Asian Journal of Water, Environment and Pollution, Vol. 14, No. 2 (2017), pp. 61–70.
DOI 10.3233/AJW-170016

Nutrient Chemistry of River Yamuna, India

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Received December 16, 2016; revised and accepted March 1, 2017

Abstract: Water samples were collected and analyzed for dissolved nutrient concentration and organic carbon in the Yamuna river system, from June 2014 to March 2015. pH, total dissolved solids (TDS), electrical conductivity (EC) and Dissolved oxygen (DO) concentration varied (Mean ± SD) in study area as 7.33±0.68, 489±305.3 (mg l^{-1}), 983.7±617.4 (µs/cm) and 5.85±3.41 (mg l^{-1}). Annual average concentrations and standard deviation of nitrate (NO_3^-N), nitrite (NO_2-N), ammonium (NH_4-N), phosphate (PO_4-P), silica (SiO_2-Si) and dissolved organic carbon (DOC-C) were 0.48±0.64, 0.14±0.30, 2.43±2.86, 0.43±0.59, 3.22±1.67 and 4.74±2.57 (mg l^{-1}), respectively in the Yamuna river system. The annual flux of nutrients from the Yamuna River for dissolved inorganic nitrogen (DIN), phosphate (PO_4-P), dissolved silica (SiO_2-Si), and dissolved organic carbon (DOC-C) were 43.5×10^4, 6.14×10^4, 40.9×10^4, 61.7×10^4 t $year^{-1}$ respectively. The positive values of the indicator of coastal eutrophication potential (ICEP) for both nitrogen and phosphate indicates an excess of nitrogen and phosphorus over silica in the Yamuna river water. Therefore, nutrient load from the Yamuna river system have the potential to create eutrophication problem in Ganga river.

Key words: Yamuna river, eutrophication, nitrogen, phosphate, ICEP.

Introduction

Nitrogen (N), phosphorus (P) and silicon (Si) are essential elements for both freshwater and marine ecosystem organisms and the riverine inputs are the major source of nutrients to the sea (Meybeck, 1982; Mayer et al., 1998; Ramesh et al., 2015). In the past decades due to increased anthropogenic activities such as intensive use of chemical fertilizers for crop production and discharge of waste from domestic and industries along with land use changes have resulted in the five and three to four times increase in loading of nitrogen and phosphate in most of the river systems all over the world (Meybeck 1982; Pizarroa et al., 2010).

The factors which control the loading rate of N, P and Si into rivers are dissimilar. Nitrate, ammonium, and phosphate loading are dependent on the fertilizer application, land use pattern and population density (Howarth et al., 1996; Caraco and Cole 1999). The rapid growth of population, urbanization, industrialization and development along the river basin has increased the stress on the river which is leading to the water pollution and deterioration of the environment (Sumok, 2001). The increased loading of nutrients in river water has resulted in putting emphasis on measuring dissolved nutrient concentration, such as nitrogen, phosphate and carbon to assess the pollution level in the aquatic system (Lima et al., 2010).

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The Yamuna River is one of the most important and sacred rivers of India. It is the largest tributary of the River Ganges, originating in the Yamunotri glacier in the Mussoorie range of the lower Himalayas. It is one of the most polluted river system in India. The stretch between Delhi to Agra have been converted into an open sewer due to the combined effect of withdrawal of water for irrigation and domestic and industrial supply along with a discharge of domestic, industrial and agricultural wastewater (CPCB, 2006; Parween et al., 2014). The objective of the present study was to quantify the spatial variation of nutrients (ammonium, nitrate, nitrite, phosphate, and silicate) and dissolved organic carbon in the Yamuna river system and its flux to River Ganga. We also identify factors affecting the nutrient chemistry in the Yamuna river system by using statistical analysis. We also assessed the effect of dissolved nutrient load transported by the Yamuna River on Ganga water quality at confluence by using indicators such as dissolved elemental ratios and parameters such as the indicator of coastal eutrophication potential (ICEP) proposed by Garnier et al. (2010).

Materials and Methods

Study Area Detail

The study area map showing river Yamuna and its tributaries along with sampling location is given in Figure 1. Yamuna River is the largest tributary of the Ganga river and its own tributaries are Chambal, Sind, Betwa and Ken in the lower plain area while Tons and Giri are in the Himalayas. The river originates from the Yamunotri glacier near Banderpunch peaks of lower Himalayas (38° 59′ N and 78° 27′ E) in the Mussoorie range at an elevation of about 6387 metres above from mean sea level of Uttarkashi district (Uttarakhand) and flows through seven states. The total catchment basin area of the Yamuna river is 3,66,223 km^2, which is 42.5% of Ganga basin and 10.7% of the total geographical landmass of the country (CPCB, 2006). The climate of the Yamuna river basin is heterogeneous and is classified as humid at the upstream Himalayan catchment, semiarid in the northwest to the western catchment, and sub-humid in southwest catchments. The average annual rainfall varies between 400 and 1500 mm which is received from the south-west monsoon from June to September months. The annual mean maximum temperature varies between 24 and 42.5 °C and mean minimum temperature ranged between –1.0 and 11.0 °C, respectively in the basin area (CPCB 2006).

The topography of Yamuna River can be classified into three groups, i.e. hilly region, foothills and plateau region, and plains and valleys. On the basis of classification 11,700 km^2 basin area is hilly (about 3.19%) while the remaining is divided between plains (161,231 km^2) and plateau (172,917 km^2) regions (CPCB, 2006). There are eight soil types present in the Yamuna river basin, major type is alluvial, medium black and mixed red and black type which covers 42%, 25.5% and 15% of the basin area respectively (CPCB, 2006).

The major land use types in the river basin are agriculture, forest, urban and barren land. The agriculture covers 60% of the area, forest area covers 12.5%, the urban area covers 2.9% and remaining 24.6% is covered by non-arable land (CPCB, 2006).

Analytical Methodology

Water samples (n = 32) were collected in acid-cleaned polyethylene bottles from Yamuna river, including the upstream region from Barkot, Dakpathar to Palla (n = 8), Delhi region from Wazirabad to Okhla barrage (n = 15) and downstream region from Palwal to Allahabad (n = 9) in pre-monsoon and post-monsoon seasons (June 2014–March 2015) (Figure 1). Water samples (n = 4) were also collected from its major tributaries (Hindon, Chambal, Ken, Betwa), where n indicated the number of samples collected during each sampling. On-site measurements included measurements of Total Dissolved Solids (TDS), Electrical Conductivity (EC), pH and Dissolved oxygen (DO) using multi-parameter probe from Hanna (HI 9828). Samples were then transported in an ice box to the laboratory. In the laboratory, water samples were filtered through precombusted and preweighed 0.45 micron nylon filter paper and then analyzed for dissolved nitrate (NO_3-N), nitrite (NO_2-N), ammonium (NH_4-N), phosphate (PO_4-P), and silica (SiO_2-Si) by using photometrically method given by APHA (1998) using UV-VIS Spectrophotometer (Thermo Scientific). Dissolved organic carbon (DOC) was analyzed using a TOC analyzer (Analytic Jena, Multi N/C 2100, Germany). Before DOC analysis, water samples were acidified with 1N HCl solution and purged with N_2 gas for removal of inorganic carbon content.

All the statistical analysis was done using "Statistical Package for Social Sciences (SPSS), version-10.0" (SPSS, Inc., Chicago, IL, USA). The Spearman correlation coefficient was used to determine significant correlations between the different parameters in the Yamuna river system. Factor analysis was carried out

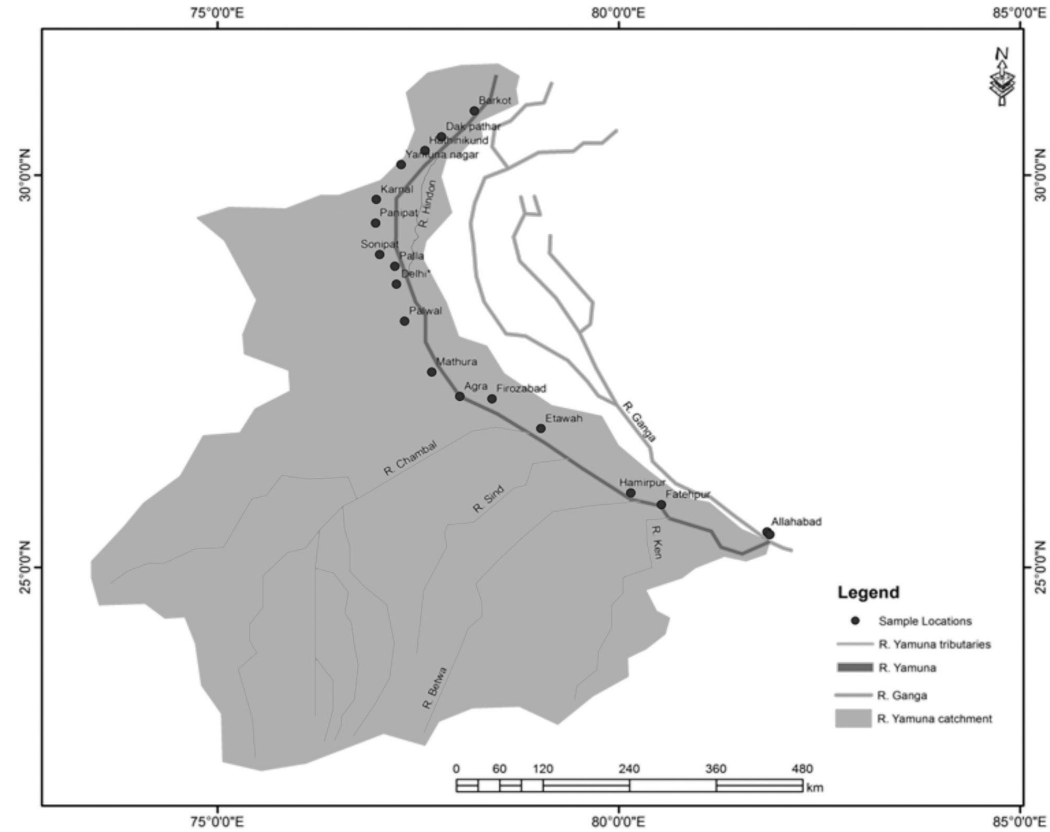

Figure 1: Line diagram of Yamuna river showing sampling locations and major tributaries.

for all the parameters to identify the factor controlling the nutrient chemistry in the river basin.

Results and Discussion

Dissolved Nutrients and Physicochemical Characteristics

The composition of Yamuna river water, including dissolved nutrients and physicochemical parameters along with its comparison with the unpolluted river is given in Table 1.

pH of Yamuna river was found mildly acidic to alkaline in nature and varied from 6.49-9.12 as found in most of the Indian rivers. EC varied from 97 to 2846 (µs/cm) and TDS ranged between 48 and 1421 (mg l^{-1}) indicated anthropogenic input mainly from domestic or industrial waste which contributes to the high dissolved organic load in Yamuna river. Both EC and TDS show increasing trend as we move from upstream to downstream indicating that as the river moves more and more solutes are getting added from both natural and anthropogenic sources present in the study areas (Table 1). DO concentration ranged from 0.41 to 12.28 with the mean and standard deviation of 5.36±0.41 (mg l^{-1}) in Yamuna river. The low dissolved oxygen concentration was observed in a Delhi stretch of the Yamuna as reported by other studies also (Katyal et al., 2012; CPCB, 2006). Delhi is the biggest polluter of River Yamuna, which contributes about 26% (year 2001) to 33% (year 2000) of total BOD load and 48% (year 2003) to 52% (year 2001) of total waste water discharge that joins the Yamuna river at Delhi by various drains (CPCB, 2006). In the Yamuna River system, the concentration of nutrients was found relatively higher in comparison to the concentration found in an unpolluted river (Meybeck, 1979, 1982) which indicates that nutrient chemistry of the river is highly influenced by the anthropogenic activities taking place in the river catchment area (Table 1). In total there are 69 Class-I cities and 61 Class-II towns in the Yamuna Basin, which generate about 8444 MLD of wastewater. Delhi alone generates about 45% of the entire sewage generated in the Basin, and contributes 36% of sewage discharged into the Yamuna river (MOEF, 2010).

NO_3-N concentration was in the range of 0.03 to 3.20 with a mean value of 0.48 (mg l^{-1}) in the Yamuna river system. The observed NO_3-N concentration in the Yamuna river system was similar to the average nitrate concentration reported for the South Asian rivers (Subramanian, 2008). The NO_3-N concentration observed in Yamuna river was four times higher than the concentration reported for unpolluted rivers (Table 1) indicating the contribution from anthropogenic sources, including both point and non-point sources present in the river basin. The major source of nitrate concentration includes agricultural runoff, domestic waste discharge, atmospheric precipitation along with the in-stream bacterial transformation of ammonium ion present in the river system. NH_4-N ion was the dominant form of dissolved inorganic nitrogen (DIN) in the range of 0.05 to 9.38 with an average value of 2.43 (mg l^{-1}) in the Yamuna river system. The NH_4-N concentration observed in Yamuna river was 120 times higher than the concentration reported for unpolluted rivers (Table 1) indicating the contribution from domestic sewage waste.

About 85% of the total pollution in the Yamuna river is caused by the domestic sources and major urban centres dumping domestic waste into Yamuna River is Panipat, Sonepat, Delhi, Ghaziabad, Mathura-Vrindavan, Agra, Etawah and Allahabad (CPCB, 2006). The observed NH_4-N concentration in the Yamuna river system was relatively higher than the concentration reported for the three major rivers of China Changjiang, the Huanghe and the Zhujiang (Shuiwang et al., 2000). The NO_2-N concentration varies from 0.001 to 1.30 with an average value of 0.14 (mg l^{-1}) in the Yamuna river system. The observed concentration was 70 times higher than the values reported for unpolluted rivers (Table 1) indicating the contribution from domestic sewage waste.

PO_4-P concentration was in the range of 0.01 to 2.28 with an average value of 0.43 (mg l^{-1}) in the Yamuna river system. The observed PO_4-P concentration in the Yamuna river system was 40 times higher than the value reported for unpolluted rivers (Table 1) indicating the contribution from anthropogenic sources, including domestic waste discharge along with agricultural runoff present in the river basin. The observed PO_4-P concentration in Yamuna river was relatively higher than the reported PO_4-P concentration in most of the Indian rivers indicating higher anthropogenic load in Yamuna river basin (Ramesh et al., 1995). PO_4-P is also an essential plant nutrient which in low concentration controls the primary productivity of aquatic ecosystem (Raimbault and Moutin, 2002). The PO_4-P enters the surface water through different sources which include approximately 45% domestic, 45% agriculture and the rest comes from industrial and background sources (Morse et al., 1993).

SiO_2-Si concentration was in the range of 0.01 to 2.28 with an average value of 0.43 (mg l^{-1}) in the Yamuna river system. SiO_2-Si concentration in river water mainly depends upon the weathering rate in the catchment area along with SiO_2-Si uptake by biota in the stream channel along with contribution from SiO_2-Si rich groundwater. SiO_2-Si concentration observed in Yamuna river was relatively lower than the value reported for unpolluted river (Table 1) which can be due to higher biotic uptake of SiO_2-Si in the eutrophic stretch of Yamuna river along with retention of SiO_2-Si within the river basin due to presence of dams and barrage in a river basin

Table 1: Annual average concentration of nutrients in the Yamuna river system and its comparison with baseline concentration of these nutrients in an unpolluted river

Yamuna river	*NH_4-N (mg/l) (mean±SD)*	*NO_3-N (mg/l) (mean±SD)*	*NO_2-N (mg/l) (mean±SD)*	*PO_4-P (mg/l) (mean±SD)*	*SiO_2-Si (mg/l) (mean±SD)*	*DOC-C (mg/l) (mean±SD)*	*DO (mg/l) (mean±SD)*	*TDS (mg/l) (mean±SD)*
Yamuna river system (including tributaries)	2.43±2.86	0.48±0.64	0.14±0.30	0.43±0.59	3.22±1.67	4.74±2.57	5.85±3.41	489±305.3
Up-Stream	0.30±0.38	0.46±0.3	0.09±0.12	0.09±0.12	3.49±2.41	1.31±0.67	8.27±2.10	197128.2
Delhi	5.24±2.57	0.20±0.21	0.04±0.05	0.48±0.43	3.52±1.15	5.40±1.79	2.50±1.88	553±236.4
Downstream	1.69±2.11	0.88±1.02	0.31±0.43	0.76±0.85	2.28±1.26	5.93±2.17	7.67±2.33	702±313.2
Tributaries	0.79±1.74	0.38±0.33	0.15±0.41	0.22±0.46	3.89±1.47	5.03±2.17	7.10±2.34	404±265.2
Unpolluted river[a]	0.02	0.10	0.002	0.01	4.85[b]	5.75		
Nutrient ratio (Yamuna river system)								
Ratios	Range	Mean ± SD						
DIN/DIP	4-147	33 ± 27						
DSi/DIN	0.1-16	2 ± 3						

[a]Meybeck (1982), [b]Meybeck (1979)

(Humborg et al., 2000). DOC-C in the river system can originate from both allochthonous carbon, which is produced on land and autochthonous carbon, which is produced within a river system (Spitzy and Leenhear, 1991). DOC-C concentration was in the range of 0.28 to 9.47 with an average value of 4.74 (mg l^{-1}) in Yamuna river system. The observed DOC-C concentration in Yamuna river system was similar to concentration observed in River Ganges and relatively higher than the DOC concentration reported in Brahmaputra (Ramesh et al., 1995).

Factors Controlling Nutrient Chemistry of Yamuna Rivers

To understand factors controlling water chemistry in the Yamuna river system we carried out statistical analysis including correlation and factor analysis (Patel et al., 2016; Raju et al., 2016). The spearman correlation coefficient was used to study the relationship between the various parameters during pre-monsoon and post-monsoon season and results are given in Table 2. Both TDS and EC showed strong correlation with NO_3-N, PO_4-P and DOC-C concentration during post-monsoon and with PO_4-P concentration during pre-monsoon season indicating an increasing contribution of dissolved nutrient in total dissolved solid load during the post-monsoon season. NH_4-N ion showed strong negative correlation with DO concentration in the Yamuna river system indicating lower oxygen concentration, especially in the Delhi stretch of Yamuna River which is measured factor behind the build up of NH_4-N concentration in the river (Table1). NH_4-N ion also showed a positive correlation with PO_4-P ion in the Yamuna river system indicating input from domestic waste pollution in the Yamuna river system (Table 2). Both NO_3-N and NO_2-N showed a positive correlation (Table 2) in the Yamuna river system which may be either due to input from the same source in the catchment area or due to the microbial transformation of NH_4-N load in the river channel.

Table 2: Spearman correlation matrix of nutrients and physiochemical characteristic in pre-monsoon and post-monsoon season in Yamuna River

	Per-Monsoon									
	pH	*TDS*	*EC*	*DO*	*NO_3-N*	*NO_2-N*	*NH_4-N*	*PO_4-P*	*SiO_2*	*DOC*
pH	1									
TDS	**-0.503**	1								
EC	**-0.531**	**0.992**	1							
DO	0.163	-0.119	-0.100	1						
NO_3-N	-0.265	0.205	0.280	0.477	1					
NO_2-N	-0.253	0.097	0.194	0.404	**0.803**	1				
NH_4-N	-0.199	0.479	0.487	**-0.691**	-0.211	-0.096	1			
PO_4-P	-0.215	**0.521**	**0.574**	-0.201	0.307	0.221	**0.560**	1		
SiO_2	**0.600**	-0.343	-0.322	0.102	-0.127	-0.053	0.037	0.167	1	
DOC	-0.004	0.318	0.315	-0.220	0.247	0.379	0.241	-0.028	-0.301	1
	Post-Monsoon									
pH	*1*									
TDS	-0.184	1								
EC	-0.176	**1.000**	1							
DO	-0.475	-0.287	-0.292	1						
NO_3-N	-0.244	**0.518**	**0.508**	0.068	1					
NO_2-N	-0.364	**0.640**	**0.633**	0.061	**0.879**	1				
NH_4-N	0.282	0.339	0.345	**-0.767**	0.075	0.171	1			
PO_4-P	-0.277	**0.719**	**0.717**	-0.135	**0.567**	**0.671**	0.436	1		
SiO_2	**0.594**	0.035	0.043	**-0.867**	-0.190	-0.124	**0.780**	0.060	1	
DOC	**0.601**	**0.695**	**0.697**	**-0.628**	-0.032	-0.244	0.306	0.269	0.441	1

Coefficients in bold are significant at $P < 0.0$.

Factor analysis serves for basic, independent dimensions of variance and with the help of linear combinations, an originally large number of variables are reduced to a few factors. These factors can be interpreted as a new variable. Factor analysis is a way of classifying manifestation of variables (Cattel, 1965; Kumar et al., 2006; Jha et al., 2009) and this analysis aims to explain the observed relation between numerous variables in terms of simpler relations. In the present study, R-mode factor analysis was done to identify the major factors which are controlling the water chemistry of the Yamuna river system. The factors with eigenvalue >1.0 within the data have considered the significant factor. The degree of association between each variable and each factor is given by its loading on that particular factor. Results of factor analysis for pre-monsoon and post-monsoon season samples of the Yamuna river system is given in Table 3. During the pre-monsoon season, three factors were identified which explain 47% variation in the measured parameter in the Yamuna river system. Factor 1 showed positive loading for TDS, EC and NH_4-N and negative loading for pH and dissolved oxygen. This factor indicates the anthropogenic contribution from domestic and industrial sewage waste which is directly discharged into the river water. Factor 2 accounts for 22.1% of the variance and the variables included are NO_3-N, NO_2-N and DOC-C which indicates the input from agricultural run-off taking place in the river catchment area. Factor 3 accounts for 17.3% variation in the data and have only SiO_2-Si as a variable which indicates a contribution from weathering reaction taking place in the catchment area along with biological uptake by biota in the river channel.

For post-monsoon season also, three factors were identified which altogether accounts for 86.7% variation in the data set. Factor 1 accounts for 42.8% variance and the variables present are TDS, EC, DO, NH_4-N, PO_4-P and SiO_2-Si. This factor indicated input from domestic and industrial sewage waste along with weathering reaction taking place in the catchment area. Factor 2 accounts for 23.7% variation in the data set and the variables present are pH and DOC which indicated high organic input from domestic waste along with runoff from catchment areas. Factor 3 accounts for 20.1% variance and it includes NO_3-N and NO_2-N indicating input from agricultural run-off along with microbial transformation process taking place in the river channel.

Dissolved Nutrient Elemental Ratio

An elemental ratio that aquatic organisms tend to require for sustained growth was given by Redfield and this includes 16:1 DIN/DIP for phytoplanktons (Redfield et al., 1963) and 1:1 for DSi/DIN for diatoms (Turner et

Table 3: Factor analysis of Yamuna river system water samples for pre and post-monsoon season

	Pre-monsoon				***Post-monsoon***			
	Factor 1	*Factor 2*	*Factor 3*	*C**	*Factor 1*	*Factor 2*	*Factor 3*	*C**
pH	-0.651	0.496	0.463	0.884	0.095	0.748	-0.415	0.741
TDS	0.956	0.044	-0.222	0.966	0.706	0.556	0.274	0.882
EC	0.956	0.041	-0.221	0.965	0.711	0.560	0.235	0.874
DO	-0.829	0.080	0.448	0.894	-0.860	-0.420	0.051	0.920
NO_3-N	-0.316	0.850	0.236	0.878	-0.182	0.109	0.866	0.795
NO_2-N	0.014	0.900	-0.001	0.810	0.157	-0.299	0.897	0.919
NH_4-N	0.906	-0.142	-0.221	0.890	0.933	0.132	-0.164	0.914
PO_4-P	0.886	-0.164	0.133	0.835	0.918	-0.048	0.104	0.855
SiO_2-Si	-0.199	0.115	0.896	0.856	0.827	0.284	-0.342	0.882
DOC-C	0.164	0.609	-0.544	0.693	0.274	0.902	-0.007	0.889
Eigen value	4.719	2.220	1.734		4.283	2.374	2.014	
% of variance	47.189	22.198	17.340		42.829	23.745	20.141	
Cummulative %	47.189	69.387	86.727		42.829	66.571	86.715	

*C denotes communalities.

al., 2003) in fresh and marine aquatic system. Significant deviation from these elemental ratios indicates a growth limiting deficiency of one element (Turner et al., 2003). In Yamuna river system the DIN/DIP molar ratio ranged from about 4 to 147 with an annual average value of 33±27 (Table 1). The DIN/DIP ratio calculated for Yamuna River was found almost two times of Redfield ratio and this indicated the P limitation in the Yamuna River (Figure 2a).

The DSi/DIN molar ratio varied from 0.1 to 16 with an annual average value of 2 ± 3 in the Yamuna River system (Table 1). The average DSi/DIN molar ratio was found higher than 1, the ratio given by Turner et al. (2003) for the aquatic system for the upstream, downstream region and tributaries of the Yamuna river system indicating that the water quality of these is conducive to the growth of diatom and hence, minimizing the chances of algal bloom (Figure 2b). When DSi/DIN molar ratio decreases below the critical ratio of 1:1, the growth of non-diatom phytoplankton species (dinoflagellates including harmful noxious bloom forming algal communities) becomes more prominent over diatom and hence leads to a fisheries food web composed of less desirable species (Officer and Ryther, 1980). The Delhi stretches of Yamuna river showed DSi/DIN molar ratio lower than 1; thus having the problem associated with eutrophication in the entire stretch (Figure 2b).

Dissolved Nutrient Load

The annual flux and specific yield of nitrogen, phosphate and silica were calculated using the nutrient concentrations, annual discharge and drainage area data. The result of the annual flux (10^4 t year^{-1}) and specific yield (tons per square kilometre per year) of dissolved nutrient transported by the Yamuna river system is given in Table 4.

Total annual transport of dissolved inorganic nitrogen (DIN) from Yamuna River was 43.56 × 10^4 t year^{-1}. NH_4-N with an annual flux of 35.2 × 10^4 t year^{-1} constituted about 80.7% of DIN load transported on the Yamuna River indicating high input from domestic sewage waste. The annual flux of PO_4-P, SiO_2-Si and DOC was estimated at 6.14 × 10^4, 40.9 × 10^4 and 61.7 × 10^4 t year^{-1} from the Yamuna River. The annual specific yield of NO_3-N and PO_4-P was 0.18 t km^{-2} year^{-1} and 0.17 t km^{-2} year^{-1} respectively in the Yamuna river system. The specific yield of nitrate was in the range reported for other major river systems, but phosphate loading in Yamuna river catchment is very high and can be one major factor behind the eutrophication problem in the Yamuna river system (Table 5).

Indicator of Coastal Eutrophication Potential (ICEP)

ICEP is based on the Redfield molar C:N:P:Si ratio of 106:1:20 (Redfield et al., 1963; Conley et al., 1993). ICEP represents the production of new non-siliceous algal biomass in the receiving water body by either nitrogen or phosphate transported in excess over the silica (Garnier et al., 2010).

We use ICEP value for nitrogen and phosphate (kg C.km^{-2}day^{-1}) to assess the impact on nutrient transported by Yamuna river on receiving water body that is Ganga river. According to nutrient considered, N-ICEP and P-ICEP were calculated by using the formula given by Garnier et al. (2010).

$$\text{N-ICEP} = \{\text{NFlx}/(14\times16) - \text{Si Flx}/(28\times20)\} \times 106 \times 12 \quad (1)$$

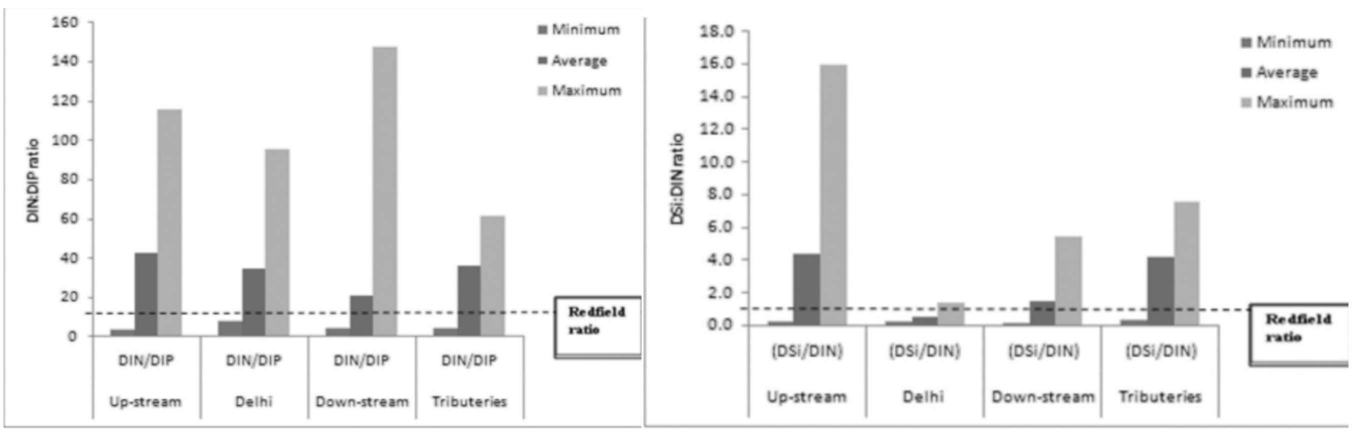

Figure 2: Comparison of DIN:DIP and DSi:DIN ratio obtained from the Yamuna river system with Redfield ratio (2014-2015): a—DIN:DIP, b—DSi:DIN.

Table 4: Annual yield and flux of nutrients in Yamuna River

Parameters	*NH_4-N*	*NO_3-N*	*NO_2-N*	*DIN-N*	*PO_4-P*	*SiO_2-Si*	*DOC-C*
Annual yield (t $km^{-2}year^{-1}$)	0.96	0.18	0.05	1.19	0.17	1.12	1.68
Annual flux (10^4 t $year^{-1}$)	35.2	6.52	1.87	43.56	6.14	40.9	61.7

Table 5: Comparison of nutrient-specific yield (tons per square kilometre per year) of Yamuna River with major world rivers

River	*Discharge (km^3year^{-1})*	*Drainage (10^3km^2)*	*NO_3-N (t $km^{-2}year^{-1}$)*	*PO_4-P (t $km^{-2}year^{-1}$)*	*SiO_2-Si (t $km^{-2}year^{-1}$)*	*Reference*
Yamuna, India	131.7	366	0.18	0.17	1.12	This study
Amazon, USA	6938	7050	0.14	0.021	3.16	DeMaster and Pope (1996)
Chagjian, China	925	1800	0.40	0.008	1.17	Liu et al. (2003)
Trinity, USA	22	46	0.27	0.03	1.09	Guo et al. (2004)
Ebro, Spain	12	89	0.15	0.002	0.14	Falco et al. (2010)
Pra Basin, Ghana	7	23	0.034	0.11	3.78	Akrasi and Ansa-Asare (2008)
Yukon, Alaska	200	855	0.008	0.0004	0.53	Guo et al. (2004)
Mississippi, USA	600	3250	0.30	0.04	0.64	Berner and Berner (1996)
Tapti, India	18.9	61	0.15	0.04	1.47	Sharma and Subramanian (2010)
Narmada, India	41.3	98	0.13			V. Subramanian (2008)

$$\text{P-ICEP} = \{\text{PFlx}/31 - \text{Si Flx}/(28\times20)\} \times 106 \times 12 \quad (2)$$

where NFlx, PFlx and SiFlx expressed in kg N km^{-2} day^{-1}, kg P $km^{-2}day^{-1}$ and kg Si $km^{-2}day^{-1}$ are the mean specific fluxes of total nitrogen, total phosphate and dissolved silica respectively, delivered at the outlet of the river basin.

The N-ICEP value was 11.6 kg C.km^{-2} day^{-1} and P-ICEP was 11.9 kg C.km^{-2} day^{-1} for the Yamuna river system. The positive value of N-ICEP and P-ICEP indicated the excess loading of nitrogen and phosphate over silica to the receiving water bodies which favour the growth of non-diatoms phytoplankton species and eutrophication. Thus, the nutrient load from the Yamuna river system has the potential to create eutrophication problem in Ganga River at its confluence point.

Conclusion

Dissolved nutrients showed significant spatial variation in the Yamuna river system indicating variation of relative input from natural and anthropogenic sources present in the catchment area with space. Nutrient concentration in the Yamuna river system is mainly controlled by anthropogenic activities including domestic and industrial sewage waste along with runoff from agricultural and urban areas occurring in the catchment areas as indicated by factor analysis. In Yamuna river system molar ratio for DIN/DIP was always found higher than 16:1, indicating phosphate limitation in biological productivity. The average molar ratio of DSi/DIN was 2 ± 3 in the Yamuna River system and its water was conducive for the growth of diatom except in Delhi stretch where DSi/DIN molar ratio was lower than 1, thus having the problem associated with eutrophication. Annual nutrient transport from Yamuna river system during 2014-2015 year for dissolved inorganic nitrogen (DIN-N), phosphate (PO_4-P), dissolved silica (SiO_2-Si) and dissolved organic carbon (DOC-C) were 43.56 × 10^4, 6.14 × 10^4, 40.9 × 10^4 and 61.7 × 10^4 t $year^{-1}$, respectively. The specific yield of phosphate ion was relatively higher compared to other major river basins of the world, indicating higher phosphate loading in Yamuna river catchment due to anthropogenic activities. The positive value of N-ICEP and P-ICEP for Yamuna river system indicates the excess loading of nitrogen and phosphorus over silica, which favours the growth of non-diatom phytoplankton species and eutrophication in the receiving water bodies that is River Ganges.

Acknowledgements

Authors are thankful to the Department of Science and Technology (DST), India for providing funding for research work presented in this paper. The authors thank Dr. Anil Kumar Haritash for providing the facility for the analysis of dissolved organic carbon. The authors also thank Dr. Anjali Singhal and Mr. Ali for providing assistance during sampling work and the Editor and anonymous reviewers for giving suggestions which have markedly improved the manuscript.

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