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Seasonal monitoring of heavy metals and physicochemical characteristics in a lentic ecosystem of subtropical industrial region, India

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Abstract Assessment of seasonal changes in surface water quality is an important aspect for evaluating temporal variations of lentic ecosystem (lakes and reservoirs) pollution due to industrial effluent discharge. In this study, nine metals and 15 physicochemical parameters, collected from four sampling sites in a tropical lake receiving the discharge from thermal power plant, coal mine, and chloralkali industry, during the years from 2004 to 2005, were analyzed. For greater efficacy in monitoring of heavy metals, particle-induced X-ray emission has been used during present investigation. Different statistical techniques like analysis of variance, Pearson correlation, principal component analysis, and factor analysis were employed to evaluate the seasonal correlations of physicochemical parameters. Most of the metals and physicochemical parameters monitored in the present study exhibited high spatial and temporal variability. Pertaining to metal pollution, the most polluted site was Belwadah, i.e., waters and sediments had the highest concentration of all the relevant metals. The reference site was characterized by the presence of low concentrations of metals in waters and in sediments. Based on the high metal concentration recorded in lake ambient, drinking, bathing, and irrigation water should not be used by the local people at the effluent discharge points.

Keywords Heavy metals · Water pollution · Principal component · Factor analysis · Biomagnification

Introduction

Water is an integral component of the environment, responsible for various life processes and hence persistence of life on this planet. Pollution of surface water and sediments with toxic chemicals and eutrophication of rivers and lakes with excess nutrients are of great environmental concern worldwide (Tripathi and Shukla 1991; Ouyanga et al. 2006; Rai 2007, 2008a, b, d; Rai and Tripathi 2007a, b, 2008, 2009). Also, the heavy metals show the high propensity for biomagnification (Rai 2008a, b, c). Industrial effluents and wastes dumped into nearby water bodies alter its physicochemical characteristics and elevate the heavy metal concentration according to the nature of effluent being discharged (Singh et al. 2005; Rai 2008a, b). Therefore, in order to understand the environmental chemistry of metals, it is necessary to include the physicochemical parameters, especially the amount of free metal ions and very

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labile complexes under the diverse range of conditions possible in natural systems (Okonkwo and Mothiba 2005).

Waste load discharged in aquatic ecosystems without pretreatment makes the water quality unfit for most other human uses. Although water bodies have some self-purification capacity, in most instances, the level and quality of effluent discharged are far beyond the purifying capacity. Particularly, lentic ecosystems are more prone to the problem of water pollution due to low capacity of self-purification and pollutant dispersal (Rai et al. 2007; Rai 2008b). There are several studies on limnological aspects of the aquatic systems in different parts of the world (Hutchinson 1975; Ravindra et al. 2003; Bellos and Sawidis 2005; Singh et al. 2005; Okonkwo and Mothiba 2005; Oyewale and Musa 2006; Ouyanga et al. 2006; Rai and Tripathi 2009). Oyewale and Musa (2006) provided information on the quality of the water and sediments of Lakes Kainji/Jebba, Nigeria. Recently, Rai (2008c, d) and Rai and Tripathi (2009) have studied the Hg and Cd concentrations in industrial effluents of thermal power plant, coal mine, and chloralkali industry in the Singrauli region and assessed their correlation with their content in water, sediment, and macrophytes of G.B. Pant Sagar.

Furthermore, it has been recognized that pollution of water by metals brings obvious changes in physicochemical properties and makes the water toxic to various life forms (Rai and Tripathi 2006, 2009).

In the light of aforesaid facts, the present study aimed to investigate the temporal (seasonal) and spatial (site wise) variation in a tropical lake, in relation to physicochemical parameters and heavy metals.

Description of study area, sources of pollution, and sampling sites

The Singrauli region straddles the border between the states of Madhya Pradesh and Uttar Pradesh in northern India. The most environmentally disturbed part of the region is a rapidly urbanizing area (Rai et al. 2007; Rai and Tripathi 2009). Until the early 1960s, Singrauli was an isolated rural area. As late as 1981, land use was divided between arable land (36%), forests (35%), and the Rihand reservoir (15%), with the remainder not available for cultivation. But now, the region is now one of India's most important energy centers. Eleven opencast mining sites, occupying nearly 200 km^2, fuel six thermal power stations that generate 6,800 MW which constitutes about 10% of India's installed generation capacity; estimated reserves are capable of supporting 20,000 MW of installed capacity for the next 130 years (2009).

Meteorological data were collected from the Central Mine Planning and Design Institute Limited, Sidhi. Climate of this area is typically monsoonal. Due to marked variation in temperature and rainfall, the year is divided into three distinct seasons, i.e., rainy (July to October), winter (November to February), and summer (March to June). Rainy season is humid and warm. It is characterized by high rainfall (about 80–90% of total annual precipitation), high relative humidity (70–80%), and low diurnal temperature fluctuation. Winter season is relatively dry with occasional rains in the month of January. Average relative humidity was around 60%. Diurnal temperature ranges between 20°C and 28°C.

G.B. Pant Sagar (study site)

This is one of Asia's largest man-made reservoirs developed at Rihand dam. Total area of the reservoir is approximately 457 km^2.The area of submergence is 46,600 ha. The released water flows to north through the industrial belt and joins the river Son near Chopan, at 15 km down to Obra. Thus, G.B. Pant Sagar is of great importance to the people of the area not only to the Singrauli region but also to the entire eastern Uttar Pradesh. The water of reservoir is used for

1. Drinking
2. Irrigation
3. Fish farming
4. Bathing
5. Generation of 300-MW hydroelectricity and industrial purposes

The rapid pace of industrialization and urbanization has given birth to the problem of water pollution of the reservoir (Rai et al. 2007).

Singrauli region lies in the close vicinity of G.B. Pant Sagar; the factories of the area regularly discharge their effluents into the reservoir. Figure 1 shows the topographical map of Singrauli region locating G.B. Pant Sagar.

Before going for detailed investigation, it was necessary for me to identify major pollution sources of G.B. Pant Sagar. Therefore, I made a general survey and observed that 11 opencast mines fueling six thermal power plants and a chloralkali industry preparing agrochemicals are major contributors. Then, we conducted spot testing of metals in effluents at 11 locations (ten discharge points) and found that Anpara, Bina, and Kannoria were the most polluted and one site near Rihand dam recorded very low concentration of different metals (Table 1). Therefore, the site near Rihand dam was selected as the relatively less polluted site or the reference site.

Henceforth, based on preliminary investigation of water quality at different spots of G.B. Pant Sagar, we have selected four sampling sites. The first site was Belwadah, which receives the Anpara effluent; the second site was Dongia nala, which receives the Kannoria effluent; the third site was Ash pond, which receives the Bina coal mine effluent and the fourth site was near Rihand dam, which was identified as the relatively unpolluted site (reference site).

Description of sampling sites

Figure 2 represents the location of different sampling sites selected for detailed investigation.

Belwadah Belwadah is a rural area located near the bank of G.B. Pant Sagar and receives the industrial effluents of Anpara thermal power plant. It is located at a distance of about 20 km from Anpara. The effluents are drained into the reservoir through long pipes. Being a governmental organization, Anpara TPP is responsible for major

Fig. 1 Topographical map of study area

Table 1 Metal concentration in effluent recorded during spot testing for site selection (average of three values)

Industries	Cu	Cr	Fe	Mn	Ni	Pb	Zn	Hg	Cd
Singrauli TPP	2.5 ± 0.4	1.2 ± 0.1	26.8 ± 3.1	19.8 ± 2.9	1.9 ± 0.2	0.10 ± 0.0	3.4 ± 0.5	0.19 ± 0.01	0.4 ± 0.01
Vindhyachal TPP	3.0 ± 0.3	1.4 ± 0.2	27.3 ± 3.9	24.7 ± 3.2	2.4 ± 0.3	0.10 ± 0.0	3.9 ± 0.6	0.21 ± 0.09	0.6 ± 0.1
Rihand TPP	3.1 ± 0.3	1.7 ± 0.2	31 ± 4.0	29 ± 3.7	2.8 ± 0.5	0.19 ± 0.01	4.2 ± 0.8	0.33 ± 0.1	0.6 ± 0.1
Renusagar TPP	3.9 ± 0.5	1.9 ± 0.3	49 ± 5.1	37 ± 2.9	3.2 ± 0.7	0.3 ± 0.09	4.7 ± 0.9	0.40 ± 0.1	0.8 ± 0.3
Anpara TPP	23 ± 3.7	32 ± 4.5	54 ± 3.9	59 ± 6.1	36 ± 4.1	9.9 ± 1.7	21 ± 2.6	4.6 ± 1.0	5.2 ± 0.7
Kannoria Chemicals	5.4 ± 1.0	6.3 ± 0.9	15.5 ± 1.4	17 ± 1.8	3.4 ± 0.3	4.6 ± 1.0	4.3 ± 0.6	8.5 ± 1.4	2.9 ± 0.3
Kakari OCM	2.9 ± 0.9	1.70 ± 0.2	12.4 ± 1.2	13.9 ± 1.5	10.9 ± 0.9	0.1 ± 0.09	1.30 ± 0.1	–	0.2 ± 0.09
Dudhichua OCM	2.3 ± 0.6	1.30 ± 0.1	2.1 ± 0.3	11.3 ± 1.6	10.3 ± 10	0.01 ± 0.0	1.10 ± 0.3	–	0.3 ± 0.0
Khadia OCM	2.5 ± 0.4	1.44 ± 0.2	2.9 ± 0.5	12.5 ± 1.4	11.9 ± 1.1	0.01 ± 0.0	1.6 ± 0.2	0.01 ± 0.0	1.2 ± 0.2
Bina OCM	2.8 ± 0.3	16.3 ± 2.3	3.1 ± 0.7	15.3 ± 1.3	12.9 ± 1.2	6.9 ±1.3	1.8 ± 0.4	0.2 ± 0.09	2.7 ± 0.4
Rihand dam (reference site)	0.1 ± 0.02	0.09 ± 0.0	1.3 ± 0.2	0.09 ± 0.01	0.2 ± 0.09	0.01 ± 0.0	1.1 ± 0.3	–	–

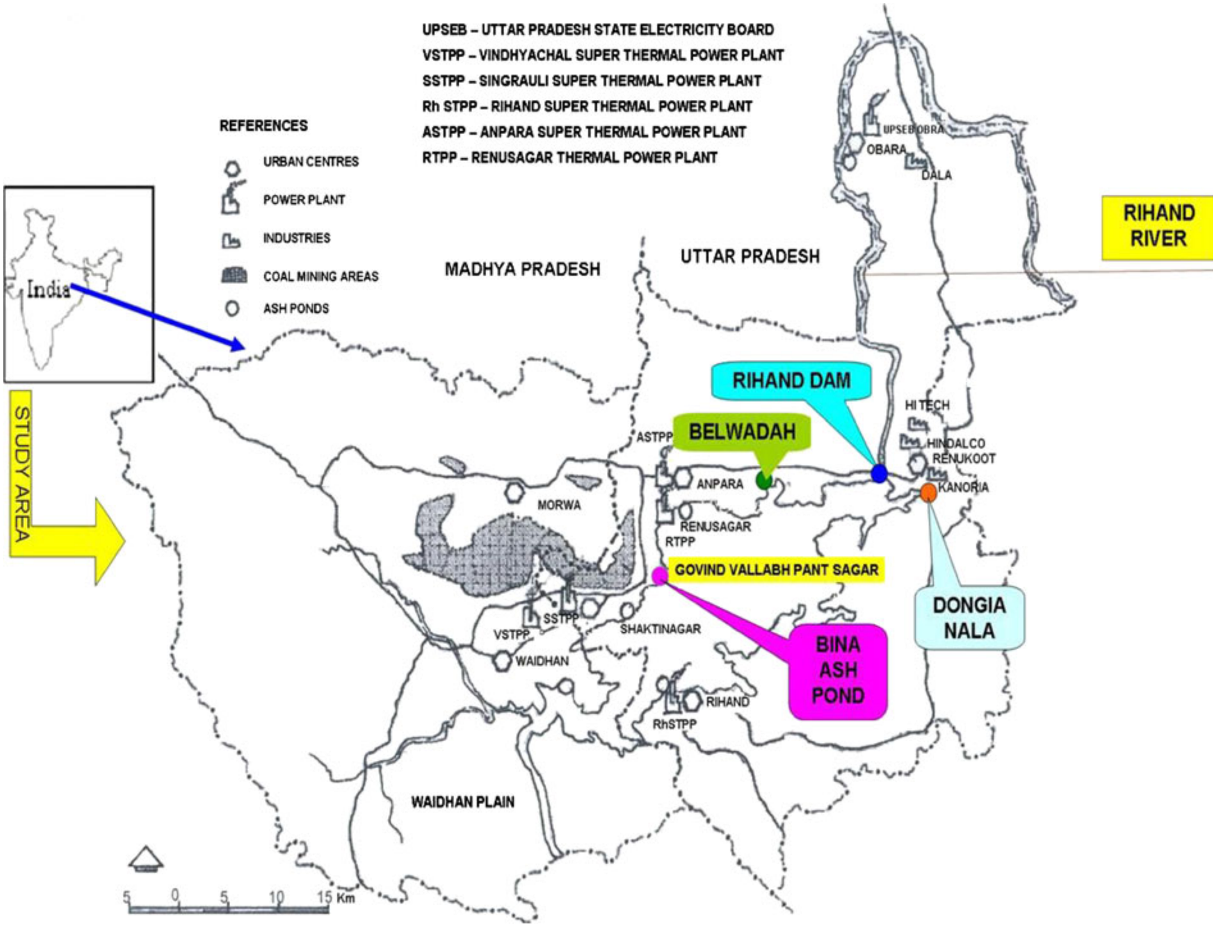


Fig. 2 Location of different sampling sites in the surrounding of G.B. Pant Sagar (Rai and Tripathi 2008)

electricity production in eastern Uttar Pradesh, India. Earlier, there were two units, i.e., Anpara A and Anpara B, but to meet the ever-growing demand of electricity Anpara C is also initiated. Although other thermal power plants also exist in Singrauli region, Anpara is selected due to its heavy and localized discharge of industrial effluents. Moreover, the site was suitable for physicochemical and biological monitoring.

Dongia nala Industrial effluent from Kannoria Chemicals mixed with domestic effluent is finally discharged into Dongia nala, a portion of G.B. Pant Sagar. Kannoria Chemicals and Industries Limited came into production in September 1964. The factory was established in the Renukoot area due to continuous availability of power and water with an objective to develop this backward area through generating employment to local inhabitants. The company diversified its activities in producing basic chemicals and pesticides, contributing to the productivity of the nation. The main products of the company are caustic soda lye, chlorine, hydrochloric acid, hydrogen, caustic soda flakes, stable bleaching powder, lindane (Tech.), lindane 1.3% dust, lindane 6.5% water-dispersible powder, lindane 20% emulsifiable concentrate, lindane 6% granules, aluminum chloride, and electric power. The raw materials used are salt, caustic soda lye, chlorine, chemical lime, chlorine, benzene, ethyl alcohol, soap stone, lindane, china clay, xylene as solvent, silica grains, aluminum, chlorine, and coal. Mercury, a poisonous heavy metal, is an essential component of raw materials and products.

Ash pond (Bina coal mine) Ash pond of G.B. Pant Sagar receives the effluent of Bina coal mine. There may be various sources of pollution in an opencast coal mine area. Mine excavations usually have water influx, either due to rainfall or to interception of groundwater flows. This water is usually an unwanted feature of mining though it can sometimes be used for processing and dust suppression and the rest may have to be pumped out. It can be contaminated by particulate matters, oil and grease, unburnt explosives, and other chemicals. If the coal seems to contain high amount of pyrites, the mine water may be acidic and thus pollutes the nearby stream after being discharged. Other major source of pollution is runoff after rain which may give rise to serious pollution problems. The disturbed land or active overburdened (OB) dumps piled up near the mine is usually very susceptive to erosion and silting is thus a widespread result. A variety of other pollutants may also be transported into water courses by runoff. A sometimes OB dump is piled up near the reservoir and thus increases the suspended particulate load in the surface water. Sometimes, spillage of oil and other toxic reagents do occur in these areas which ultimately affects the water regime. There may be also the possibility of leaching of pollutants from overburdened dumps. In OB dumps, some rainfall is likely to permeate into them and may dissolve some toxic metals from the heap and may contaminate the water course. The water used by the Bina mine community in domestic and sanitary purpose also becomes a source of pollution if not treated properly before discharge. It may be contaminated with detergents, suspended solids, and organic matters.

Rihand dam (reference site) Rihand dam is situated near Pipri location of the Singrauli region. Rihand dam connects the Rihand River and G.B. Pant Sagar. In the close vicinity of this dam, there is no industrial establishment. All environmental parameters were similar to polluted sites except the presence of point source of pollution. Spot testing also revealed very low metal concentration at Rihand dam among ten spots investigated (Table 1). Therefore, it was selected as the reference site in order to compare the data recorded from polluted sites. Sampling location was 3 km away from Rihand dam.

Methodology

For analysis of physicochemical characteristics of effluent, water samples from different sampling points were collected (in triplicate) at monthly intervals in the second week of each month from January 2004 to December 2005. Triplicates of 2 L each were collected at a time in plastic bottles between 8 and 12 h from various effluent generation points and brought to the laboratory in ice boxes for the analysis of various physicochemical characteristics (APHA 2000). Nitrate and phosphate were estimated as total N and total P, respectively.

Heavy metal analysis in water and sediments

A total of nine metals (Cu, Cr, Fe, Mn, Ni, Pb, Zn, Hg, and Cd) were investigated during the present study period (January 2004 to December 2005). Samples for heavy metal analysis were collected quarterly (in triplicate) during the month of March, June, September, and December. Filtered water samples from all sampling sites were wet-digested in HNO_3–$HClO_4$ (3:1, *v*/*v*) mixtures at 80°C and oven-dried; sieved sediments (top 15-cm sediment was collected) from all sites were wet-digested in HNO_3–$HClO_4$ (3:1, *v*/*v*) mixtures at 80°C. The concentrations of heavy metals in filtrate of water and sediment samples were determined with particle-induced X-ray emission (PIXE). Analysis of heavy metals through different methods reveals large deviation; therefore, for greater efficacy, PIXE has been used during the present investigation. PIXE has been proven as an analytical tool capable of detecting elemental concentrations down to parts per million (Murozono et al. 1999). PIXE was successfully used for heavy metal analysis because of its very high sensitivity for study of wastewater and plant tissue analysis (Mireles et al. 2004). PIXE results indicating higher accuracy have been used for samples were irradiated 3 to 10 min in a vacuum chamber by 3-MeV protons. LEGe detector was used to measure the concentrations of heavy metals in the samples. For PIXE spectrum analysis, a least square fitting computer program based on the pattern analysis method (Murozono et al. 1999) was used.

Statistical analysis

Correlation coefficients (Pearson correlation) were calculated between physicochemical variables, metals in effluent, water, and sediments, and metals in water and plants which were further used to construct correlation matrix. Analyses of variance (ANOVA) were computed between months, sampling sites, and sampling sites × months (interaction) for each parameter. Student's *t* test was applied between different sampling sites. Principal component analysis (PCA) and factor analysis (FA) were applied to minimize the data and sort the most important variable. PCA was applied to explain the variance of a large dataset of intercorrelated variables with a smaller set of independent variables (principal components).

Results

The values of different physicochemical parameters recorded in effluent are mentioned in Table 2.

Water quality parameters of G.B. Pant Sagar

Temperature values showed marked variation at different sites depending on the nature of effluent being discharged into G.B. Pant Sagar. Among different sites, temperature was recorded maximum at the Belwadah site (32.5 ± 2.1°C), receiving discharge of the Anpara thermal power plant site during June, and minimum (16.7 ± 0.7°C) during January at Rihand dam (reference site). At Belwadah, temperature was recorded highest (32.5 ± 2.1°C) in June and lowest (20 ± 0.7°C) in January. At Dongia nala, temperature was recorded highest (29 ± 0.8°C) during June and lowest (19 ± 1.1°C) during January. At Ash pond, temperature was recorded highest during June (27.8 ± 1.3°C) and lowest (18.9 ± 0.9°C) during January. Also, at Rihand dam near Pipri, which was the reference site, temperature was recorded highest (23.2 ± 1.2°C) during June and lowest (16.7 ± 0.7°C) during January (Fig. 3a). As far as seasonal variation among sites is concerned, temperature values were recorded maximum during summer while minimum during winter months.

During the present study, marked variations in values of transparency have been recorded. Transparency was lowest (8.5 ± 0.9 cm) at Belwadah and highest (23.5 ± 1.5 cm) at the reference site. Site wise, monthly maximum (14.1 ± 1.1 cm) was observed during January at Belwadah site with minimum (8.5 ± 0.9 cm) during September. At Dongia nala, transparency was maximum (14.8 ± 1.2 cm) during January and minimum (11.5 ± 0.8 cm) during September while, at Ash pond,

Table 2 Physicochemical characteristics of effluents discharged into G.B. Pant Sagar

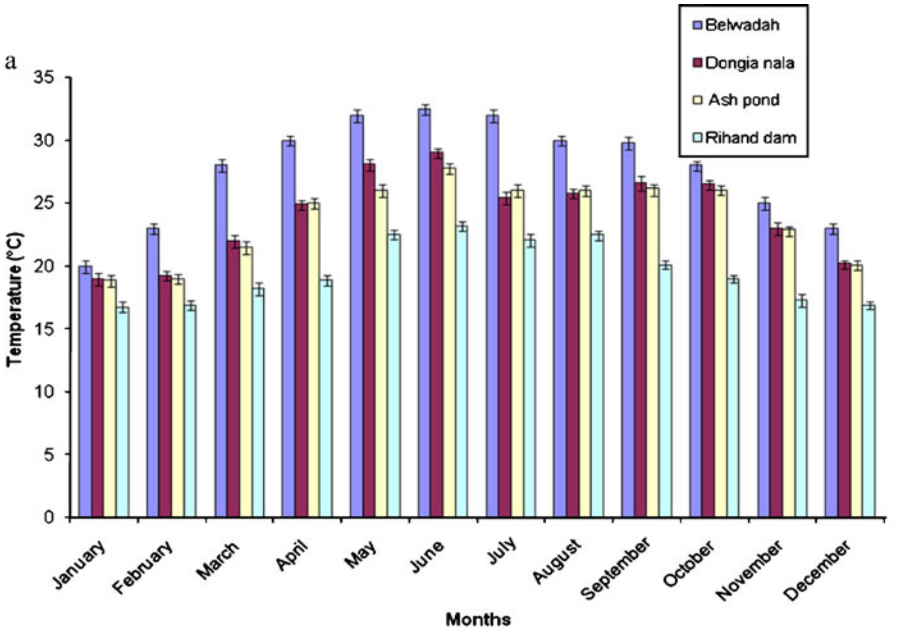
Physicochemical parameters	Anpara lowest value and highest value	Kannoria lowest value and highest value	Bina lowest value and highest value
Temperature (°C)	27 ± 1.2	25 ± 1.1	26 ± 1.4
	41 ± 1.4	39 ± 1.4	36 ± 1.3
TSS (mg L^{-1})	995 ± 22.8	98 ± 2.8	199 ± 2.2
	2,750 ± 144	329 ± 3.1	570 ± 4.1
TDS (mg L^{-1})	510 ± 17.4	390 ± 20.4	760 ± 8.9
	850 ± 26.2	725 ± 34	1,430 ± 101
pH	7.53 ± 0.3	2.9 ± 0.12	5.8 ± 0.11
	8.55 ± 0.2	4.3 ± 0.2	7.5 ± 2.0
Electrical conductivity (μmho cm^{-1})	210 ± 4.8	810 ± 41	193 ± 5.2
	630 ± 9.3	1,990 ± 105	550 ± 3.9
BOD	138 ± 4.8	74 ± 6.9	129 ± 7.9
	175 ± 7.3	98 ± 7.6	158 ± 8.3
Total acidity (mg L^{-1})	21 ± 1.2	121 ± 11.7	19.9 ± 1.9
	40 ± 1.4	489 ± 14.0	37.9 ± 2.6
Alkalinity (mg L^{-1})	110 ± 8.1	63 ± 8.0	87.5 ± 1.6
	330 ± 4.3	117 ± 1.9	290 ± 1.4
Chloride (mg L^{-1})	370 ± 11.1	990 ± 33	269 ± 6.4
	593 ± 10.3	2,500 ± 99.3	430 ± 9.2
Hardness (mg L^{-1}CaCO$_3$)	354 ± 21.6	690 ± 3.9	290 ± 7.1
	633 ± 23.7	980 ± 47	489 ± 12.3
Nitrate (mg L^{-1})	43 ± 9.6	37.8 ± 1.8	149 ± 1.9
	159 ± 11.3	68.4 ± 1.3	391 ± 18.7
Phosphate (mg L^{-1})	3.3 ± 0.3	2.2 ± 0.3	4.1 ± 0.7
	9.2 ± 0.7	7.3 ± 0.7	10.4 ± 0.9

it was maximum (14.2 ± 1.3 cm) during January and minimum (12.1 ± 2.6 cm) during August. At Rihand dam, it was recorded maximum (23.5 ± 1.5 cm) during January and minimum (17.2 ± 1.4 cm) during September (Fig. 3b). Maximum values of transparency were recorded in winter followed by summer and least in the rainy season.

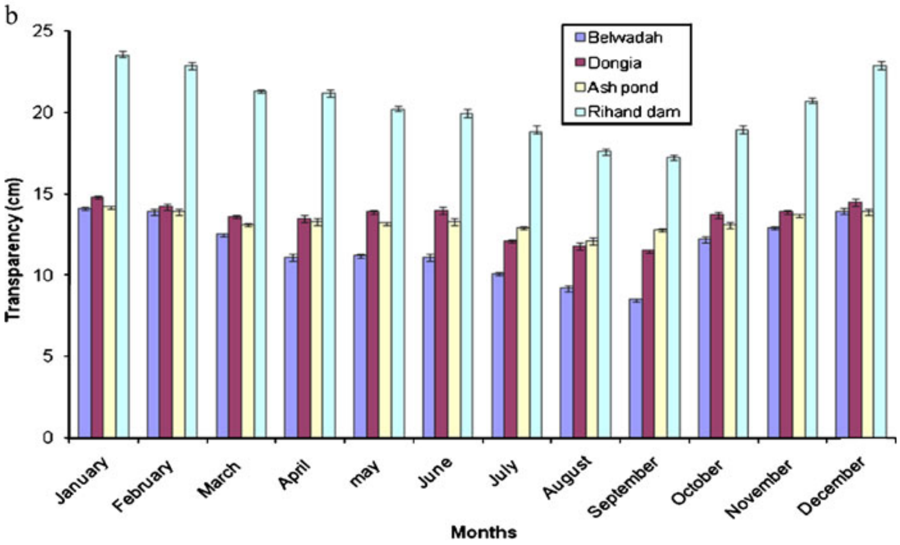
Total suspended solid (TSS) also showed marked variations at different sites depending on the nature of effluent. Among different sites, TSS was maximum (933 ± 30 mg L^{-1}) during September at Belwadah site and minimum (50 ± 1.8 mg L^{-1}) during January at Rihand dam. Site wise, monthly maximum (933 ± 30 mg L^{-1}) was observed during September at Belwadah site with minimum (230 ± 13.4 mg L^{-1}) during January. At Dongia nala, TSS was highest (128 ± 12.1 mg L^{-1}) during September and lowest (66.4 ± 11.8 mg L^{-1}) during February while, at Ash pond, it was maximum (189 ± 13.9 mg L^{-1}) during September and minimum (130 ± 11.7 mg L^{-1}) during January. At Rihand dam, it was recorded maximum (79.9 ± 1.6 mg L^{-1}) during August and minimum (50 ± 1.8 mg L^{-1}) during January (Fig. 3c). Maximum TSS load was recorded during rainy season followed by summer while minimum values were recorded during the winter season.

Among different sites, total dissolved solid (TDS) values were recorded highest at Ash pond site (703 ± 37.4 mg L^{-1}) followed by Belwadah (605 ± 31.3 mg L^{-1}) and Dongia nala (405 ± 37 mg L^{-1}). The TDS values were recorded minimum at the reference site (60 ± 6.4 mg L^{-1}). Site wise, at Belwadah site, monthly maximum (605 ± 31.3 mg L^{-1}) was recorded during September with minimum (440 ± 16.5 mg L^{-1}) during May. At Dongia nala, TDS was maximum (405 ± 37 mg L^{-1}) during September and minimum (315 ± 26.6 mg L^{-1}) during May while at Ash pond it was maximum (703 ± 37.4 mg L^{-1}) during September and minimum (340 ± 14.3 mg L^{-1}) during May. At Rihand dam, it was recorded maximum (115 ± 11.1 mg L^{-1}) during September and minimum (60 ± 6.4 mg L^{-1}) during April

Fig. 3 **a–o** Monthly variations in physicochemical characteristics of G.B. Pant Sagar at different sampling sites (mean values January 2004–December 2005)



Monthly variation in temperature of G.B. Pant Sagar at different sites (Mean values from January 2004 to December 2005)



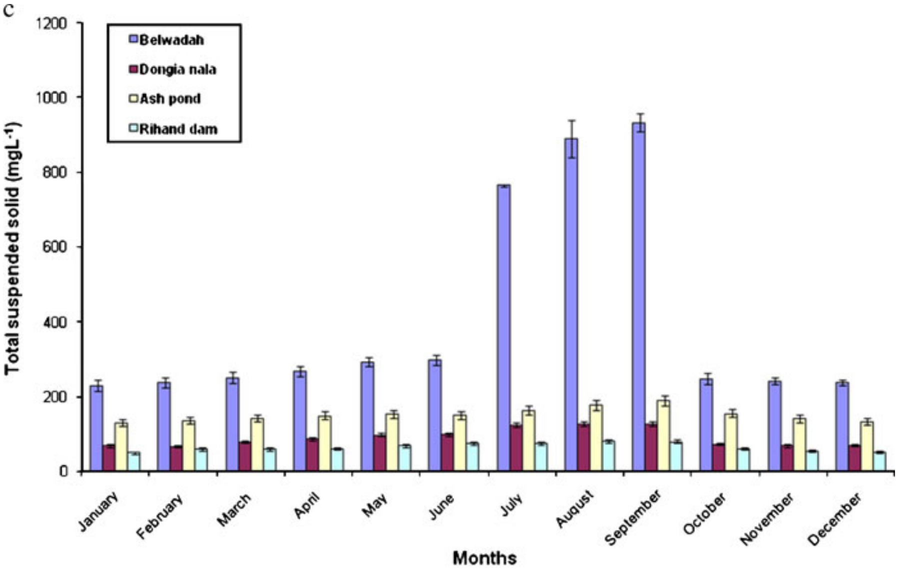
Monthly variation in Transparency of G.B. Pant Sagar at different sites (Mean values from January 2004 to December 2005)

(Fig. 3d). The values were recorded highest during rainy season followed by winter and lowest during summer months.

The values of pH recorded marked fluctuation primarily due to the varying chemical composition of different industrial effluent. Among different sites, pH was recorded highest (8.03 ± 0.30) during January at Belwadah, receiving thermal power effluent, followed by reference site and Ash pond. It was recorded lowest at Dongia nala (3.90 ± 0.29) during June. Site wise, at Belwadah site, monthly maximum (8.03 ± 0.30) was recorded

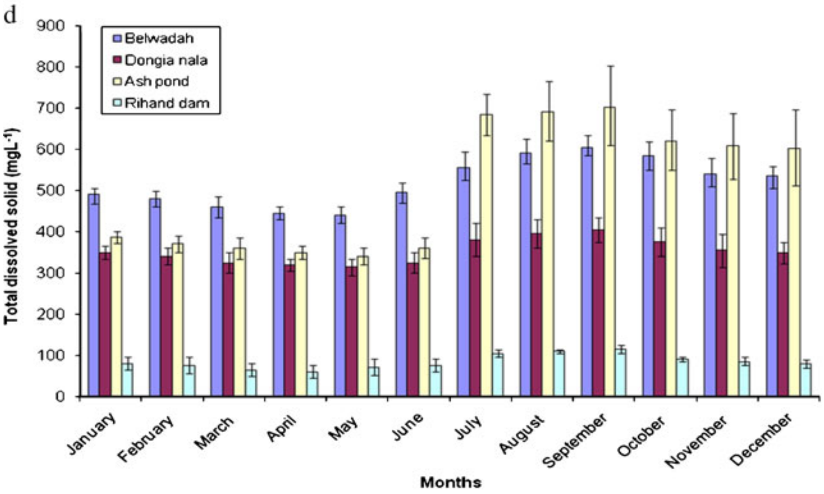
Fig. 3 (continued)

c



Monthly variation in TSS of G.B. Pant Sagar at different sites (Mean values from January 2004 to December 2005)

d

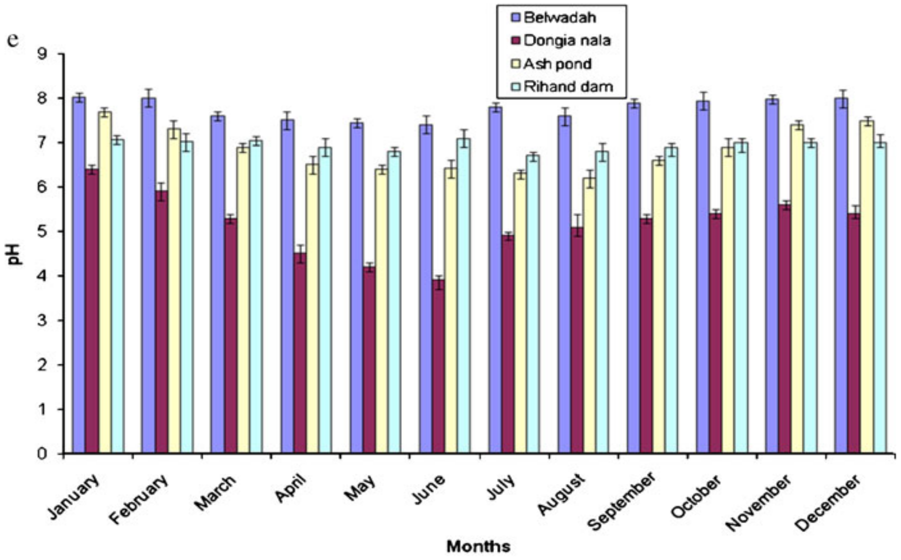


Monthly variation in TDS of G.B. Pant Sagar at different sites (Mean values from January 2004 to December 2005)

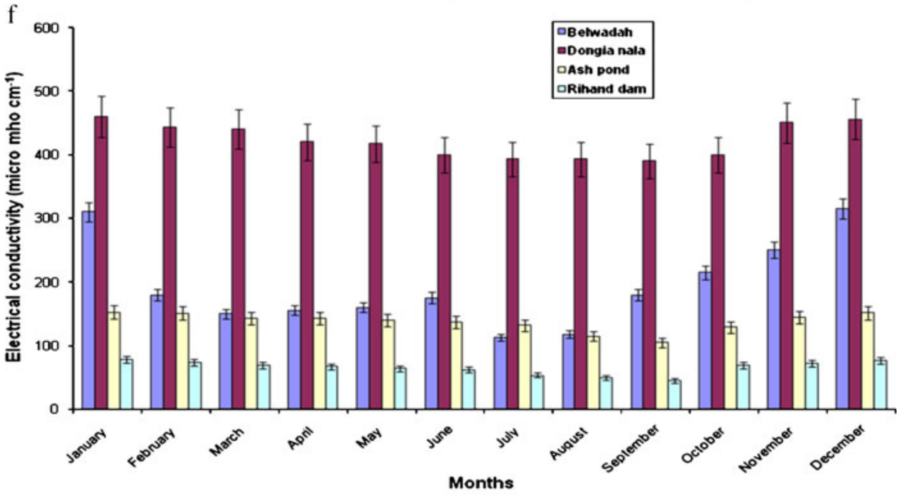
during January with minimum (7.41 ± 0.23) during June. At Dongia nala, pH was maximum (6.4 ± 0.33) during January and minimum (3.90 ± 0.29) during June while, at Ash pond, it was maximum (7.70 ± 0.49) during January and minimum (6.20 ± 0.5) during August. At Rihand dam, it was recorded maximum (7.06 ± 0.3) during January and minimum (6.70 ± 0.4) during July (Fig. 3e). As far as seasonal variation is concerned, pH values were generally recorded highest during winter followed by rainy season while least during summer season.

Electrical conductance (EC) was recorded highest (460 ± 21 μmho cm^{-1}) at Dongia nala during January and lowest (44.9 ± 2.9 μmho cm^{-1}) during the month of September at Rihand dam. Site wise, at Belwadah site, monthly maximum was recorded (315 ± 9.3 μmho cm^{-1}) during December with minimum recorded (113 ± 6.5 μmho cm^{-1}) during July. At Dongia nala, EC

Fig. 3 (continued)



Monthly variation in pH of G.B. Pant Sagar at different sites (Mean values from January 2004 to December 2005)

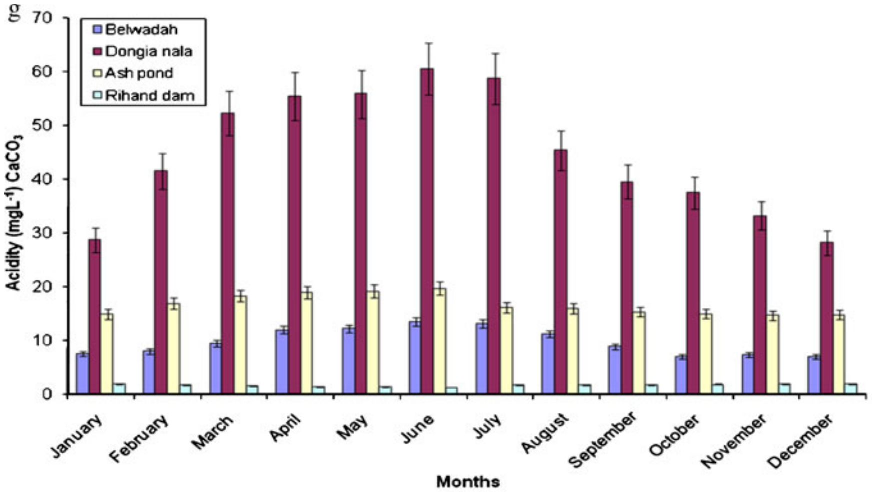


Monthly variation in EC of G.B. Pant Sagar at different sites (Mean values from January 2004 to December 2005)

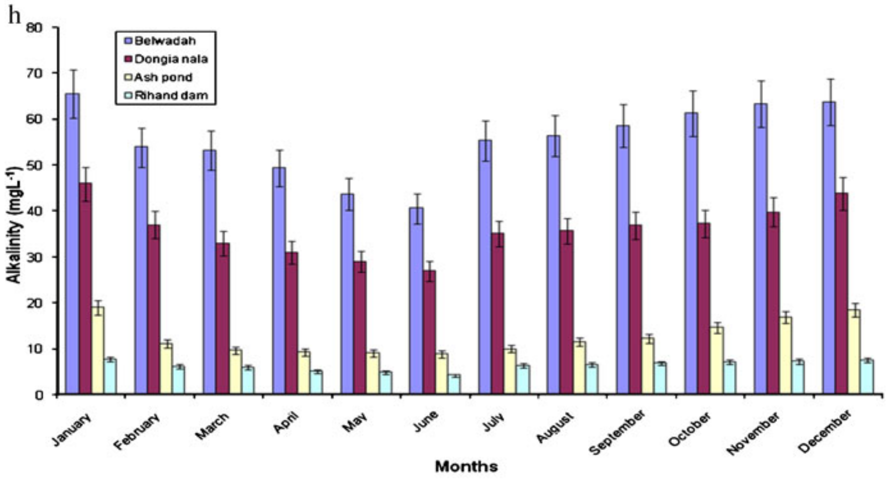
was maximum (460 ± 21 μmho cm^{-1}) during January and minimum (390 ± 23 μmho cm^{-1}) during September while, at Ash pond, it was maximum (153 ± 5.4 μmho cm^{-1}) during January and minimum (105 ± 3.2 μmho cm^{-1}) during September. At Rihand dam, it was recorded maximum (78.3 ± 3.3 μmho cm^{-1}) during January and minimum (44.9 ± 2.9 μmho cm^{-1}) during the month of September (Fig. 3f). EC values were recorded highest during winter followed by summer and least in rainy season.

Acidity was recorded highest (60.5 ± 4.1 mg L^{-1}) at Dongia nala during June and lowest (1.3 ± 0.4 mg L^{-1}) also during June at Rihand dam. Site wise, at Belwadah site, monthly maximum was recorded (13.5 ± 1.1 mg L^{-1}) during June with minimum (7 ± 0.9 mg L^{-1}) during December. At Dongia nala, acidity was maximum (60.5 ± 4.1 mg L^{-1}) during June and minimum (28.2 ± 1.9 mg L^{-1}) during December while, at Ash pond, it was maximum (19.7 ± 1.7 mg L^{-1}) during June and minimum (14.7 ±

Fig. 3 (continued)



Monthly variation in acidity of G.B. Pant Sagar at different sites (Mean values from January 2004 to December 2005)



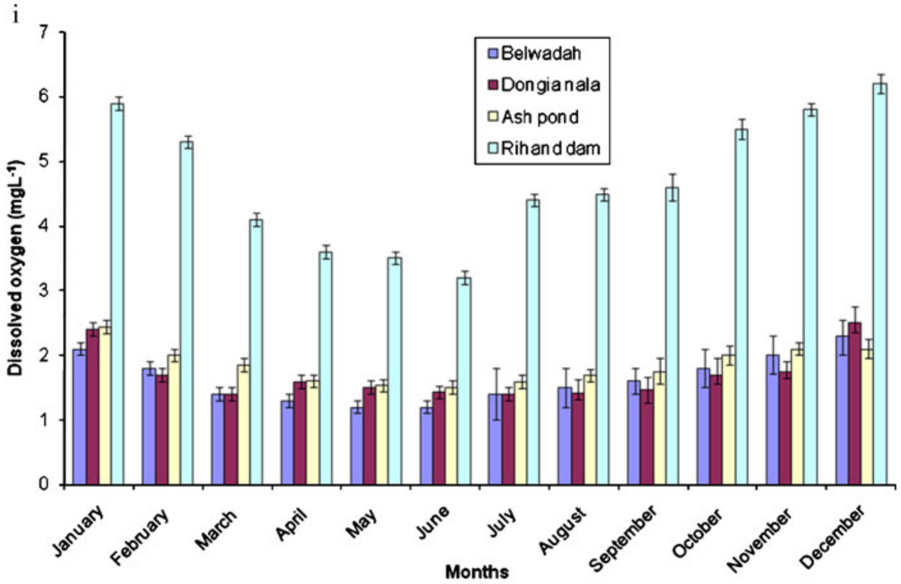
Monthly variation in alkalinity of G.B. Pant Sagar at different sites (Mean values from January 2004 to December 2005)

1.0 mg L^{-1}) during November. At Rihand dam, it was recorded maximum (1.91 ± 0.3 mg L^{-1}) during January and minimum (1.3 ± 0.4 mg L^{-1}) during December, respectively (Fig. 3g). There was marked seasonal variation in acidity and generally it was highest in summer followed by rainy season and lowest during winter.

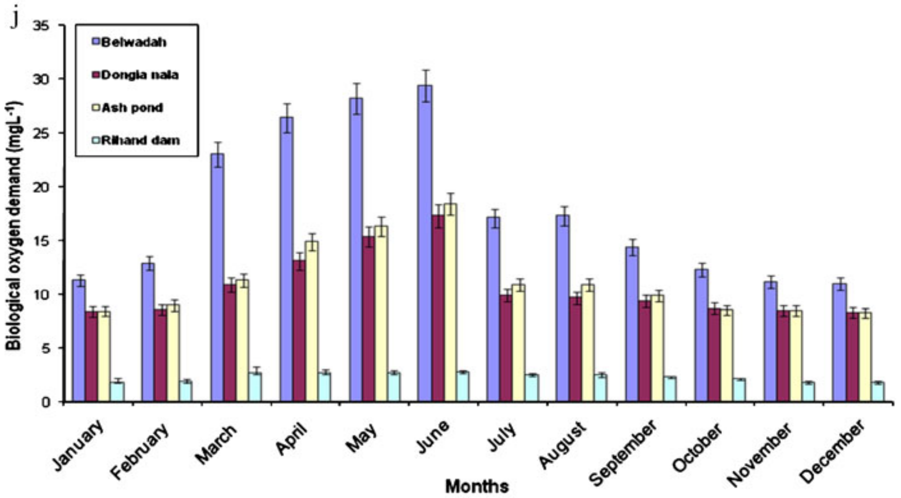
Among different sites, alkalinity was recorded highest (65.5 ± 4.4 mg L^{-1}) at Belwadah during January and lowest (4.3 ± 1.1 mg L^{-1}) during June at Rihand dam. Site wise, at Belwadah site, monthly maximum was recorded (65.5 ± 4.4 mg L^{-1}) during January with minimum (40.6 ± 2.8 mg L^{-1}) during June. At Dongia nala, alkalinity was recorded maximum (46 ± 4.6 mg L^{-1}) during January and minimum (26.9 ± 2.1 mg L^{-1}) during June while, at Ash pond, it was maximum (19.0 ± 1.9 mg L^{-1}) during January and minimum (8.9 ± 1.1 mg L^{-1}) during June. At Rihand dam, alkalinity was recorded maximum (7.8 ± 1.2 mg L^{-1}) during January and minimum (4.3 ± 1.1 mg L^{-1}) during June (Fig. 3h). Generally, the alkalinity values were recorded highest during winter followed by rainy and least during summer.

Dissolved oxygen (DO) values were recorded lowest at Belwadah site (1.20 ± 0.2 mg L^{-1}) followed by Dongia nala (1.4 ± 0.1 mg L^{-1}) and Ash pond of Bina coal mine (1.51 ± 0.2 mg L^{-1})

Fig. 3 (continued)



Monthly variation in DO of G.B. Pant Sagar at different sites (Mean values from January 2004 to December 2005)

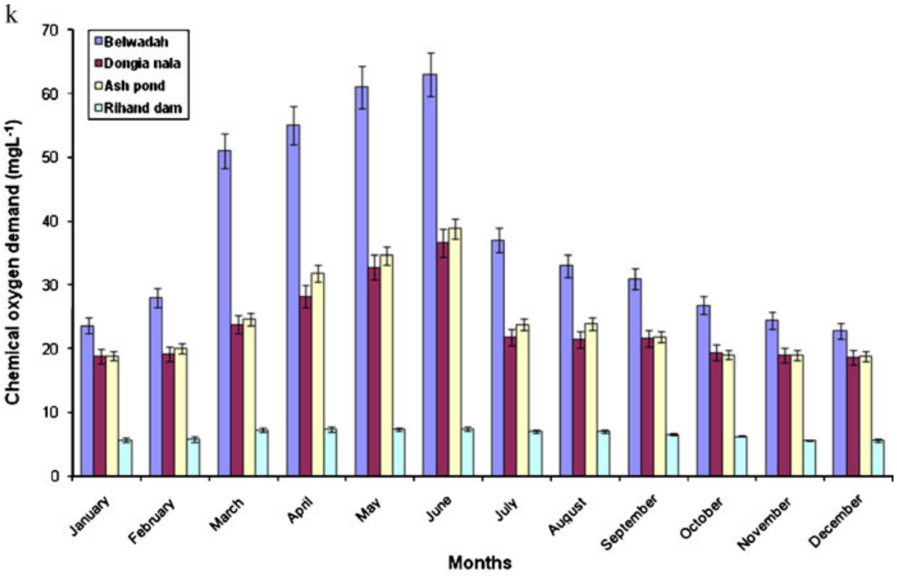


Monthly variation in BOD of G.B. Pant Sagar at different sites (Mean values from January 2004 to December 2005)

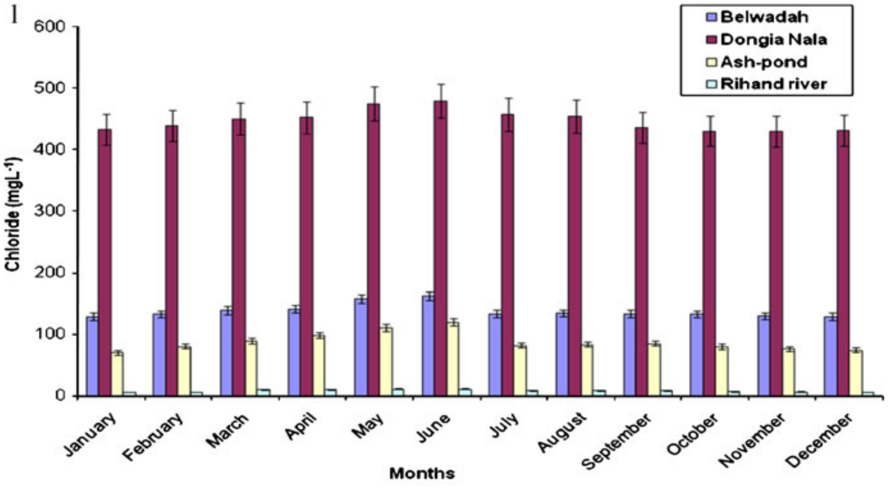
while highest at Rihand dam (6.2 ± 0.4 mg L^{-1}). Site wise, at Belwadah site, monthly maximum was recorded (2.3 ± 0.4 mg L^{-1}) during December with minimum (1.20 ± 0.2 mg L^{-1}) during June. At Dongia nala, DO was recorded maximum (2.5 ± 0.3 mg L^{-1}) during December while minimum (1.4 ± 0.1 mg L^{-1}) during July while, at Ash pond, it was maximum (2.44 ± 0.3 mg L^{-1}) during the month of January with minimum (1.51 ± 0.2 mg L^{-1}) during June. At the reference site (Rihand dam), DO was recorded maximum (6.2 ± 0.4 mg L^{-1}) during December and minimum (3.2 ± 0.2 mg L^{-1}) during June (Fig. 3i). Seasonally, higher DO values were recorded during winter season followed by rainy and least during summer season.

Biological oxygen demand (BOD) values reflected the pollution load due to industrial effluents at different sampling sites of G.B. Pant Sagar. BOD values were recorded highest at Belwadah

Fig. 3 (continued)



Monthly variation in COD of G.B. Pant Sagar at different sites (Mean values from January 2004 to December 2005)



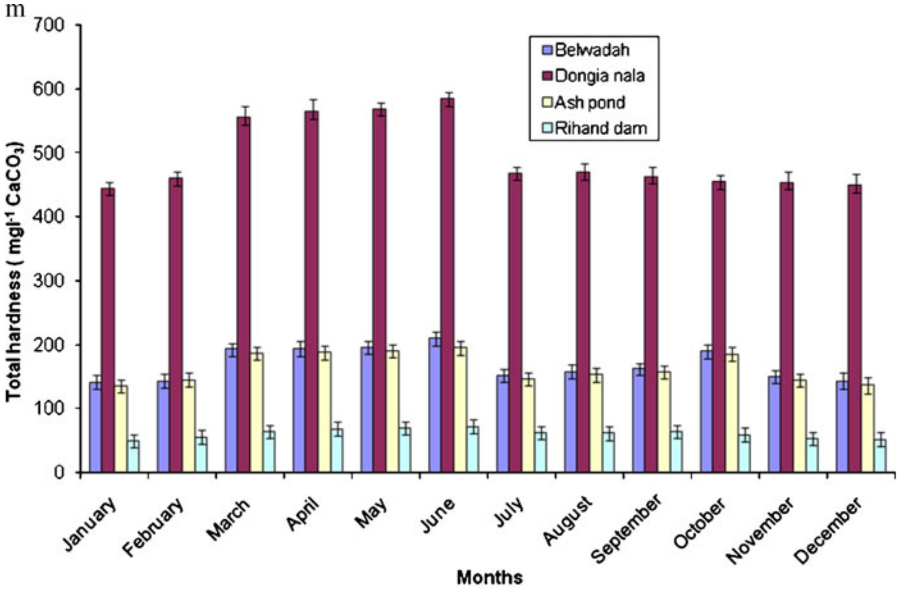
Monthly variation in chloride of G.B. Pant Sagar at different sites (Mean values from January 2004 to December 2005)

site (29.4 ± 2.1 mg L^{-1}) followed by Ash pond of Bina coal mine and Dongia nala. Among different sites, it was lowest (1.78 ± 0.3 mg L^{-1}) at Rihand dam (reference site). Site wise, at Belwadah site, monthly maximum was recorded (29.4 ± 2.1 mg L^{-1}) during June with minimum (11 ± 1.4 mg L^{-1}) during December. At Dongia nala, BOD was maximum (17.3 ± 2.5 mg L^{-1}) during June and minimum (8.3 ± 1.1 mg L^{-1}) during December while, at Ash pond, it was maximum (18.4 ± 2.4 mg L^{-1}) during the month of June with minimum (8.3 ± 1.1 mg L^{-1}) during December. At the reference site (Rihand dam), it was recorded maximum (2.73 ± 0.4 mg L^{-1}) during June and minimum (1.78 ± 0.3 mg L^{-1}) during December (Fig. 3j). Maximum values were recorded during summer followed by rainy and least in winter season.

Among different sites, chemical oxygen demand (COD) was also recorded maximum at

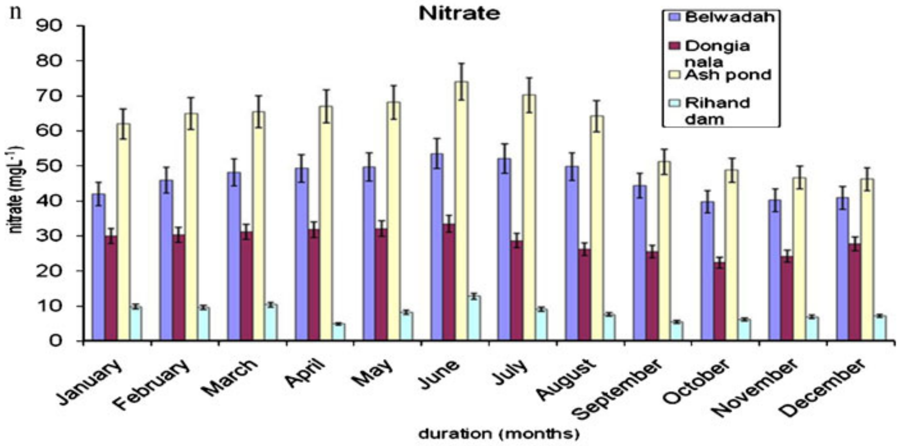
Fig. 3 (continued)

m



Monthly variation in hardness of G.B. Pant Sagar at different sites (Mean values from January 2004 to December 2005)

n

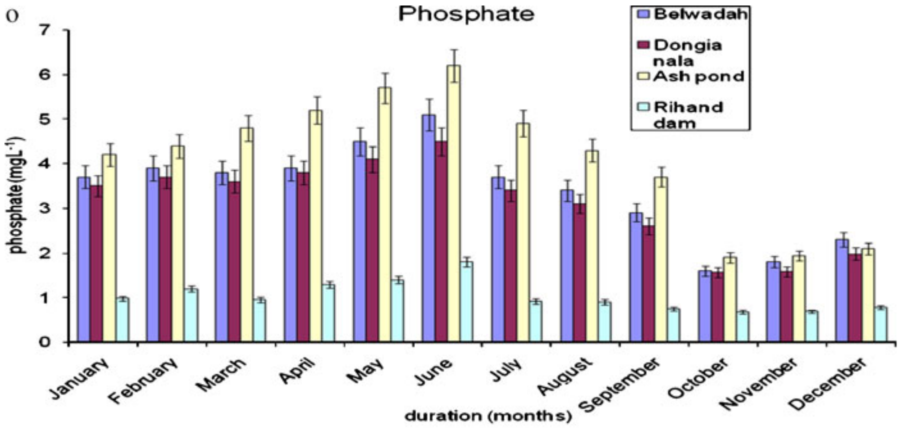


Monthly variation in nitrate of G.B. Pant Sagar at different sites (Mean values from January 2004 to December 2005)

Belwadah and minimum at the reference site (Rihand dam). Site wise, at Belwadah site, monthly maximum was recorded (63±4.1 mg L^{-1}) during June with minimum (22.8 ± 3.8 mg L^{-1}) during December. At Dongia nala, COD was maximum (36.6 ± 4.2 mg L^{-1}) during June and minimum (18.6 ± 2.7 mg L^{-1}) during December while, at Ash pond also, it was maximum (38.8 ± 3.9 mg L^{-1}) during the month of June with minimum (18.82 ± 1.6 mg L^{-1}) during December. At Rihand dam, it was recorded maximum (7.46 ± 1.1 mg L^{-1}) during June and minimum (5.58 ± 0.8 mg L^{-1}) during December (Fig. 3k). Seasonal variation followed the same trend as of biological oxygen demand, i.e., maximum values were recorded during summer followed by rainy and least in winter season.

Chloride values were recorded highest at Dongia nala (479 ± 21 mg L^{-1}) followed by Belwadah and Ash pond site of the reservoir. Lowest value of chloride (6.0 ± 0.4 mg L^{-1}) was recorded at Rihand dam (reference site).

Fig. 3 (continued)



Monthly variation in phosphate of G.B. Pant Sagar at different sites (Mean values from January 2004 to December 2005)

Site wise, at Belwadah site, monthly maximum was recorded (162 ± 8.1 mg L^{-1}) during June with minimum (129 ± 3.2 mg L^{-1}) during January. At Dongia nala, chloride was maximum (479 ± 21 mg L^{-1}) during June and minimum (429 ± 10.9 mg L^{-1}) during November while, at Ash pond, it was recorded maximum (120.4 ± 8.2 mg L^{-1}) during the month of June with minimum (70.2 ± 5.2 mg L^{-1}) during January. At the reference site (Rihand dam), it was recorded maximum (11.3 ± 0.8 mg L^{-1}) during June and minimum (6.0 ± 0.4 mg L^{-1}) during January (Fig. 3l). Chloride values were recorded highest during summer followed by rainy and least during winter season.

Hardness values were recorded highest (585 ± 15.9 mg L^{-1}) at Dongia nala site followed by Belwadah and Ash pond of Bina coal mine plant and lowest (50 ± 3.2 mg L^{-1}) at Rihand dam. Site wise, at Belwadah site, monthly maximum was recorded (210 ± 13.9 mg L^{-1}) during June with minimum (140 ± 4.2 mg L^{-1}) during January. At Dongia nala, hardness was recorded maximum (585 ± 15.9 mg L^{-1}) during June and minimum (444 ± 14.1 mg L^{-1}) during January while, at Ash pond, it was recorded maximum (195 ± 7.9 mg L^{-1}) during the month of June with minimum (135 ± 11.3 mg L^{-1}) during January. At Rihand dam, it was recorded maximum (72 ± 6.8 mg L^{-1}) during June and minimum (50 ± 3.2 mg L^{-1}) during January (Fig. 3m). Higher values were recorded during summer followed by rainy and least during winter season.

Nitrate was recorded highest (74.1 ± 1.6 mg L^{-1}) at Ash pond and lowest (4.9 ± 0.2 mg L^{-1}) at Rihand dam. Site wise, at Belwadah site, monthly maximum was recorded (53.5 ± 1.2 mg L^{-1}) during June with minimum (39.8 ± 0.9 mg L^{-1}) during October. At Dongia nala, nitrate was maximum (33.5 ± 1.5 mg L^{-1}) during June and minimum (22.4 ± 1.2 mg L^{-1}) during October while, at Ash pond, it was maximum (74.1 ± 1.6 mg L^{-1}) during the month of June with minimum (46.2 ± 1.2 mg L^{-1}) during December. At Rihand dam, nitrate was recorded maximum (12.8 ± 0.7 mg L^{-1}) during June and minimum (4.9 ± 0.2 mg L^{-1}) during April (Fig. 3n). Seasonally, higher values of nitrate were recorded in summer followed by winter and rainy season.

Phosphate values were recorded highest (6.2 ± 0.4 mg L^{-1}) at Ash pond and lowest (0.68 ± 0.2 mg L^{-1}) at Rihand dam. Site wise, at Belwadah site, monthly maximum was recorded (5.1 ± 0.3 mg L^{-1}) during June with minimum (1.6 ± 0.2 mg L^{-1}) during October. At Dongia nala, phosphate was maximum (4.5 ± 0.2 mg L^{-1}) during June and minimum (1.56 ± 0.2 mg L^{-1}) during October while, at Ash pond, it was maximum (6.2 ± 0.4 mg L^{-1}) during the month of June with minimum (1.9 ± 0.1 mg L^{-1}) during October. At Rihand dam, phosphate was recorded maximum (1.8 ± 0.3 mg L^{-1}) during June and minimum (0.68 ± 0.1 mg L^{-1}) during October (Fig. 3o). Seasonally, higher values were observed in summer followed by rainy and winter season.

Table 3 Metal concentration in effluent before being discharged into G.B. Pant Sagar (all values in milligram per liter)

Metals examined	Anpara	Kannoria	Bina	Standard (CPCB)	Standard (EPA)
Cu	39 ± 3.1	5.9 ± 1.0	17.5 ± 1.4	3.0	5.0
Cr	44 ± 4.6	7.9 ± 1.1	3.9 ± 0.7	0.10	2.0
Fe	94 ± 9.5	16.5 ± 1.4	18 ± 1.3	3.0	100
Mn	98 ± 11.0	18.9 ± 1.6	15 ± 1.7	5.0	5.0
Ni	54 ± 8.9	3.7 ± 0.8	8.6 ± 1.4	3.0	5.0
Pb	19.8 ± 3.4	5.9 ± 0.7	3.0 ± 0.4	0.10	0.10
Zn	38 ± 8.4	4.9 ± 0.5	12.0 ± 1.0	5.0	5.0
Hg	6.5 ± 1.4	9.8 ± 2.5	0.4 ± 0.01	0.01	0.01
Cd	6.0 ± 1.0	3.1 ± 0.3	3.0 ± 0.7	2.0	1.0

CPCB Central Pollution Control Board (1998; Government of India, New Delhi), *EPA* Environmental Protection Agency (USA)

Heavy metals in the water and sediments of G.B. Pant Sagar

The average values of heavy metal concentration recorded in different industrial effluents during the course of study period are shown in Table 3. In effluents, values recorded for most of the metals were well above the permissible limit prescribed by the Central Pollution Control Board (CPCB) and the Environmental Protection Agency (EPA). Further, metal concentration in water (Table 4) and sediment (Table 5) of G.B. Pant Sagar was also recorded during the course of this study.

Copper (Cu) In water, Cu concentrations were recorded maximum (27 ± 1.4 mg L^{-1}) at Belwadah site followed by Ash pond (6.8 ± 1.1 mg L^{-1}) and Dongia nala (1.2 ± 0.2 mg L^{-1}). Cu concentrations were recorded minimum (0.01 ± 0.0 mg L^{-1}) at Rihand dam (reference site) during September. In sediment, Cu concentration was maximum (28 ± 2.7 mg kg^{-1}) at Ash pond site followed by Belwadah (20 ± 2.1 mg kg^{-1}) and Dongia nala (3.6 ± 1.1 mg kg^{-1}) while it was minimum (0.6 ± 0.1 mg kg^{-1}) at Rihand dam. Regarding seasonal variation, it is evident from the Tables 4 and 5 that metal contents in reservoir water and sediments were particularly

Table 4 Metal concentrations in G.B. Pant Sagar water (all values in milligram per liter)

Month	Cu	Cr	Fe	Mn	Ni	Pb	Zn	Hg	Cd
Belwadah									
March	22 ± 2.1	29 ± 2.7	33 ± 2.4	18 ± 1.4	26 ± 1.9	13 ± 0.9	13 ± 0.01	1.8 ± 0.1	4.1 ± 0.6
June	27 ± 1.4	34 ± 4.1	41 ± 2.9	22 ± 1.9	36 ± 3.1	17 ± 1.7	21 ± 1.1	2.0 ± 0.3	4.5 ± 0.9
Sept.	16 ± 1.4	19 ± 1.6	22 ± 2.2	11 ± 1.1	16 ± 1.2	8 ± 0.79	11 ± 0.9	1.1 ± 0.3	2.9 ± 0.4
Dec.	24 ± 1.8	32 ± 1.8	37 ± 2.7	19 ± 1.0	29 ± 1.8	15 ± 1.2	14 ± 1.1	1.7 ± 0.3	3.7 ± 0.8
Dongia nala									
March	0.9 ± 0.1	0.7 ± 0.2	4.6 ± 0.06	2.9 ± 0.7	0.9 ± 0.1	0.7 ± 0.1	3.0 ± 0.1	3.9 ± 0.3	0.7 ± 0.09
June	1.2 ± 0.2	0.8 ± 0.2	5.1 ± 0.4	3.1 ± 0.9	1.3 ± 0.2	1.1 ± 0.2	3.2 ± 0.3	4.1 ± 0.4	0.9 ± 0.1
Sept.	0.6 ± 0.1	0.3 ± 0.01	1.2 ± 0.1	1.8 ± 0.2	0.4 ± 0.09	0.3 ± 0.01	1.9 ± 0.09	2.7 ± 0.1	0.3 ± 0.05
Dec.	0.8 ± 0.2	0.5 ± 0.09	3.9 ± 0.9	2.6 ± 0.1	0.6 ± 0.07	0.4 ± 0.09	1.7 ± 0.1	2.9 ± 0.1	0.5 ± 0.03
Ash pond									
March	5.4 ± 1.3	0.18 ± 0.01	41.3 ± 1.7	0.2 ± 0.01	3.2 ± 0.6	0.9 ± 0.1	4.2 ± 0.90	0.17 ± 0.01	1.0 ± 0.3
June	6.8 ± 1.1	0.2 ± 0.01	38 ± 3.1	0.4 ± 0.09	3.7 ± 0.7	1.1 ± 0.2	5.1 ± 0.8	0.19 ± 0.01	1.2 ± 0.2
Sept.	4.3 ± 1.2	0.09 ± 0.01	27.5 ± 1.4	0.02 ± 0.0	1.9 ± 0.4	0.3 ± 0.09	2.9 ± 0.30	0.01 ± 0.0	0.6 ± 0.01
Dec.	4.9 ± 0.9	0.1 ± 0.04	34 ± 2.7	0.3 ± 0.04	2.1 ± 0.9	0.4 ± 0.1	3.2 ± 0.4	0.1 ± 0.01	0.8 ± 0.1
Rihand dam									
March	0.01 ± 0.01	0.02 ± 0.021	1.1 ± 0.2	1.3 ± 0.4	0.07 ± 0.01	0.06 ± 0.01	1.0 ± 0.2	–	0.01 ± 0.0
June	0.02 ± 0.02	0.03 ± 0.031	1.2 ± 0.4	1.5 ± 0.2	0.09 ± 0.01	0.08 ± 0.01	1.2 ± 0.3	–	0.02 ± 0.0
Sept.	0.01 ± 0.0	–	0.9 ± 0.1	1.1 ± 0.2	0.01 ± 0.0	0.02 ± 0.0	0.8 ± 0.1	–	0.01 ± 0.00
Dec.	0.1 ± 0.03	0.01 ± 0.01	1.1 ± 0.2	1.4 ± 0.3	0.08 ± 0.01	0.09 ± 0.01	0.9 ± 0.1	–	0.01 ± 0.01

Table 5 Metal concentrations in G.B. Pant Sagar sediments (all values in milligram per kilogram)

Month	Cu	Cr	Fe	Mn	Ni	Pb	Zn	Hg	Cd
Belwadah									
March	20 ± 2.1	30 ± 2.3	69 ± 5.0	110 ± 7.1	35 ± 3.3	10.0 ± 1.0	55 ± 3.9	1.2 ± 0.3	1.4 ± 0.3
June	17 ± 1.9	19 ± 2.1	48 ± 4.9	90 ± 6.2	31 ± 3.0	9.0 ± 0.7	51 ± 3.3	1.2 ± 0.2	1.3 ± 0.2
Sept.	14 ± 1.7	16 ± 1.9	40 ± 3.7	78 ± 6.7	23 ± 2.9	6.0 ± 0.9	47 ± 3.1	1.0 ± 0.2	1.1 ± 0.4
Dec.	18 ± 1.3	27 ± 1.7	65 ± 6.2	105 ± 7.8	33 ± 2.8	8.0 ± 0.5	49 ± 3.7	0.8 ± 0.1	1.2 ± 0.1
Dongia nala									
March	3.6 ± 1.1	1.4 ± 0.9	12 ± 1.2	12 ± 1.4	0.8 ± 0.1	3.1 ± 0.9	7.9 ± 1.0	6.8 ± 0.4	1.2 ± 0.9
June	2.4 ± 0.5	1.2 ± 0.7	8.0 ± 1.0	9.0 ± 1.5	0.7 ± 0.1	2.3 ± 0.7	7.4 ± 0.9	5.2 ± 0.4	0.8 ± 0.2
Sept.	1.9 ± 0.6	0.7 ± 0.1	6.0 ± 0.9	7.0 ± 1.1	0.4 ± 0.1	1.2 ± 0.2	6.1 ± 1.1	4.1 ± 0.2	0.4 ± 0.1
Dec.	2.5 ± 0.9	1.3 ± 0.3	10 ± 1.3	10 ± 1.0	0.5 ± 0.1	1.8 ± 0.3	6.8 ± 0.7	4.9 ± 0.6	0.6 ± 0.1
Ash pond									
March	28 ± 2.7	8.5 ± 1.2	85 ± 4.1	133 ± 6.2	27 ± 2.9	7.5 ± 1.1	57 ± 2.9	3.2 ± 0.4	4.6 ± 1.0
June	26 ± 2.3	7.9 ± 1.0	79 ± 4.0	127 ± 7.1	23 ± 2.6	6.0 ± 1.0	53 ± 2.7	2.9 ± 0.5	4.1 ± 0.7
Sept.	17 ± 2.0	3.9 ± 0.9	42 ± 3.7	90 ± 5.1	12 ± 1.3	5.3 ± 0.9	40 ± 1.9	1.0 ± 0.1	2.7 ± 0.5
Dec.	21 ± 2.1	4.1 ± 0.9	51 ± 3.9	96 ± 5.3	18 ± 1.7	6.8 ± 0.8	49 ± 2.3	2.3 ± 0.3	3.8 ± 0.9
Rihand dam (reference site)									
March	0.6 ± 0.1	0.5 ± 0.1	1.9 ± 0.3	2.1 ± 0.3	0.3 ± 0.09	0.2 ± 0.01	1.7 ± 0.5	0.05 ± 0.01	0.2 ± 0.09
June	0.4 ± 0.09	0.4 ± 0.9	2.1 ± 0.4	1.6 ± 0.2	0.1 ± 0.08	0.18 ± 0.01	1.5 ± 0.4	0.02 ± 0.0	0.1 ± 0.01
Sept.	0.6 ± 0.1	0.3 ± 0.1	1.2 ± 0.2	2.3 ± 0.1	0.4 ± 0.03	0.3 ± 0.01	1.9 ± 0.3	0.01 ± 0.0	0.3 ± 0.08
Dec.	0.5 ± 0.1	0.4 ± 0.08	1.9 ± 0.3	2.0 ± 0.1	0.2 ± 0.01	0.19 ± 0.01	1.3 ± 0.1	0.03 ± 0.01	0.19 ± 0.07

high during presummer and summer season, i.e., March and June. However, comparatively low values for all metals were recorded during rainy season, i.e., September which may be due to the result of dilution due to addition of rainwater and subsequent outflow of reservoir water.

Chromium (Cr) In water, Cr concentrations were recorded maximum (34 ± 4.1 mg L^{-1}) at Belwadah site followed by Dongia nala (0.8 ± 0.2 mg L^{-1}) and Ash pond (0.2 ± 0.01 mg L^{-1}). Cr concentrations were observed below detection limit (BDL) at Rihand dam during September. In sediment, Cr concentrations were recorded maximum (30 ± 2.3 mg kg^{-1}) at Belwadah site followed by Ash pond (8.5 ± 1.2 mg kg^{-1}) and Dongia nala (1.4 ± 0.9 mg kg^{-1}) while it was minimum (0.3 ± 0.1 mg kg^{-1}) at Rihand dam during the month of September. Seasonal variations followed almost the same trend of monthly variation as Cu. Metal content in reservoir water and sediments were particularly high during presummer and summer season, i.e., March and June. Comparatively low values for all metals were found during rainy season, i.e., September.

Iron (Fe) In water, Fe concentrations were recorded maximum (41.3 ± 1.7 mg L^{-1}) at Ash pond site followed by Belwadah (41 ± 2.9 mg L^{-1}) and Dongia nala (5.1 ± 0.4 mg L^{-1}). Fe concentration was minimum (0.9 ± 0.1 mg L^{-1}) at Rihand dam during the month of September. In sediment, Fe concentration was maximum (85 ± 4.1 mg kg^{-1}) at Ash pond site followed by Belwadah (69 ± 5.0 mg kg^{-1}) and Dongia nala (12 ± 1.2 mg kg^{-1}) while it was minimum (1.2 ± 0.2 mg kg^{-1}) at the reference site during the month of September. Seasonal variations followed almost the same trend of monthly variation as for Cu and Cr.

Manganese (Mn) In water, Mn concentrations were recorded maximum (22 ± 1.9 mg L^{-1}) during June at Belwadah site followed by Dongia nala (3.1 ± 0.9 mg L^{-1}) and Rihand dam (1.5 ± 0.2 mg L^{-1}). Mn concentration was minimum (0.02 ± 0.00 mg L^{-1}) at Ash pond site during September. In sediment, Mn concentration was maximum (133 ± 6.2 mg kg^{-1}) at Ash pond site followed by Belwadah (110 ± 7.1 mg kg^{-1}) and Dongia nala (12 ± 1.4 mg kg^{-1}) while it was minimum (1.6 ± 0.2 mg kg^{-1}) at Rihand dam during the month of June. Seasonal variations followed almost the same trend.

Nickel (Ni) In water, Ni concentrations were recorded maximum (36 ± 3.1 mg L^{-1}) at Belwadah site followed by Ash pond (3.7 ± 0.7 mg L^{-1}) and Dongia nala (1.3 ± 0.2 mg L^{-1}) while Ni concentrations were found minimum (0.01 ± 0.0 mg L^{-1}) at Rihand dam during September. In sediment, Ni concentrations was maximum (35 ± 3.3 mg kg^{-1}) at Belwadah site followed by Ash pond (27 ± 2.9 mg kg^{-1}) and Dongia nala (0.8 ± 0.1 mg kg^{-1}) while it was minimum (0.1 ± 0.08 mg kg^{-1}) at Rihand dam during the month of June. Seasonal variations followed almost the same trend of monthly variation as others.

Lead (Pb) In water, Pb concentrations were recorded maximum (17 ± 1.7 mg L^{-1}) at Belwadah site followed by Ash pond (1.1 ± 0.2 mg L^{-1}) and Dongia nala (1.1 ± 0.2 mg L^{-1}). Pb concentration was minimum (0.02 ± 0.0 mg L^{-1}) at Rihand dam during September. In sediment, Pb concentration was maximum (10 ± 1.0 mg kg^{-1}) at Belwadah site followed by Ash pond (7.5 ± 1.1 mg kg^{-1}) and Dongia nala (3.1 ± 0.9 mg kg^{-1}) while it was minimum (0.18 ± 0.01 mg kg^{-1}) at Rihand dam during the month of June. Seasonal variations followed almost the same trend of monthly variation as others.

Zinc (Zn) In water, Zn concentrations were recorded maximum (21 ± 1.1 mg L^{-1}) at Belwadah site during June followed by Ash pond (5.1 ± 0.8 mg L^{-1}) and Dongia nala (3.2 ± 0.3 mg L^{-1}). Zn concentration was minimum (0.8 ± 0.1 mg L^{-1}) at the reference site during September whereas, in sediment, Zn concentration was maximum (57 ± 2.9 mg kg^{-1}) at Ash pond site followed by Belwadah (55 ± 3.9 mg kg^{-1}) and Dongia nala (7.9 ± 1.0 mg kg^{-1}) while it was minimum (1.3 ± 0.1 mg kg^{-1}) at the reference site during the month of December.

Mercury (Hg) In water, Hg concentrations were recorded maximum (4.1 ± 0.4 mg L^{-1}) at Dongia nala site followed by Belwadah (2.0 ± 0.3 mg L^{-1}) and Ash pond (0.19 ± 0.01 mg L^{-1}). Hg concentrations were found BDL at Rihand dam (reference site) during all the seasons. In sediment, Hg concentration was maximum (6.8 ± 0.4 mg kg^{-1}) at Dongia nala site followed by Ash pond (1.2 ± 0.4 mg kg^{-1}) and Belwadah (1.2 ± 0.3 mg kg^{-1}) while it was minimum (0.02 ± 0.0 mg kg^{-1}) at Rihand dam during the month of June. Seasonal variations followed almost the same trend of monthly variation as others.

Cadmium (Cd) In water, Cd concentrations were recorded maximum (4.5 ± 0.9 mg L^{-1}) at Belwadah site followed by Ash pond (1.2 ± 0.2 mg L^{-1}) and Dongia nala (0.9 ± 0.1 mg L^{-1}). Cd concentration was minimum (0.01 ± 0.00 mg L^{-1}) at Rihand dam during September. In sediment, Cd concentration was maximum (4.6 ± 1.0 mg kg^{-1}) at Ash pond site (unlike metal concentration in water) followed by Belwadah (1.4 ± 0.3 mg kg^{-1}) and Dongia nala (1.2 ± 0.9 mg kg^{-1}) while it was minimum (0.1 ± 0.01 mg kg^{-1}) at Rihand dam during the month of June. Seasonal variations followed almost the same trend of monthly variation as the above-mentioned metals.

At some sites, metal concentrations in sediment were recorded minimum during the month of June. All the metals analyzed in wastewaters followed the same seasonal trend, i.e., high during the summer season, from March until June, and low during the rainy month, starting from September, which may be explained as a rain-dilution effect. The most polluted site was Belwadah, i.e., waters and sediments had the highest concentration of all the relevant metals. The reference site was characterized by the presence of low concentrations of metals in waters and in sediments (Tables 4 and 5).

Discussion

Temperature was recorded maximum at Belwadah site during June as it received heated effluent of the Anpara thermal power plant site and lowest during January at the reference site. All the chemical, biochemical, and biological activities are influenced by temperature. Therefore, it is an important factor of aquatic ecosystem. Temperature also plays an important role in solubility of gases (Reid 1961) and alters the saturation values of solids and gases in water. In aquatic ecosystems, the temperature rarely exceeds 37°C (Warren 1971). Ambasht and Tripathi (1978) have recorded the temperature of effluent water from a fertilizer factory around 50°C. A significant positive correlation ($p < 0.01$) between temperature, BOD, and COD was recorded while a significant negative correlation ($p < 0.05$) was obtained between temperature and DO. Higher temperature favors the growth of decomposer organisms which also consume a good part of dissolved oxygen (Mishra 2006).

Water transparency is directly related with seasons and the sampling points. Transparency is an important factor for water quality determination which influences the penetration of light used in the process of photosynthesis by aquatic plants. Transparency is inversely proportional to the turbidity of water and is affected by the concentration of suspended solid particles and microorganisms (Hutchinson 1975). In terms of Secchi disk, it was lowest at the Belwadah site and Ash pond followed by Dongia nala of the Kannoria chemicals. Transparency was recorded maximum at the reference site due to lack of point and nonpoint pollution sources causing turbidity. Since the thermal power effluent contained the residuals of coal burning, e.g., fly ash, the transparency was recorded minimum at Belwadah. At Ash pond, the mine effluent was responsible for low transparency. Permissible limit of transparency has not been decided by various environmental monitoring agencies. Maximum values of transparency were recorded in winter followed by summer and least in rainy season. A significant negative correlation ($p < 0.01$) was obtained with TDS, TSS, NO_3^-, BOD, and COD while transparency showed significant positive correlation ($p < 0.01$) with DO and alkalinity. Higher suspended solid values might be, therefore, responsible for low transparency values at Belwadah and Dongia nala.

TSS gives us more information about the solid load transported into the water bodies by the streams and the catchments areas. It may be on account of humus, fine debris, and liquid effluents discharged into the water bodies. According to the CPCB (1998), permissible limit of TSS for inland surface water is 100 mg L^{-1}. It was maximum (933 ± 30 mg L^{-1}) at the Belwadah site during September and lowest (50 ± 1.8 mg L^{-1}) during January at the reference site. TSS was exceptionally high at Belwadah followed by Ash pond due to high content of fly ash and mine discharge, respectively. TSS showed significant positive correlation ($p < 0.01$) with BOD, COD, and pH while it showed significant negative correlation ($p < 0.01$) with transparency, DO, and acidity. Depending upon the nature and concentration, suspended solids may interfere with the self-purification capacity of water by diminishing light penetration and hence photosynthetic reactions (Rai and Tripathi 2006). In extreme cases, silt deposition can lead to flooding and interfere with other biological activities (Tiwary 2001). In thermal power and coal mine effluent, TSS normally contains high amount of fine coal particles and makes surface water blackish and reduces aesthetic values of receiving water bodies (Rai and Tripathi 2006). Maximum TSS load was recorded during rainy season followed by summer while minimum values were recorded during the winter season.

TDS mainly consist of inorganic minerals including organic matter and large variety of salts. Total dissolved solids in the present study were higher during the rainy season. This is possibly due to a greater input of surface runoff from the surrounding watershed region. According to the CPCB (1998), permissible limit of TDS for the discharge into inland surface water is 2,100 mg L^{-1}. However, the permissible limit of TDS for drinking water, as laid down by the US Public Health (USPH) Drinking Water Standards, World Health Organization (WHO), and Bureau of Indian Standard (BIS), is 500 mg L^{-1}. TDS was recorded maximum at Ash pond site (703 ± 37.4 mg L^{-1}) followed by Belwadah (605 ± 31.3 mg L^{-1}) and Dongia nala (405 ± 37 mg L^{-1}) and minimum at the reference site (60 ± 6.4 mg L^{-1}). TDS showed significant positive correlation ($p < 0.01$) with BOD, nitrate, and chloride while significant negative correlation ($p < 0.01$) was observed with transparency, DO, and pH. Maximum TDS during rainy season at Ash pond might be due to the excess mine effluent drainage from surrounding areas of the Bina coal mine. Tiwary (2001) reported TDS in the range of 200–860 mg L^{-1} from Indian coalfields. Dissolved cations included calcium, magnesium, sodium, and potassium; the major anions were sulfate, chloride, fluoride, nitrate, bicarbonate, and carbonate. Of these, thiosulfate and sulfuric minerals may create environmental problems through their oxidation reaction with water leading to acid formation. They originate from the dissolution of pyretic sulfur in the underground mines and their concentrations are generally found high in mine water and, therefore, increase the hardness of water and thus reduce its utility as a drinking water Tiwary (2001).

pH of water is regarded as a critical factor in survival of aquatic plants and planktonic organisms (Mishra 2006). Most of the chemical and biochemical reactions are influenced by the hydrogen ion concentration of waters. It serves as an index to denote the extent of pollution in the case of acidic and alkaline wastes. The adverse effects of the acids appear below pH 5.0 and of alkaline more than pH 9.5. In natural waters, pH ranges from 6.5 to 8.5 (Warren 1971). According to CPCB (1998), permissible limit of pH for the discharge into inland surface water is 5.5 to 9.0. At present sites, pH was recorded maximum (8.03 ± 0.30) during January at Belwadah followed by the reference site and Ash pond. It was lowest (3.90 ± 0.29) at Dongia nala during June. Lowest values of pH were recorded at Dongia nala which might be due to the acidic nature of constituents discharged from Kannoria effluent. As far as seasonal variation is concerned, pH values were generally recorded highest during winter followed by rainy season while least during summer season. pH showed significant positive correlation ($p < 0.01$) with alkalinity, DO, and TSS while significantly negative correlation ($p < 0.01$) with acidity, nitrate, and phosphate. It also showed significant negative correlation ($p < 0.05$) with TDS. At Dongia nala, pH indicated a slightly acidic nature, indicating the acidic nature of effluent discharged into the reservoir. Low pH values at Ash pond in certain months might be attributed to acid generation from the oxidation of sulfur-bearing minerals like pyrites in coal mines. This occurs only when the minerals react with water and oxygen in the presence of *Thiobacillus* bacteria to produce sulfuric acid and iron hydroxide or iron sulfate (Tiwary 2001).

EC gives information about the level of electrolytes present in aquatic ecosystems. Conductivity mostly depends on the nature of various dissolved ionized substances, their actual and relative concentrations, and temperature (Mishra 2006). CPCB has not mentioned any maximum permissible limit for EC. Change in electrical conductance reflects fluctuations in ionic concentrations of water bodies. According to WHO guidelines (2004) for drinking water, maximum permissible limit of EC is 400 mS m^{-1}. In our investigation, electrical conductance was highest at Dongia nala (460 ± 21 μmho cm^{-1}) during January and lowest (44.9 ± 2.9 μmho cm^{-1}) during the month of September at the reference site. It showed significant positive correlation ($p < 0.01$) with chloride, hardness, and acidity while significant positive correlation ($p < 0.05$) with DO. Electrical conductance was recorded maximum at Dongia nala, which might be due to higher discharge of chloralkali products having high conductance.

Acidity is the quantitative capacity to react with a strong base to a designated pH (8.3 corresponding to CO_2 and 4.2 corresponding to minerals). It has pronounced effect on the pH of water (Mishra 2006). Warren (1971) found lowering of pH in water as a result of decomposition of organic matters which releases CO_2. Acidity was highest at Dongia nala during June and lowest also during June at the reference site. Acidity showed significant positive correlation ($p < 0.01$) with EC, chloride, hardness, nitrate, and phosphate while significant negative correlation ($p < 0.01$) with alkalinity pH and TSS. Further, it showed significant positive correlation ($p < 0.05$) with BOD and COD while significant negative correlation ($p < 0.05$) with DO. Acid leachate and effluent may have twofold adverse effects upon aquatic biota; the acidic pH may harm aquatic organisms and the elevated heavy metals may have toxic effects upon aquatic life, wild life, and surrounding vegetation (Tiwary 2001; Rai 2008a).

Alkalinity is an important parameter for the water quality determination. It is a quantitative estimation to neutralize a strong acid to a designated pH. Since the alkalinity of most of the surface waters is primarily a function of carbonate, bicarbonate and hydroxide ion are, therefore, taken as indicative of the concentration of these constituents (Mishra 2006). According to (Schaeperclaus et al. 1990), aquatic systems have been categorized into three categories with respect to the alkalinity: less productive 0–15 mg L^{-1}; medium productive 15–100 mg L^{-1}; and highly productive aquatic ecosystems with 100–250 mg L^{-1} alkalinity values. Alkalinity was highest (65.5 ± 4.4 mg L^{-1}) at Belwadah during January and lowest (4.3 ± 1.1 mg L^{-1}) during June at the reference site. Therefore, the alkalinity values reflected the reservoir in medium-productive range according to the aforesaid classification. Alkalinity showed significant positive correlation ($p < 0.01$) with transparency, DO, and also with TSS ($p < 0.05$) while significant negative correlation ($p < 0.01$) with acidity, nitrate, and TDS.

DO influences the distribution and abundance of algal population in an aquatic ecosystem. It is of paramount importance to all living organisms and is considered to be the important factor which to a greater extent can reveal the nature of whole aquatic ecosystem at a glance (Mishra 2006). DO data are valuable in the determination of water quality criteria of an aquatic body. Most of the physical, chemical, and biological activities are directly related to the DO content in natural water and wastewater (Rai and Tripathi 2006). DO showed significant positive correlation ($p <$ 0.01) with transparency, pH, and alkalinity while it showed significant negative correlation ($p <$ 0.01) with BOD, COD, temperature, hardness, nitrate, phosphate, TSS, and TDS while with acidity, chloride, hardness, and EC it showed significant negative correlation at $p < 0.05$. Seasonally, at different sampling sites, higher DO values were recorded during winter season followed by rainy and least during summer season. A lower temperature is known to favor greater dissolution of oxygen in water while at high temperature the dissociation coefficient of oxygen in water is low (Ravindra et al. 2003). High pollution load may also decrease the DO values to a considerable level which may be due to decomposition of organic compounds by microbes which require oxygen for oxidation process. Royal Commission, 1898 (see Lester 1969), has classified the rivers according to their DO content as: very clean (DO 7.0 mg L^{-1}); clean/fairly clean/moderate (DO 6.0 mg L^{-1}); doubtful (DO 5.0 mg L^{-1}); and bad (DO 4.0 mg L^{-1}). The permissible limits of DO for drinking water, as laid down by the USPH Drinking Water Standards are 4.0 to 6.0 (see Ravindra et al. 2003). Lowest value of DO at Belwadah might be due to discharge of thermal effluent which may be responsible for decrease in DO values. Quality of water was bad in terms of DO at all the sites except the reference site. Therefore, water of G.B. Pant Sagar was found to be unsuitable for drinking purposes at three polluted sites. There are other reports of too low dissolved oxygen ranging from 1.0 to 4.0 mg L^{-1} in wastewater (Kumar et al. 1974; Ramaswamy and Somashekhar 1982; Tripathi et al. 1989; Mishra 2006). DO in good quality streams are usually more than 6 mg L^{-1}, which promotes proper growth of fish and other aquatic organisms (Ravindra et al. 2003). However, all the polluted sites recorded DO values well below this norm and are, therefore, not suitable for fish farming.

BOD is an approximate measure of the amount of biochemically degradable organic matter present in the water and it is used mainly to determine degree of pollution in water bodies and their self-purification capacity, pollution stress of wastewaters, and efficiency of waste treatment plants (Mishra 2006; Rai and Tripathi 2006). Increases in BOD values indicate high pollution intensity and more consumption of dissolved oxygen of water. Royal Commission, 1898 (see Hynes 1966), has classified the water quality of rivers according to their BOD content as: very clean (0–1 mg L^{-1}); clean/fairly clean/moderate (1–2 mg L^{-1}); doubtful (3–5 mg L^{-1}); and bad (5–10 mg L^{-1}). According to CPCB (1998), permissible limit of BOD for the discharge into inland surface water is 30 mg L^{-1}. Biological oxygen demand was recorded maximum at Belwadah followed by Ash pond and Dongia nala. It was observed minimum at the reference site. BOD showed significant positive correlation ($p <$ 0.01) with COD, temperature, nitrate, phosphate, TSS, and TDS while at $p < 0.05$ with acidity. It showed significant negative correlation ($p < 0.01$)

with DO and transparency. BOD showed 99.9% positive correlation with COD which is worth to mention. Being located in an industrial region, the reservoir receives the discharge from various industries and also its self-purification capacity is far less than rivers, therefore, BOD was higher at all the polluted sites as compared to four categories of water quality as described by the Royal Commission. Higher values of BOD at Belwadah, Ash pond, and Dongia nala might also be due to the seepage of domestic wastes into mines and thermal effluent channel as the drainage system was not proper.

COD is also an important parameter to evaluate pollution stress. The COD is a measure of oxygen equivalent to the organic matter content of the water susceptible to oxidation by a strong chemical oxidant and thus is an index of organic pollution in the aquatic ecosystems (Ravindra et al. 2003). COD indicates a close relationship with BOD and organic matter (Rai and Tripathi 2006). Pollution load and the rough idea of BOD values can be derived from COD especially in case of industrial effluents (Mishra 2006). COD estimation of water quality takes less time also in comparison to BOD. According to CPCB (1998), permissible limit of COD for the discharge into inland surface water is 250 mg L^{-1}. COD was also maximum at Belwadah and minimum at the reference site. COD showed significant positive correlation ($p < 0.01$) with BOD, temperature, nitrate, TDS, TSS, and at $p < 0.05$ with acidity while COD showed significant negative correlation ($p < 0.01$) with DO and transparency. At Belwadah and Ash pond, chemical oxygen demand was found comparatively high due to the presence of coal particles in the mine water as suspended solids. In addition, the presence of high BOD and COD also might be due to contamination of mine and thermal power effluent with organic pollutants. The results of DO, BOD, and COD at Ash pond site were in accordance with the findings of Mishra (2006).

The major sources of chloride in natural waters are sediments (Mishra 2006). High chloride content is considered to be the indicator of pollution which is either due to organic wastes of fecal origin or industrial effluents (Ambasht and Tripathi 1978; Ravindra et al. 2003; Rai and Tripathi 2006). According to Sreenivasan (1965), chloride concentration between 4 and 10 mg L^{-1} indicates the purity of water. According to BIS, permissible limit of chloride is 250 mg L^{-1}. Chloride was recorded highest at Dongia nala followed by Belwadah and Ash pond while lowest values were recorded at the reference site. Chloride showed significant positive correlation ($p < 0.01$) with electrical conductance, hardness, TDS, and acidity while it showed negative correlation with DO ($p < 0.05$). Since Kannoria Chemicals manufactures chloralkali products like gamaxine and HCl, therefore, its effluent recorded very high chloride content and its ultimate discharge into Dongia nala leads to high chloride content in the G.B. Pant Sagar. At Ash pond and Belwadah, the higher value of TDS might be responsible for higher chloride content. Mishra (2006) also reported a very high chloride concentration in polluted lakes by industrial effluents. Zafar (1964) has also reported a high chloride concentration due to sewage and industrial contamination. Canfield (1984) made an extensive study of Florida Lake in the USA and recorded a very high 4,000 mg L^{-1} chloride which, although after rainy season, was diluted up to 1,700 mg L^{-1}.

Hardness of water is contributed mainly by the presence of principal cations like Ca^{2+} and Mg^{2+}, etc. The anions are HCO_3^-, CO_3^{-2}, SO_4^{-2}, Cl^-, and NO_3^-. Sawyer (1960) classified waters on the basis of hardness values into four types: soft (0–75 mg L^{-1}); moderately hard (75–150 mg L^{-1}); hard (150–300 mg L^{-1}); very hard (300 mg L^{-1} and above). A hardness of 300 mg L^{-1} is, however, permissible for domestic use, whereas it should be 2 to 80 mg L^{-1} for boiler feeders, 10 to 250 mg L^{-1} for various food processing industries, and 0.05 mg L^{-1} for laundry and textile industries. For agriculture, an upper limit of 150 mg L^{-1} is usually recommended (Ravindra et al. 2003). According to BIS, permissible limit of hardness for the discharge into inland surface water is 300 mg L^{-1}. Water hardness was recorded maximum at Dongia nala site (very hard type) followed by Belwadah and Ash pond (hard type) and minimum at the reference site (soft type). Hardness showed significant positive correlation ($p < 0.01$) with chloride, electrical conductivity, and acidity while it showed significant negative correlation ($p < 0.01$) with DO. Due to the discharge of chemicals imparting hardness to water, it was recorded maximum at Dongia nala. Higher amount of hardness in mine and thermal effluent may be attributed to higher TDS values, sulfates, and chloride. Problem of hardness is also a matter of concern in northern coalfields which reduces the utility of water for various purposes like drinking and bathing (Tiwary 2001; Mishra 2006).

Nitrate N is the end product of aerobic decomposition of organic matter and is the most oxidized form of nitrogen commonly present in natural waters. Nitrate N is an important nutrient for aquatic life and in the presence of other nutrients such as phosphate it enhances the growth of algal bloom causing eutrophication (Mishra 2006; Rai and Tripathi 2006). According to the Royal Commission (see Lester 1969), the water should be very clean if nitrate is below 0.5 mg L^{-1}, clean below 2.0 mg L^{-1}, fairly clean below 2.6 mg L^{-1}, doubtful below 4.0 mg L^{-1}, and bad above 4.0 mg L^{-1}. Nitrification usually takes place at high temperature and high DO content when microbial activities are usually at maximum. Nitrate was recorded maximum near Ash pond of Bina coalmine and minimum at the reference site. Nitrate showed significant positive correlation ($p < 0.01$) with phosphate, BOD, COD, and acidity while it showed significant negative correlation ($p < 0.01$) with DO, transparency, pH, and alkalinity. Nitrate ions are originated from explosives, which are used to blast the coal in the mines (Tiwary 2001; Mishra 2006). It is generally found in pit water or waste rock from spilled or undetonated explosives or by leaching under wet blast condition.

Phosphate P is an essential plant nutrient and can play an important role of limiting factor (Dugan 1972) and responsible for the growth of plants specially phytoplanktons in water ecosystems (Hutchinson 1975). Phosphate content was recorded maximum near Ash pond of Bina coalmine and minimum at the reference site. Phosphate showed significant positive correlation ($p < 0.01$) with alkalinity, nitrate, COD, BOD, and acidity while it showed significant negative correlation ($p < 0.01$) with DO and at $p < 0.05$ with pH.

Correlation matrix between various parameters revealed that most of the parameters were found to bear statistically significant correlation with each other indicating close association of these parameters with each other. However, dissolved oxygen showed significantly negative correlation with all investigated parameters (BOD, COD, temperature, hardness, nitrate, phosphate, TSS, TDS, chloride, acidity, hardness, and EC) except transparency, pH, and alkalinity with which it had a positive correlation. PCA provides information on the most meaningful parameters, which describe whole dataset rendering data reduction with minimum loss of original information (Singh et al. 2005). Seven principal components were obtained with eigenvalues >1 summing almost 99% of the total cumulative variance in the water dataset. Further, FA was applied, which extracted four major variables, i.e., DO, alkalinity, pH, and transparency out of whole dataset. FA attempts to extract a lower dimensional linear structure from the dataset. It further reduces the contribution of less significant variables obtained from PCA and the new group of variables is extracted through rotating the axis defined by PCA application (Singh et al. 2005). The application of aforesaid different multivariate approaches for the interpretation of these complex data matrices offers a better understanding of water quality and ecological status of the studied systems, allows the identification of the possible factors/sources that influence the water systems, and offers a valuable tool for reliable management of water resources as well as rapid solutions on pollution problems. DO can serve as a single useful index of water quality because, with increase in the value of most of these parameters and metals, the DO decreased. Alkalinity serves as a pH reservoir for inorganic carbon. It is usually taken as an index of productive potential of the water (Ravindra et al. 2003). Therefore, along with DO, assessment of alkalinity, pH, and transparency values may only represent the aquatic ecosystem health in its totality.

One-way ANOVA between sites were significant ($p < 0.01$) between groups and within groups for all the above-mentioned physicochemical parameters. One-way ANOVA between months were also significant ($p < 0.01$) between groups as well as within groups except BOD, COD, hardness, nitrate, and phosphate.

The variation in various physicochemical characteristics between the reference site and different polluted sites was tested for significance of difference using a *t* test. During different seasons, all the parameter values differed significantly ($p < 0.01$). This showed that reservoir water quality was largely affected by various effluents discharged at the polluted sites, which caused the significant variations in water quality of G.B. Pant Sagar.

Based on maximum permissible limits for these parameters, it may be concluded that the water of reservoir at different polluted sites is not suitable for drinking, bathing, wildlife, fisheries, recreation, irrigation, and industrial cooling.

Metals in water and sediments

In the present study, at several sites and seasons, the heavy metals in industrial effluent and reservoir water were above the permissible limit as prescribed by EPA, WHO, CPCB, and BIS (Rai et al. 2007). Seasonal variations in metal concentration (in effluent, water, and sediments) recorded during present investigation were in accordance with the findings of Ali et al. (1999). Cu in effluent showed significant positive correlation with Cu in water (0.984; $p < 0.01$), while no correlation was observed with Cu in sediment. Among various metals recorded in effluents of different polluted sites, Cu showed significant positive correlation with Cr (0.944), Fe (0.967), Ni (0.978), Pb (0.917), and Mn (0.955) at $p < 0.01$. Among physicochemical characteristics, Cu in water showed significant positive correlation with TSS (0.590; $p < 0.05$), BOD (0.79; $p < 0.05$), COD (0.77; $p < 0.05$), and alkalinity (0.615; $p < 0.05$) while it showed significant negative correlation with DO (0.831; $p < 0.01$) and EC (0.648; $p < 0.05$) of water. Cr in effluent showed significant positive correlation with Cr in water (0.987; $p < 0.01$) and with Cr in sediment (0.843; $p < 0.01$). Among various metals recorded in effluents of different polluted sites, Cr showed significant positive correlation with Fe (0.996), Zn (0.967), Ni (0.992), Pb (0.996), and Mn (0.955) at $p < 0.01$. With different physicochemical characteristics, Cr in water showed significant positive correlation with TSS (0.603; $p < 0.05$), BOD (0.89; $p < 0.01$), COD (0.87; $p < 0.01$), and alkalinity (0.738; $p < 0.01$) while it showed significant negative correlation with DO (0.871; $p < 0.01$) and acidity (0.808; $p < 0.01$) of water. Fe in effluent showed no correlation with both Fe in water and in sediment. Among various metals recorded in effluents of different polluted sites, Fe showed significant positive correlation with Cd (0.963), Zn (0.998), Ni (0.992), Pb (0.986), and Mn (0.997) at $p < 0.01$. With different physicochemical characteristics, Fe in water showed significant positive correlation with TSS (0.621; $p < 0.05$), BOD (0.594; $p < 0.05$), COD (0.87; $p < 0.01$), and alkalinity (0.732; $p < 0.01$) while it showed significant negative correlation with DO (0.791; $p < 0.01$) and acidity (0.822; $p < 0.01$) of water.

Mn in effluent showed significant positive correlation with Mn in water (0.87; $p < 0.01$), while no correlation was observed with Mn in sediment. With various metals recorded in effluents of different polluted sites, Mn showed significant positive correlation with Zn (0.993), Ni (0.993), and Pb (0.985) at $p < 0.01$. With different physicochemical characteristics, Mn in water showed significant positive correlation with TSS (0.671; $p < 0.05$), BOD (0.584; $p < 0.05$), COD (0.89; $p < 0.01$), and alkalinity (0.732; $p < 0.01$) while it showed significant negative correlation with acidity (0.822; $p < 0.01$) of water. Ni in effluent showed significant positive correlation with Ni in water (0.966; $p < 0.01$) and Ni in sediment (0.783; $p < 0.05$). With various metals recorded in effluents of different polluted sites, Ni showed significant positive correlation with Zn (0.999), Cd (0.960), and Pb (0.978) at $p < 0.01$. With different physicochemical characteristics, Ni in water showed significant positive correlation with TSS (0.619; $p < 0.05$), BOD (0.662; $p < 0.05$), COD (0.629; $p < 0.01$), and alkalinity (0.706; $p < 0.05$) while it showed significant negative correlation with acidity (0.814; $p < 0.01$). Pb in effluent showed significant positive correlation with Pb in water (0.966; $p < 0.01$) and sediment (0.638; $p < 0.05$). With various metals recorded in effluents of different polluted sites, Pb showed significant positive correlation with Zn (0.974), Cd (0.967), and Zn (0.978) at $p < 0.01$. With different physicochemical characteristics, Pb in water showed significant positive correlation with TSS (0.629; $p < 0.05$) and alkalinity (0.752; $p < 0.05$) while it showed significant negative correlation with acidity (0.824; $p < 0.01$) and DO (0.819; $p < 0.01$) of water.

Zn in effluent showed significant positive correlation with Zn in water (0.951; $p < 0.01$) while no correlation was observed with Zn in sediment. With various metals recorded in effluents of different polluted sites, Zn showed significant positive correlation with Cd (0.952) at $p < 0.01$. With different physicochemical characteristics, Zn in water showed significant positive correlation with TSS (0.622; $p < 0.05$) and alkalinity (0.692; $p < 0.05$) while it showed significant negative correlation with acidity (0.815; $p < 0.01$) of water. Hg in effluent showed significant positive correlation with Hg in water (0.985; $p < 0.01$) and significant positive correlation with Hg in sediment (0.618; $p < 0.05$). With various metals recorded in effluents of different polluted sites, Hg showed no correlation. With different physicochemical characteristics, Hg in water showed significant positive correlation with TDS (0.611; $p < 0.05$) of water.

All the metals except Hg showed significant positive correlation with more than one metal. DO of water at polluted sites showed significant negative correlation with all the recorded metals except Hg, Zn, Mn, and Ni. Generally, all the metals recorded during the course of the present study have shown significant positive correlation with TSS and alkalinity except Hg which showed significant positive correlation with TDS. Almost all the metals recorded in water showed significant positive correlation with BOD and COD. Therefore, we can infer that increase in the metal concentration of different polluted sites was marked by increase in TSS, BOD, COD, and alkalinity (increase in pH) while it was marked by decrease in DO and acidity.

Most heavy metals in aquatic ecosystems eventually become associated with particulate matter, which settles and accumulate in the bottom sediments (Rai and Tripathi 2009). The accumulation of pollutants in the bottom sediments of water bodies and the remobilization of these substances from the sediments are considered as the two most important mechanisms in the regulation of pollutant concentrations in an aquatic environment (Linnik and Zubenko 2000). The heavy metal pollution of aquatic ecosystems is often reflected in high metal levels in the sediments and macrophytes as compared to concentrations in water (Rai 2008c). Water bodies with slow water exchange rates (e.g., lakes and reservoirs) accumulate heavy metals in their bottom sediments in considerable quantities. This phenomenon has both positive and negative features. Bottom sediments promote self-purification in the aquatic environment because of heavy metal accumulation. Heavy metal accumulation in the bottom sediments can be reversed causing adverse impact on water quality, especially in relation to heavy metals. Under certain conditions, bottom sediments can be a strong source of secondary water pollution (Denisova et al. 1989; Linnik et al. 1993; Rai and Tripathi 2009). This is evident as release of heavy metals from bottom sediments is promoted, for example, by a deficit in dissolved oxygen or by decrease in pH and thus elevating metal concentrations in water (Rai 2008c). In the present study, metal concentration in water with sediment was only correlated in case of Hg, Ni, Pb, and Cr whereas others have not shown any such sort of correlation. These findings were in accordance with Morillo et al. (2002), who investigated partitioning of metals in sediments from the Odiel River (Spain) and reported that Pb, Fe, Cr, and Ni are strongly linked to the sediments, while Cd, Zn, and Cu are the most mobile metals.

Conclusion

Instead of monitoring a plethora of parameters, monitoring of few parameters (e.g., DO, transparency, pH, and alkalinity in present investigation) can reflect the aquatic ecosystem health in totality. Henceforth, the study presents the inevitability and utility of multivariate statistical assessment of large and complex databases in order to get better information about the quality of surface water, the design of sampling and analytical protocols, and the effective pollution control/management of the surface waters. Metal concentrations near effluent discharge point of the reservoir were well above the permissible limit. As mentioned earlier, the water of G.B. Pant Sagar is used for drinking, irrigation, bathing, and other domestic uses. Therefore, in view of the present observation, the author recommends that water of the reservoir should not be used by the local people of Singrauli region for the aforesaid purposes, particularly at effluent discharge points of the polluted sites.

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