.99}}$, $P_{\text{JASO, p(JASO)>0.90}}$, $P_{\text{JASO, p(JASO)>0.95}}$, $P_{\text{JASO, p(JASO)>0.99}}$, $P_{\text{ASO, p(JASO)>0.90}}$, $P_{\text{ASO, p(JASO)>0.95}}$, $P_{\text{ASO, p(JASO)>0.99}}$ | Total precipitation [mm] in JJAS, JAS, JASO, and ASO on days with precipitation greater than 90th, 95th or 99th percentile (calculated based on 35 yrs of daily precipitation in JJAS, JAS, JASO, and ASO for 1981-2015) | 12         |         |
| Temperature                    | $T_{\text{Annual}}$, $T_{\text{JJAS}}$, $T_{\text{JAS}}$, $T_{\text{JASO}}$, $T_{\text{ASO}}$ | Average annual (Annual) and average JJAS, JAS, JASO, and ASO temperature [$^\circ$C] | 5          | 1       |
| Year                           |                                           | Calendar year [unitless]                                                              | 1          | 1       |
| **TOTAL**                      |                                           |                                                                                       | **52**     | **6**   |
Table S6. Linear model for representing dissolved inorganic nitrogen fluxes (Q_{DIN}) [kg N km^{-2} yr^{-1}] in each of the seven basins. The predictor variables in each model were selected based on the superset presented in Table S5. \( P_{p>90} \) is total precipitation on days with precipitation above the 90\textsuperscript{th} percentile calculated based on daily precipitation amounts for 1981-2015 [mm]. \( P_{JJAS} \) is total precipitation in June, July, August, and September [mm]. \( P_{Annual} \) is total annual precipitation [mm]. \( n_{P>10 \text{mm}} \) is the number of days with precipitation greater than 10 mm [days]. \( N_{Fert,Dep} \) is fertilizer application rate and NOx deposition [kg N km^{-2} yr^{-1}]. \( T_{JAS} \) is average temperature in July, August, and September [°C]. Y is calendar year (1981 to 2014).

| Basin               | Model for predicting annual DIN flux                                                                 | \( R^2 \) |
|---------------------|-------------------------------------------------------------------------------------------------------|----------|
| Brahmani & Baitarni | \( Q_{DIN} = 106 + 1.108 \cdot P_{p>0.90} \)                                                      | 0.38     |
| Subernarekha        | \( Q_{DIN} = -431 + 0.986 \cdot P_{JJAS} \)                                                        | 0.64     |
| Narmada             | \( Q_{DIN} = -1160 + 0.61 \cdot P_{JJAS} + 0.346 \cdot N_{Fert,Dep} \)                           | 0.75     |
| Mahanadi            | \( Q_{DIN} = -613 + 0.473 \cdot P_{JJAS} + 0.168 \cdot N_{Fert,Dep} \)                           | 0.91     |
| Godavari            | \( Q_{DIN} = 2047 + 0.447 \cdot P_{Annual} - 86.6 \cdot T_{JAS} \)                              | 0.87     |
| Cauvery             | \( Q_{DIN} = -68.9 + 12.3 \cdot n_{P>10 \text{mm}} \)                                             | 0.40     |
| Krishna             | \( Q_{DIN} = 1310 + 0.190 \cdot P_{Annual} - 53.8 \cdot T_{JAS} \)                              | 0.38     |
| All basins          | \( Q_{DIN} = -18,600 + 0.702 \cdot P_{Annual} + 9.07 \cdot Y \)                                | 0.57     |
**Table S7.** Percentage of the area of Indian states falling within each of the seven examined basins.

| States                        | Brahmani & Baitarni | Suberna- rekha | Narmada | Mahanadi | Godavari | Cauvery | Krishna |
|-------------------------------|---------------------|----------------|---------|----------|----------|---------|---------|
| Andhra Pradesh (incl. Telangana) | 1.0%                | 0.5%           | 54.2%   | 27.7%    |          |         |         |
| Chhattisgarh                  | 19.4%               | 15.8%          | 0.2%    |          |          |         |         |
| Gujarat                       | 4.2%                |                |         |          |          |         |         |
| Jharkhand                     | 2.3%                | 18.3%          | 58.2%   |          |          |         |         |
| Karnataka                     | 26.1%               | 27.6%          |         |          |          |         |         |
| Kerala                        | 7.6%                |                |         |          |          |         |         |
| Madhya Pradesh                | 26.6%               | 0.0%           | 7.7%    |          |          |         |         |
| Maharashtra                   | 0.5%                | 0.1%           | 47.9%   | 21.8%    |          |         |         |
| Orissa                        | 42.3%               | 11.1%          |         |          |          |         |         |
| Puducherry                    | 6.6%                | 27.6%          |         |          |          |         |         |
| Tamil Nadu                    | 36.5%               |                |         |          |          |         |         |
| West Bengal                   | 3.8%                |                |         |          |          |         |         |