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Hydrochemistry of reservoirs of Damodar River basin, India: weathering processes and water quality assessment

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Abstract Water samples collected from the six reservoirs of Damodar River basin in pre- and post-monsoon, have been analysed, to study the major ion chemistry and the weathering and geochemical processes controlling the water composition. Ca, Na and HCO_3 dominate the chemical composition of the reservoir water. The seasonal data shows a minimum concentration of most of the ions in post-monsoon and a maximum concentration in pre-monsoon seasons, reflecting the concentrating effects due to elevated temperature and increased evaporation during the low water level period of the pre-monsoon season. Water chemistry of the reservoirs strongly reflects the dominance of continental weathering aided by atmospheric and anthropogenic activities in the catchment area. Higher concentration of SO_4 and TDS in Panchet, Durgapur and

Tenughat reservoirs indicate mining and anthropogenic impact on water quality. The high contribution of (Ca + Mg) to the total cations, high concentration of dissolved silica, relatively high (Na + K)/TZ⁺ ratio (0.3) and low equivalent ratio of (Ca + Mg)/(Na + K) suggests combined influence of carbonate and silicate weathering. Kaolinite is the possible mineral that is in equilibrium with the water, implying that the chemistry of reservoir water favours kaolinite formation. The calculated values of SAR, RSC and sodium percentage indicate the 'excellent to good quality' of water for irrigation uses.

Keywords Hydrochemistry · Reservoirs · Damodar River · Weathering · Anthropogenic · Water Quality · Solute Flux · India

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Introduction

Reservoirs play a very important role in the geochemical cycling of elements and influence the chemical composition and material transfer of the river system. It has been observed that the rivers of the Indian subcontinents show pronounced spatial variability in sediment and dissolved load, primarily in response to the lithology, river-bed slope and human interference i.e.-deforestation, cultivation, construction of dams and urbanisation (Subramanian 1987, 1993). Chakrapani and Subramanian (1990)

observed that in the Mahanadi River basin about 65% of the sediments are either trapped by dams/reservoirs constructed along the course of river or deposited in the channels as bed sediments. Milliman and Mead (1983) pointed out that the suspended sediment loads normally transported to the oceans by the Colorado River have been reduced to nearly nothing and in the Mississippi River by one third by the construction of dams. Therefore, when the effluent and/or sediment loaded river or any other channel meets the reservoir, various physico-chemical reactions take place and a large part of the

effluent and sediment in one form or other either settles down, adheres, or is adsorbed by the sediments depending upon the physico-chemical conditions and on the species of the pollutants, nutrients, or trace metals under consideration. Heavy metals are not permanently fixed on sediments and can be released back to the water column by changes in environmental conditions, such as pH, redox potential, and the presence of organic chelators (Forstner and Wittmann 1983).

Reservoir water derives its composition from the feeding river system, weathering and geochemical processes operating in the catchments and anthropogenic sources. Natural composition of reservoir waters are essentially regulated by the breakdown of rock matrix in response to the reactive rain water containing dissolved carbon-dioxide; however, deviations in natural water chemistry could be introduced by man at any stage or location in the drainage basin. The main chemical processes, which releases ions into solutions are hydrolysis, reduction, oxidation or chelation (Drever 1988). The relative importance of each chemical weathering process varies with the weathering materials and the conditions of the weathering environment. The important factors that pose a threat to the reservoir water quality are:

- Discharge of the industrial wastes into the river/reservoir.
- Multipurpose use of a single water body (agriculture, human consumption, recreation fishing, hydropower etc.)
- Large-scale settlement around the reservoir water bodies.

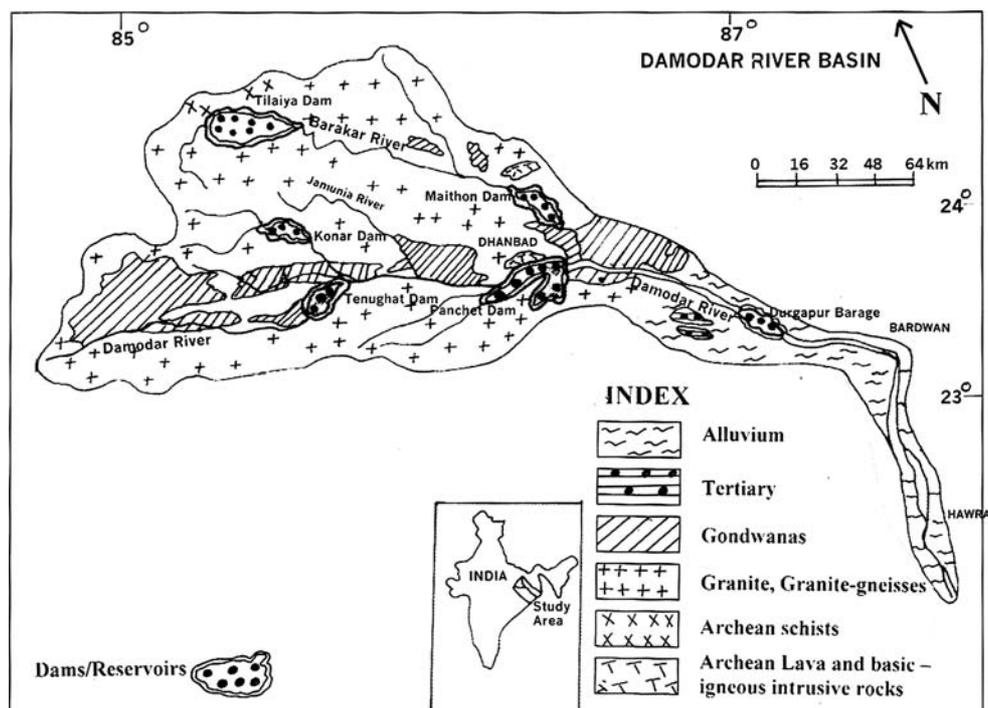
- Presence of mining/industrial activities in the catchments.
- Problems arising due to siltation of water bodies.
- Eutrophication, which is directly attributed to over fertilisation of a water body by human activities usually by wastewater discharge.

In the present work, a detailed hydrogeochemical study of six reservoirs of Damodar River Basin has been carried out to determine the major ion chemistry of these reservoirs and to understand the weathering and geochemical processes controlling the water composition and suitability of water for irrigation purposes.

Damodar River basin

The Damodar River basin area extends from 22°45'N to 24°30'N and 84°45'E to 88°00'E circumscribing parts of Jharkhand and West Bengal, which is about 11.7 and 8.5% of the total geographical area of these two states (Fig. 1). It is a small-rain fed river (541 km long), originating from Khamerpet Hill (elev. 1068 m), near the trijunction of Palamu, Ranchi and Hazaribag districts of Jharkhand. It flows through the cities Ramgarh, Bokaro, Dhanbad, Asansol, Durgapur, Bardwan and Hawrah, before ultimately joining the lower Ganga (Hooghly estuary) at Shayampur, 55 km downstream of Hawrah. A unified two-stage development scheme for construction of a series of dams across the Damodar and its tributaries was implemented in the early 1950s. Dams at Tenughat and Panchet and barrage at Durgapur on the Damodar

Fig. 1 Damodar River basin map showing the major geological formation and location of studied reservoirs



mainstream have been constructed for the purpose of flood control, power generation, soil conservation and irrigation. Three more dams namely Tilaiya, Maithon and Konar on the tributaries - Barakar and Konar River have been constructed on the later date (Fig. 1).

The Damodar River flows through granites and granitic-gneisses of Archeans, sandstones and shales of the Gondwanas and the Recent alluvials. The lithology of the reservoirs is dominated by the quartzites, quartz-mica-schists, biotite-gneiss, biotite-schist, garnetiferous-gneiss and schist, acid granulites with hornblend and amphibolites of Archean age (Ghose 1983). Gondwana rocks consisting of sandstones, shales and fire clays with coal seams are forming the part of the catchments of Tenughat, Panchet and Durgapur Barrage. Though not rich in metallic minerals, the Damodar basin is the storehouse of Indian coal. Other than coal, fire clay, bauxite, mica, limestones are associated with the geological formation of the basin. Besides domestic effluents, these reservoirs receive the pollution load from the various sources like coal washeries, coal mining effluent, mining dumps, coke industries, thermal power plants, mining machineries and vehicular sources. These point and non-point sources of pollution severely affected the quality of the water and sediments.

Materials and methods

Sixty water samples were collected from six reservoirs from various locations in the month of March (pre-monsoon) and October (post-monsoon) in year 2003. The samples were collected in 1-litre narrow-mouth pre-washed polyethylene bottles. Five samples were collected from different locations in each reservoir. A boat was used to collect the representative samples and to cover the entire reservoir. Electrical conductivity (EC) and pH values were measured in the field using a portable conductivity and pH meter. In the laboratory, the water samples were filtered through 0.45 μm Millipore membrane filters to separate the suspended sediments. The molybdosilicate and acid titration methods were used to determine the concentration of dissolved silica and bicarbonate (APHA 1985). Major anions (F, Cl, NO_3 , SO_4) and cations (Ca, Mg, Na, K) were measured by Ion Chromatograph (Dionex-120) by using anion and cation column, respectively. The analytical precision was maintained by running the known standard after every 15 samples. An overall precision, expressed as percent relative standard deviation (RSD) was obtained for the entire samples. Analytical precision for Ca, Mg, Na, and K were within 10% and overall data reproducibility for

Table 1 Chemical characteristics of reservoirs of Damodar River basin in Premonsoon (March 2003)

| Reservoirs | St. Code | pH | EC | TDS | F | Cl | NO_3 | HCO_3 | SO_4 | H_4SiO_4 | Ca | Mg | Na | K | TH | Na% | SAR | RSC |
|------------|----------|-----|-----|-----|------|------|---------------|----------------|---------------|--------------------------|------|------|------|-----|-----|------|------|------|
| Tenughat | TD-1 | 7.5 | 257 | 192 | 0.75 | 15.6 | 0.06 | 86 | 12.7 | 27.2 | 20.3 | 6.1 | 17.1 | 6.1 | 76 | 37.2 | 0.85 | 0.65 |
| | TD-2 | 8.3 | 172 | 161 | 0.78 | 4.3 | 0.04 | 84 | 12.4 | 23.3 | 19.1 | 5.7 | 9.3 | 2.0 | 71 | 24.3 | 0.48 | 0.67 |
| | TD-3 | 8.3 | 171 | 163 | 0.75 | 4.8 | 0.26 | 85 | 12.7 | 22.2 | 19.0 | 5.6 | 10.2 | 2.8 | 71 | 26.8 | 0.53 | 0.68 |
| | TD-4 | 8.2 | 171 | 158 | 0.68 | 4.4 | 0.21 | 82 | 12.6 | 21.8 | 19.1 | 5.6 | 9.6 | 2.2 | 71 | 25.1 | 0.50 | 0.63 |
| | TD-5 | 8.1 | 172 | 166 | 0.53 | 4.2 | 0.14 | 86 | 12.4 | 24.4 | 19.3 | 5.6 | 10.2 | 3.2 | 71 | 26.9 | 0.52 | 0.69 |
| Panchet | PD-1 | 8.5 | 272 | 216 | 0.86 | 9.5 | 0.32 | 102 | 33.1 | 17.7 | 23.9 | 10.0 | 15.0 | 3.2 | 101 | 26.7 | 0.65 | 0.66 |
| | PD-2 | 8.7 | 253 | 203 | 0.67 | 8.9 | 0.43 | 94 | 33.0 | 18.5 | 18.8 | 9.8 | 16.1 | 3.1 | 87 | 30.9 | 0.75 | 0.66 |
| | PD-3 | 8.3 | 291 | 228 | 0.60 | 9.0 | 0.28 | 110 | 34.2 | 18.6 | 26.4 | 10.3 | 15.1 | 3.2 | 108 | 25.4 | 0.63 | 0.72 |
| | PD-4 | 8.5 | 271 | 202 | 0.58 | 6.2 | 0.26 | 94 | 34.1 | 17.5 | 24.0 | 9.3 | 13.5 | 2.9 | 98 | 25.2 | 0.59 | 0.55 |
| | PD-5 | 8.6 | 277 | 215 | 0.57 | 8.8 | 0.08 | 102 | 33.3 | 17.7 | 22.9 | 10.1 | 16.4 | 3.1 | 99 | 28.7 | 0.72 | 0.68 |
| Durgapur | DB-1 | 8.7 | 247 | 195 | 0.50 | 7.2 | 0.39 | 102 | 19.8 | 16.2 | 23.0 | 8.0 | 15.6 | 2.6 | 90 | 29.3 | 0.72 | 0.77 |
| | DB-2 | 8.5 | 248 | 195 | 0.69 | 8.0 | 0.15 | 102 | 19.6 | 15.0 | 21.0 | 7.5 | 16.9 | 3.9 | 83 | 33.3 | 0.80 | 0.84 |
| | DB-3 | 8.3 | 254 | 204 | 1.00 | 7.2 | 0.45 | 110 | 18.5 | 18.0 | 23.1 | 7.7 | 15.6 | 2.8 | 89 | 29.5 | 0.72 | 0.91 |
| | DB-4 | 8.2 | 258 | 199 | 1.60 | 7.9 | 0.41 | 106 | 18.3 | 15.8 | 22.9 | 7.7 | 15.2 | 2.7 | 89 | 29.1 | 0.70 | 0.85 |
| | DB-5 | 7.6 | 263 | 210 | 1.64 | 8.0 | 0.31 | 122 | 16.1 | 10.8 | 23.8 | 7.8 | 15.6 | 3.1 | 92 | 29.3 | 0.71 | 1.09 |
| Konar | KD-1 | 7.7 | 125 | 117 | 0.32 | 3.5 | 0.28 | 61 | 3.0 | 20.1 | 16.2 | 3.6 | 6.8 | 1.7 | 55 | 23.6 | 0.40 | 0.45 |
| | KD-2 | 8.0 | 126 | 122 | 0.65 | 4.6 | 0.28 | 69 | 3.0 | 16.2 | 16.0 | 3.5 | 6.8 | 1.7 | 54 | 24.0 | 0.40 | 0.59 |
| | KD-3 | 7.8 | 124 | 117 | 0.60 | 4.2 | 0.27 | 65 | 3.0 | 15.5 | 16.1 | 3.4 | 6.9 | 1.9 | 54 | 24.5 | 0.41 | 0.53 |
| | KD-4 | 8.0 | 123 | 115 | 0.71 | 4.2 | 0.35 | 63 | 3.0 | 15.8 | 15.9 | 3.4 | 6.9 | 1.9 | 53 | 24.8 | 0.41 | 0.49 |
| | KD-5 | 8.1 | 126 | 116 | 0.56 | 3.5 | 0.24 | 63 | 2.8 | 18.4 | 15.2 | 3.3 | 6.8 | 1.7 | 51 | 24.9 | 0.41 | 0.52 |
| Tilaiaya | Til-1 | 8.5 | 224 | 188 | 0.09 | 13.3 | 0.11 | 115 | 2.6 | 13.1 | 19.3 | 6.1 | 16.0 | 1.7 | 73 | 33.5 | 0.81 | 1.16 |
| | Til-2 | 8.6 | 191 | 184 | 0.83 | 4.9 | 0.03 | 122 | 2.2 | 11.0 | 19.0 | 5.9 | 15.8 | 1.5 | 72 | 33.5 | 0.81 | 1.29 |
| | Til-3 | 8.5 | 197 | 182 | 0.87 | 5.3 | 0.35 | 118 | 2.3 | 11.8 | 19.7 | 5.9 | 16.1 | 1.6 | 74 | 33.5 | 0.82 | 1.20 |
| | Til-4 | 7.6 | 221 | 180 | 0.79 | 4.1 | 0.46 | 114 | 1.4 | 15.2 | 19.5 | 6.0 | 16.7 | 1.6 | 73 | 34.3 | 0.85 | 1.14 |
| | Til-5 | 7.1 | 223 | 174 | 0.84 | 4.5 | 0.32 | 110 | 2.2 | 11.5 | 20.3 | 6.0 | 16.3 | 1.5 | 75 | 33.3 | 0.82 | 1.05 |
| Maithon | MD-1 | 8.5 | 172 | 165 | 0.46 | 4.0 | 0.22 | 102 | 2.4 | 18.6 | 18.1 | 5.2 | 12.7 | 1.8 | 66 | 31.0 | 0.68 | 1.01 |
| | MD-2 | 8.4 | 170 | 166 | 1.59 | 4.9 | 0.29 | 100 | 2.6 | 19.0 | 18.1 | 5.2 | 12.5 | 1.6 | 66 | 30.6 | 0.67 | 0.98 |
| | MD-3 | 8.5 | 172 | 165 | 0.50 | 4.1 | 0.26 | 102 | 2.5 | 19.4 | 17.8 | 5.2 | 12.4 | 1.3 | 66 | 30.4 | 0.67 | 1.01 |
| | MD-4 | 8.5 | 166 | 160 | 0.55 | 3.8 | 0.23 | 98 | 2.5 | 18.4 | 18.7 | 5.2 | 11.8 | 1.3 | 68 | 28.7 | 0.62 | 0.92 |
| | MD-5 | 8.5 | 170 | 165 | 0.49 | 4.0 | 0.19 | 102 | 2.8 | 17.4 | 18.3 | 5.2 | 13.4 | 1.3 | 67 | 31.5 | 0.71 | 1.00 |

Units mg l^{-1} except pH, EC ($\mu\text{S cm}^{-1}$), Na (%), SAR and RSC (meq l^{-1})

Table 2 Chemical characteristics of reservoirs of Damodar River basin in Postmonsoon (October 2003)

| Reservoirs | St. Code | pH | EC | TDS | F | Cl | NO ₃ | HCO ₃ | SO ₄ | H ₄ SiO ₄ | Ca | Mg | Na | K | TH | Na% | SAR | RSC |
|------------|----------|-----|-----|-----|------|-----|-----------------|------------------|-----------------|---------------------------------|------|-----|------|-----|----|------|------|------|
| Tenughat | TD-1 | 8.1 | 206 | 158 | 0.65 | 9.9 | 0.45 | 76 | 10.2 | 17.5 | 16.8 | 5.9 | 15.8 | 4.9 | 66 | 37.2 | 0.85 | 0.58 |
| | TD-2 | 8.1 | 156 | 119 | 0.54 | 4.1 | 0.20 | 59 | 10.2 | 18.5 | 11.7 | 4.6 | 7.9 | 2.0 | 48 | 24.3 | 0.50 | 0.48 |
| | TD-3 | 8.0 | 151 | 112 | 0.5 | 4.0 | 0.22 | 57 | 9.2 | 16.7 | 10.6 | 4.3 | 7.4 | 2.1 | 44 | 26.8 | 0.48 | 0.49 |
| | TD-4 | 8.0 | 147 | 103 | 0.45 | 4.0 | 0.32 | 52 | 8.7 | 15.4 | 9.9 | 4.1 | 6.6 | 2.1 | 42 | 25.1 | 0.44 | 0.43 |
| | TD-5 | 8.1 | 143 | 101 | 0.4 | 3.9 | 0.35 | 51 | 8.2 | 15.1 | 9.8 | 4.2 | 6.8 | 2.2 | 42 | 26.9 | 0.46 | 0.41 |
| Panchet | PD-1 | 7.8 | 249 | 198 | 0.56 | 7.2 | 0.86 | 111 | 15.9 | 16.0 | 26.3 | 6.4 | 11.4 | 2.3 | 92 | 26.7 | 0.51 | 0.90 |
| | PD-2 | 7.9 | 236 | 187 | 0.67 | 8.2 | 0.67 | 105 | 14.9 | 14.8 | 23.5 | 6.2 | 10.8 | 2.2 | 84 | 30.9 | 0.51 | 0.87 |
| | PD-3 | 7.7 | 196 | 167 | 0.62 | 7.6 | 1.06 | 85 | 18.3 | 13.7 | 20.9 | 5.8 | 11.5 | 2.8 | 76 | 25.4 | 0.57 | 0.63 |
| | PD-4 | 7.8 | 211 | 181 | 0.7 | 8.1 | 1.23 | 96 | 16.9 | 15.5 | 22.8 | 6.0 | 10.6 | 2.9 | 81 | 25.2 | 0.51 | 0.76 |
| | PD-5 | 7.8 | 228 | 196 | 0.86 | 8.4 | 0.98 | 107 | 17.6 | 16.6 | 24.6 | 6.2 | 11.1 | 3.1 | 87 | 28.7 | 0.52 | 0.88 |
| Durgapur | DB-1 | 8.0 | 177 | 161 | 1.27 | 6.6 | 0.84 | 84 | 11.7 | 13.7 | 18.7 | 6.2 | 15.3 | 2.8 | 72 | 29.3 | 0.78 | 0.64 |
| | DB-2 | 7.8 | 176 | 150 | 0.9 | 6.4 | 0.76 | 82 | 10.7 | 12.8 | 17.9 | 5.0 | 11.6 | 1.9 | 65 | 33.3 | 0.62 | 0.69 |
| | DB-3 | 7.8 | 168 | 145 | 0.83 | 6.3 | 0.68 | 81 | 9.5 | 11.5 | 16.1 | 4.4 | 12.3 | 2.6 | 58 | 29.5 | 0.70 | 0.74 |
| | DB-4 | 8.0 | 187 | 157 | 0.89 | 6.9 | 0.87 | 87 | 12.8 | 13.7 | 18.2 | 4.1 | 10.8 | 2.0 | 62 | 29.1 | 0.59 | 0.80 |
| | DB-5 | 8.1 | 193 | 166 | 0.93 | 6.8 | 0.90 | 90 | 13.9 | 14.4 | 18.6 | 5.1 | 12.8 | 2.2 | 68 | 29.3 | 0.68 | 0.80 |
| Konar | KD-1 | 8.1 | 107 | 99 | 0.36 | 3.2 | 0.56 | 53 | 3.1 | 15.1 | 13.7 | 3.1 | 5.9 | 1.7 | 47 | 23.6 | 0.37 | 0.39 |
| | KD-2 | 7.9 | 111 | 98 | 0.45 | 3.1 | 0.66 | 52 | 3.0 | 14.8 | 14.4 | 3.0 | 5.7 | 1.5 | 48 | 24.0 | 0.36 | 0.37 |
| | KD-3 | 7.9 | 106 | 93 | 0.43 | 3.2 | 0.45 | 50 | 2.1 | 14.9 | 12.9 | 2.9 | 5.2 | 1.3 | 44 | 24.5 | 0.34 | 0.38 |
| | KD-4 | 7.9 | 116 | 101 | 0.39 | 3.2 | 0.67 | 54 | 2.3 | 15.2 | 15.4 | 3.2 | 5.6 | 1.7 | 52 | 24.8 | 0.34 | 0.36 |
| | KD-5 | 8.1 | 114 | 98 | 0.42 | 3.0 | 0.50 | 52 | 2.2 | 15.1 | 14.7 | 3.2 | 5.3 | 1.6 | 50 | 24.9 | 0.33 | 0.35 |
| Tilaiaya | Til-1 | 8.1 | 187 | 148 | 0.87 | 5.8 | 0.76 | 91 | 5.1 | 13.2 | 16.9 | 4.2 | 8.7 | 2.0 | 60 | 33.5 | 0.49 | 0.89 |
| | Til-2 | 8.0 | 155 | 141 | 0.75 | 4.3 | 0.47 | 85 | 4.0 | 13.2 | 17.4 | 4.1 | 10.0 | 2.2 | 60 | 33.5 | 0.56 | 0.78 |
| | Til-3 | 7.9 | 147 | 136 | 0.86 | 5.0 | 0.45 | 83 | 2.5 | 12.9 | 16.3 | 3.7 | 9.8 | 2.2 | 56 | 33.5 | 0.57 | 0.80 |
| | Til-4 | 8.0 | 143 | 135 | 1.35 | 5.2 | 0.34 | 81 | 2.6 | 11.7 | 17.9 | 3.7 | 9.9 | 2.1 | 60 | 34.3 | 0.56 | 0.72 |
| | Til-5 | 8.1 | 177 | 156 | 0.89 | 7.5 | 0.76 | 88 | 3.1 | 15.7 | 18.5 | 4.9 | 13.8 | 3.1 | 66 | 33.3 | 0.74 | 0.78 |
| Maithon | MD-1 | 8.0 | 177 | 164 | 0.9 | 4.6 | 0.94 | 97 | 3.3 | 16.3 | 26.5 | 4.0 | 9.1 | 1.4 | 82 | 31.0 | 0.43 | 0.76 |
| | MD-2 | 8.0 | 165 | 155 | 0.75 | 4.9 | 0.66 | 93 | 3.4 | 15.8 | 22.0 | 4.3 | 9.4 | 1.6 | 73 | 30.6 | 0.48 | 0.79 |
| | MD-3 | 7.6 | 138 | 137 | 0.83 | 4.1 | 0.18 | 82 | 3.1 | 15.7 | 17.5 | 3.8 | 8.9 | 1.2 | 59 | 30.4 | 0.50 | 0.75 |
| | MD-4 | 7.8 | 143 | 125 | 0.95 | 5.1 | 0.60 | 69 | 3.6 | 16.1 | 16.5 | 3.4 | 8.5 | 1.2 | 55 | 28.7 | 0.50 | 0.57 |
| | MD-5 | 8.1 | 137 | 122 | 0.73 | 6.2 | 0.97 | 64 | 3.9 | 14.9 | 17.3 | 3.6 | 9.2 | 1.8 | 58 | 31.5 | 0.53 | 0.47 |

Units mg l⁻¹ except pH, EC (μS cm⁻¹), Na (%), SAR and RSC (meq l⁻¹)

anions (F, Cl, NO₃, HCO₃ and SO₄) was found within 5%. Cationic and anionic charge balance (<10%) is an added proof of the precision of the data.

Results and discussion

Hydrochemistry

The major ion compositions of the reservoir of Damodar River basin for pre-monsoon and post-monsoon seasons are given in Tables 1 and 2. The tables also show the pH, EC, total hardness (TH), sodium adsorption ratio (SAR), %Na and residual sodium carbonate (RSC). The analytical results show the alkaline nature of water as pH ranges from 7.1 – 8.6 during pre-monsoon and 7.5 – 8.1 in post-monsoon. The measured pH in post-monsoon samples is slightly less as compared to the pre-monsoon. Such differences in pH are related to the variation in conductivity and bicarbonate concentration. EC, which is a measurement of the ionic strength of solution, varies between 123 μS cm⁻¹ and 291 μS cm⁻¹ in pre-monsoon and 106–249 μS cm⁻¹ during post-monsoon seasons. The reservoir water is characterised by a medium total dissolved solid (TDS) concentration

of 174 and 140 mg l⁻¹ respectively for pre and post-monsoon seasons. In general, EC and TDS show the low concentration during post-monsoon and higher values in the pre-monsoon period.

The major anions constitute more than 65% of the TDS. Bicarbonate is the dominant dissolved ion, it accounts for almost 55% of the TDS and its concentration varies between 61 mg l⁻¹ and 122 mg l⁻¹ in pre-monsoon and 50–112 mg l⁻¹ in the post-monsoon season. On an equivalent basis, bicarbonate accounts for 78% of the total anions. Bicarbonate is followed by SO₄, which accounts for 11% of the total anions and its concentration varies between 1.4–34.2 mg l⁻¹ and 2.1–18.3 mg l⁻¹ during pre and post-monsoon respectively. Concentration of chloride varies between 3.5 mg l⁻¹ and 15.5 mg l⁻¹ in pre-monsoon to 3.0–10.0 mg l⁻¹ in post-monsoon and contributes 9% of the total anionic concentration in equivalent unit. The concentration of other measured anions i.e. –F (0.73 mg l⁻¹), NO₃(0.45 mg l⁻¹), are low and they have very little contribution (<3%) to the total anionic budget.

The major cations constitute around 24% of the TDS. Calcium and sodium are the dominant cations accounting for 12 and 7% of the TDS respectively. Calcium concentration ranges from 15.2 mg l⁻¹ to

26.4 mg l⁻¹ during pre-monsoon and 9.7–26.5 mg l⁻¹ in the post-monsoon season. The average concentration of sodium in pre and post monsoon was found 12.9 mg l⁻¹ (6.8–17.1 mg l⁻¹) and 9.6 mg l⁻¹ (5.2–15.8 mg l⁻¹) respectively. Concentration of other two cations i.e.

Mg and K ranges between 3.3–17.6 mg l⁻¹ and 1.3–6.1 mg l⁻¹ respectively in pre-monsoon and 2.9–6.4 mg l⁻¹ and 1.2–4.9 mg l⁻¹ in post-monsoon seasons. Dissolved silica varies between 10.8 mg l⁻¹ and 27.2 mg l⁻¹ in pre-monsoon and 11.5–18.5 mg l⁻¹ in

Fig. 2 Seasonal and spatial variation in concentration of dissolved ions

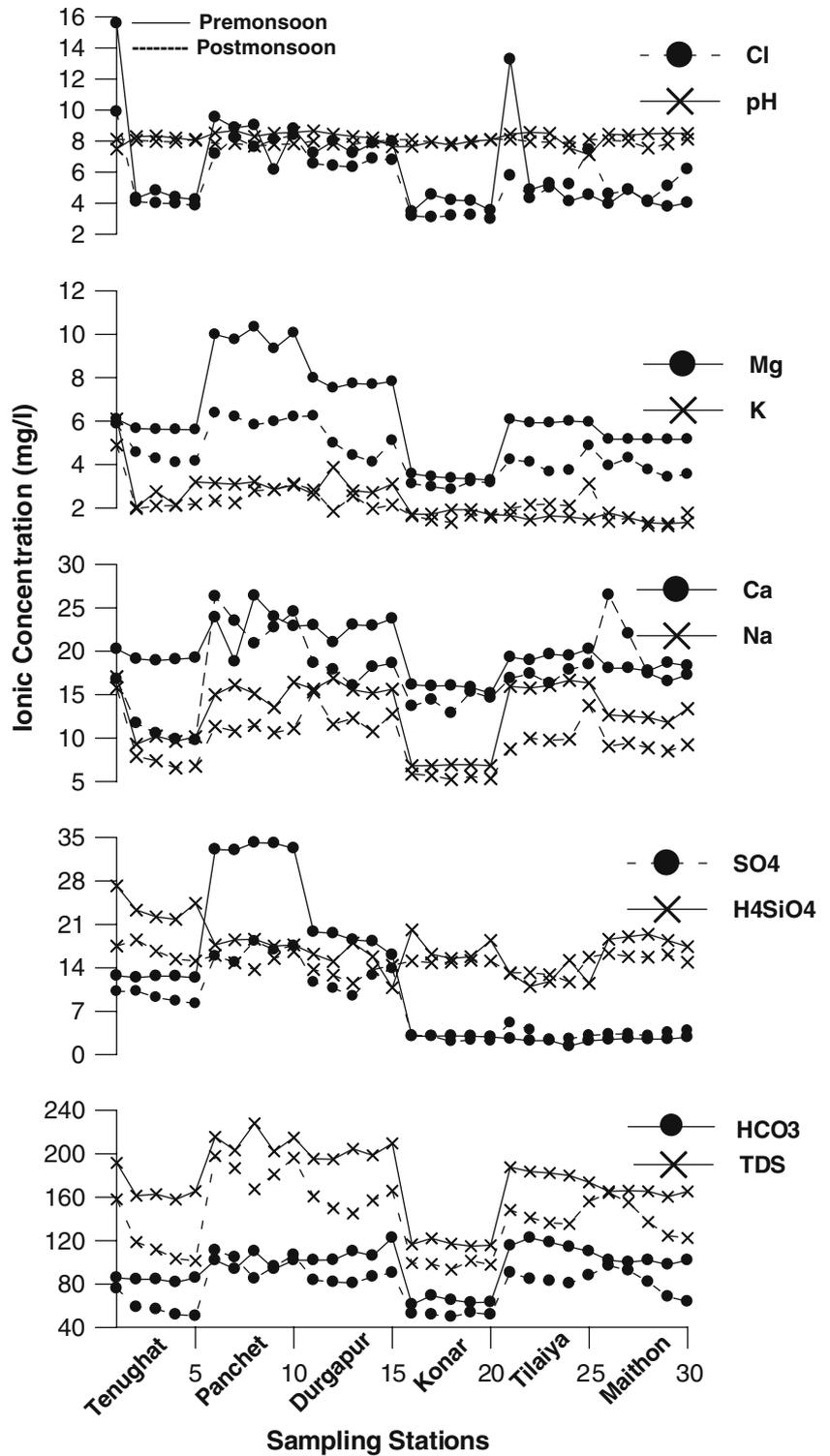


Fig. 3 Variation of the weight ratio of Na/(Na + Ca) as a function of TDS (after Gibbs 1970)

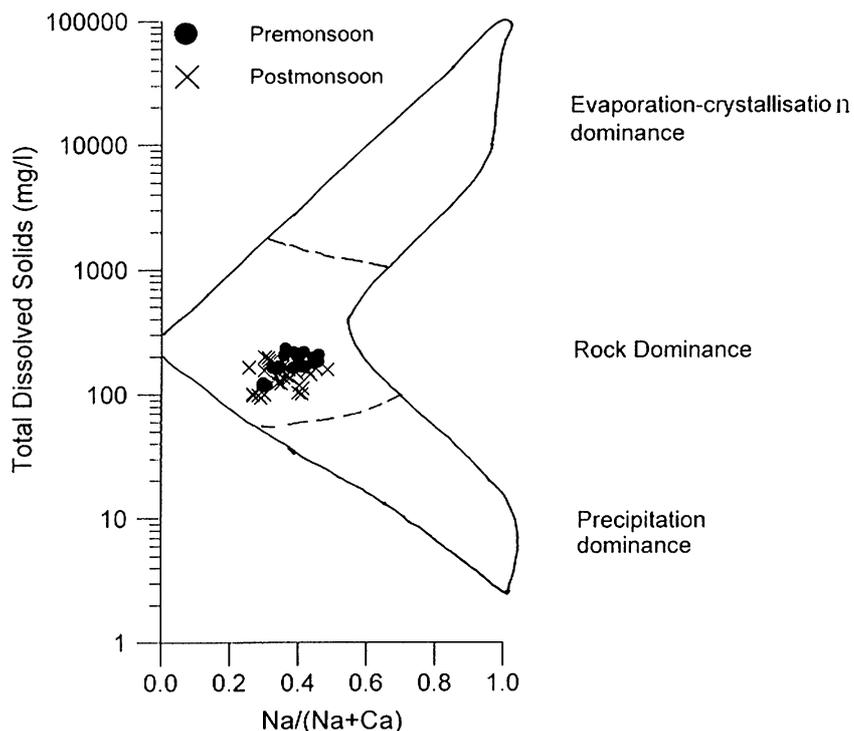


Table 3 Estimated atmospheric contributions to the solute chemistry of different reservoirs (in %)

| Reservoirs | F | Cl | NO ₃ | SO ₄ | Ca | Mg | Na | K |
|--|------|------|-----------------|-----------------|------|------|------|-----|
| Tenughat | 52 | 8 | 80 | 22 | 5 | 3 | 3 | 9 |
| Panchet | 47 | 6 | 40 | 10 | 4 | 2 | 2 | 9 |
| Durgapur | 31 | 7 | 43 | 16 | 4 | 2 | 2 | 10 |
| Konar | 64 | 13 | 58 | 89 | 6 | 4 | 4 | 15 |
| Tilaiya | 39 | 8 | 61 | 88 | 5 | 3 | 2 | 13 |
| Maithon | 40 | 10 | 55 | 82 | 4 | 3 | 2 | 18 |
| Average | 45 | 8.6 | 61 | 51 | 5 | 3 | 3 | 12 |
| Average Rainwater Composition (in µeq/l) | 16.5 | 13.2 | 4.0 | 51.1 | 42.5 | 11.7 | 11.4 | 6.5 |

post-monsoon. Dissolved silica accounts for 11% of the TDS. The average concentration of dissolved silica (10.8 mg l^{-1}) is higher than the Indian average (7 mg l^{-1}) and comparable to global average values (12 mg l^{-1}) for an aquatic system (Subramanian 1979). A high concentration of dissolved silica in the reservoir water reflects contribution from weathering of silicate rocks. At most of the sampling stations concentrations of dissolved silica are higher than chloride and sulphate.

Seasonal and spatial variation in the major ions

Seasonal data on the major ion chemistry of different reservoirs of Damodar basin water shows that average EC is minimum ($165 \text{ } \mu\text{S cm}^{-1}$) during the post-monsoon and maximum ($203 \text{ } \mu\text{S cm}^{-1}$) in pre-monsoon, indicates an increased concentration of major ions in the pre-

monsoon season. This increase in ionic concentrations during pre-monsoon period may be due to the evaporation effect during this low water level period aided by elevated temperature in this region. Calcium, sodium, magnesium, bicarbonate, sulphate, dissolved silica and TDS show a similar trend as EC, with the lowest concentration during post-monsoon and highest during pre-monsoon period. Chloride and potassium also have relatively high percentage contribution to the total cations and total anions in pre-monsoon season; however, nitrate and fluoride do not show any systematic seasonal variations.

Figure 2 shows the seasonal and spatial variation in concentration of measured parameters in the different reservoirs of Damodar River water. Variations in ionic concentration in inter and intra reservoir water is related to the diluting and concentrating effects of feeding river inflows, change in catchment lithology and anthropo-

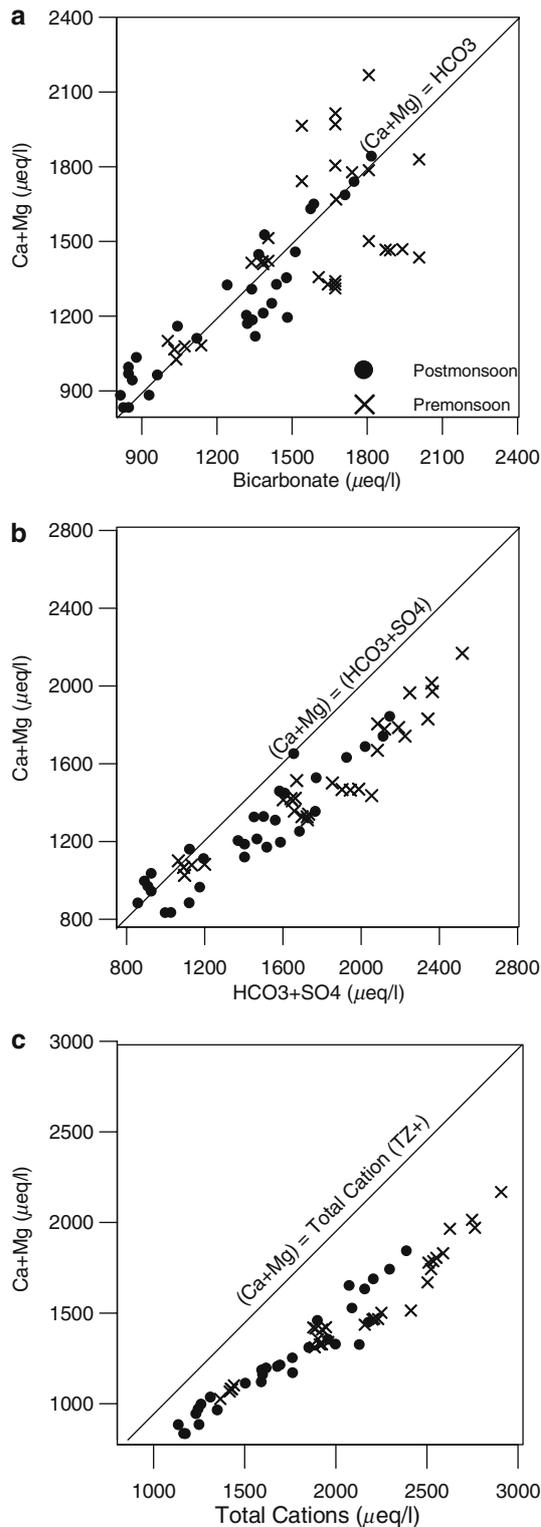


Fig. 4 Scatter diagram between **a** (Ca+Mg) vs Bicarbonate **b** (Ca+Mg) vs (HCO₃+SO₄), **c** (Ca+Mg) vs Total cations (TZ⁺)

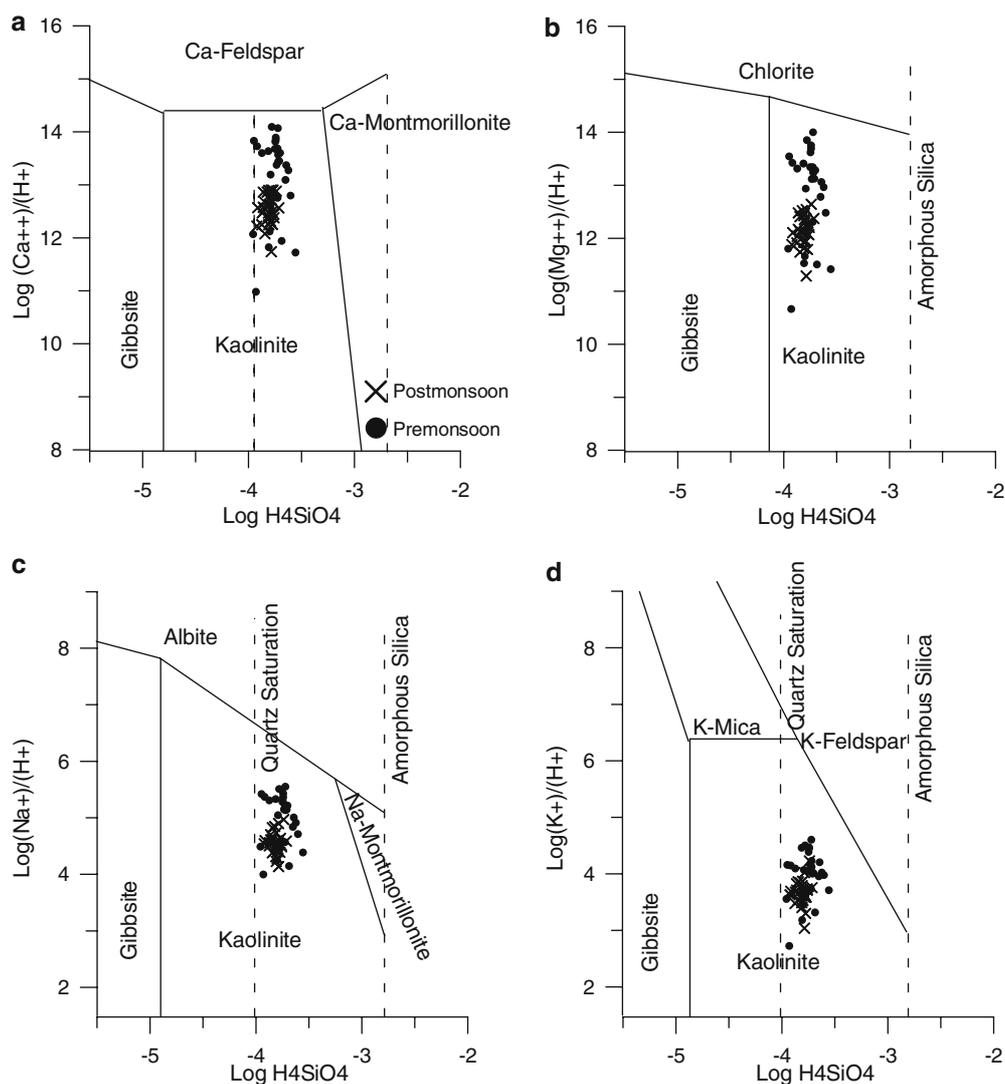
genic inputs. The six studied reservoirs may be divided into two groups on the basis of catchment lithology and hydrochemical characteristics:

- The first group includes the reservoirs—Tenughat, Panchet and Durgapur, characterized by high ionic concentration. The high concentration of dissolved ions in these reservoirs may be attributed to the anthropogenic contribution from the feeding river system (Damodar), running through the rich industrial and human settlement belt. The Damodar River received high domestic and industrial discharge load in the middle stretch between Bokaro, Dhanbad and Durgapur from coke, steel, thermal power plants, coal washeries and other coal-based industries. Further, these reservoirs show the relatively high concentration of sulphate, attributes to the oxidative weathering of pyrites (associated with the coal seams) in the catchment areas and anthropogenic inputs.
- The second group includes the Tilaiya, Maithon and Konar reservoirs constructed on the tributaries - Barakar and Konar Rivers and characterised by low ionic concentration. The catchments of these reservoirs consist of less reactive crystalline rocks of granites and granitic gneisses and devoid of any coal-bearing sedimentary formations, explaining the low conductivity and sulphate concentration. The relatively higher TDS for Tilaiya may be attributed to the domestic discharge from the Hazaribag town of having 5–6 lakh populations.

Source and mechanism controlling water chemistry

The three major sources of dissolved ions into the inland waters are (1) atmospheric deposition of salts (2) weathering of rock-forming minerals (silicates, carbonates, evaporate and sulphide) and (3) anthropogenic input (Berner and Berner 1987; Zhang et al. 1995; Sarin and Krishnaswamy 1984; Singh and Hasnain 1998, 1999, 2002). A rough estimate of the atmospheric contribution to the aquatic system can be assessed by comparing the chemical composition with the local rainwater chemistry (Pandey and others 1994; Sarin and others 1989). In this study, the chemical composition of rainwater collected at Dhanbad has been used to decipher the contribution of salts from the atmospheric deposition (Table 3). This assessment indicates that a significant part of the F (31–64%), SO₄ (16–89%), K (9–18%) and Cl (7–13%) in these reservoirs can be of atmospheric origin. High atmospheric contributions of F and SO₄ indicate anthropogenic sources (coal-fired thermal power plants, mine-fire and coke oven plants) in this mining and industrial belt. The low atmospheric contribution of Ca, Mg, Na (<5%) indicates that weathering of the drainage basin is the major source of these ions and for a significant part of K and SO₄. Gibbs

Fig. 5 Stability diagram for silicate systems



(1970) boomerang plot also places the reservoir waters in the region of rock dominance, indicating that rock weathering is a primary factor controlling the water composition (Fig. 3).

In the reservoir waters of Damodar River basin, Ca and Mg together constitute 72% of the total cations and HCO_3^- contribute about 78% to the total anionic balance. Carbonate and silicate weathering and evapo-

rite dissolution can supply Ca and Mg in water, whereas the source for Na and K are atmospheric deposition, evaporite dissolution and silicate weathering. The atmospheric and evaporite contribution can be assessed by chloride as an index ion (Appelo and Postma 1993). The sodium concentration in the analysed waters is significantly in excess over chloride and high Na/Cl (3.1) and $(\text{Na} + \text{K}/\text{Cl})$ i.e. -3.5, suggesting that much of the alkalis in these waters originate from a source other than precipitation and probably from the weathering of silicate minerals. On an average $(\text{Na} + \text{K})$ contributes 28% of the total cationic balance and relatively high concentration of dissolved silica and $(\text{Na} + \text{K})/\text{TZ}^+$ ratio of (0.3) suggests that silicate weathering could be the major source of alkalis. However, this is an upper limit of silicate weathering, as there could be other evaporite sodium/potassium minerals and/or contribution from alkaline soil and ground water. The evaporite encrus-

Table 4 Mineralogy of suspended sediments

| Dams/Reservoirs | Quartz | Feldspar | Mica | Kaolinite |
|-----------------|--------|----------|------|-----------|
| Tenughat | 64.6 | 7.2 | 13.4 | 14.8 |
| Panchet | 55.5 | 6.1 | 19.7 | 18.7 |
| Durgapur | 67.0 | 18.7 | 31.5 | 6.6 |
| Konar | 60.5 | 13.4 | 14.4 | 11.7 |
| Tilaiya | 57.8 | 19.7 | 9.9 | 12.6 |
| Maithon | 61.5 | 16.4 | 11.6 | 10.5 |

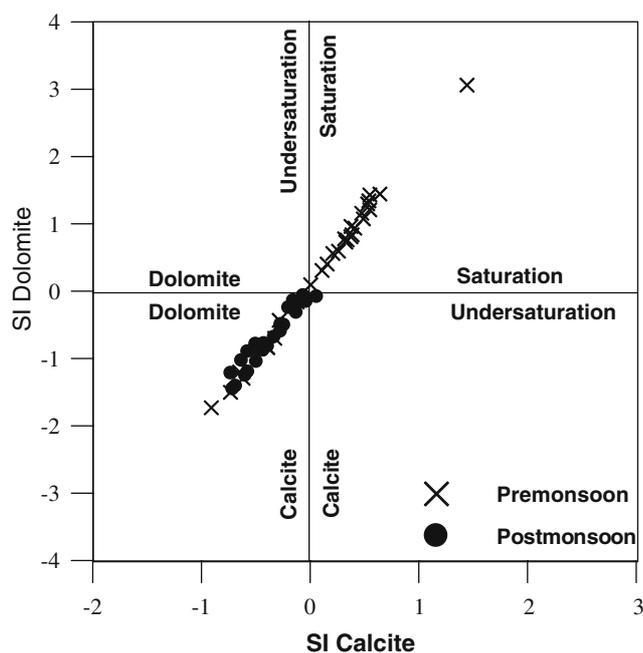


Fig. 6 Saturation indices for calcite (SIc) and dolomite (SID)

tations of sodium/potassium salts developed in some part of the drainage area due to cyclic wetting and drying during high and low flow period. This aids the formation of alkaline/saline soils, which may also serve as a source of sodium and potassium (Sarin et al. 1989).

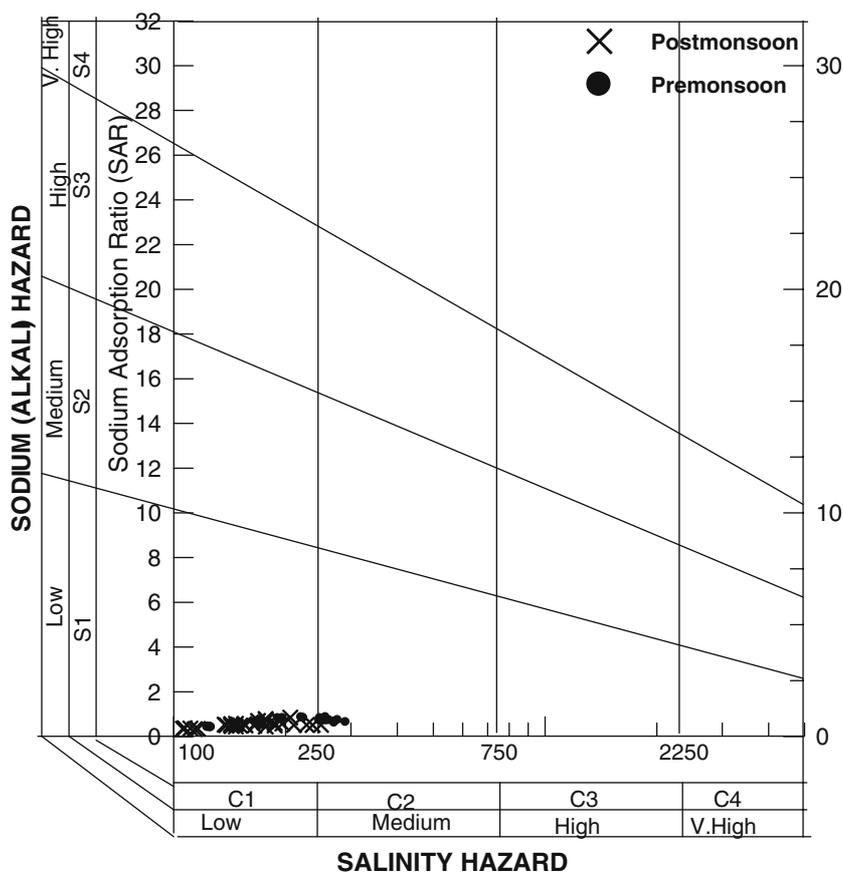
The $(Ca + Mg)/HCO_3$ ratio marks the upper limit of bicarbonate input from the weathering of carbonate rock (Stallard and Edmond 1983). The variation diagram between $Ca + Mg$ vs HCO_3 for the reservoir water samples show that in many samples, $(Ca + Mg)$ contents is in excess of alkalinity, the magnitude of excess being larger for the reservoirs having coal-bearing formations in the catchments i.e. Panchet ($Ca + Mg/HCO_3 = 1.11$), Tenughat ($Ca + Mg/HCO_3 = 1.02$) and Durgapur ($Ca + Mg/HCO_3 = 1.07$). The excess of $Ca + Mg$ over bicarbonate in these waters indicated some extra source of Ca and Mg and demanding that part of the excess positive charge has to be balanced by other anions like SO_4 and/or Cl . However, in many samples, $Ca + Mg$ falls below the 1:1 trend, the departure from the equiline being more pronounced for the reservoirs—Konar ($Ca + Mg/HCO_3 = 0.97$), Tilaiya ($Ca + Mg/HCO_3 = 0.82$) and Maithon ($Ca + Mg/HCO_3 = 0.90$), having the catchment devoid of coal-bearing formation and composed of less reactive phases such as granitic gneisses, granites, quartzites, quartz mica-schists, biotite gneiss, biotite schist and garnetiferous gneiss (Fig. 4a). The excess of bicarbonate over $Ca + Mg$ requires that part of the alkalinity should be balanced by alkalis ($Na + K$). A plot of $(Ca + Mg)$ versus $(HCO_3 + SO_4)$ shows better correlation throughout the data range (Fig. 4b); most of

the plotted points fall below the 1:1 equiline requiring a portion of the $(HCO_3 + SO_4)$ to be balanced by the alkalis ($Na + K$). Further, the plot of $(Ca + Mg)$ vs Total Cations (TZ^+) shows that the plotted points fall far below the equiline, the departure being more pronounced at high concentration and during lean flow period (pre-monsoon), reflecting an increasing contribution of Na and K with increasing dissolved solids (Fig. 4c).

For the reservoirs of Damodar Rive basin, the fractions of cations derived from evaporates complexes with Cl are likely to be insignificant since (1) the reservoirs have usually low Cl concentration and high Na/Cl ratio (3.1) (2) the water samples is characterized by high Mg/Na ratios (0.67–1.18) whereas input from evaporites will have very low (< 0.2) Mg/Na ratios (Negrel and others 1993). The dissolved chemistry of reservoirs is likely to be determined by two component mixing from dissolution of silicates and of carbonates and the relative significance of these two sources can be explained by cationic abundance and their ratios. Water draining only carbonates show Ca and Mg dominated reservoirs and Ca/Na ratios close to 50, Mg/Na close to 10 and HCO_3/Na ratios close to 120 (Negrel and others 1993; Meybeck 1986; Stallard 1980). The end member having lower Na normalised ratios is that water draining silicates. The molar Ca/Na of average crustal continental rocks is close to 0.6 (Talor and McLennan 1985), and due to the higher solubility of Na to Ca , lower Ca/Na molar ratio are expected in the dissolved load of rivers draining silicates. The chemical composition assigned for the silicate end member is $Ca/Na = 0.35 \pm 0.15$, $Mg/Na = 0.24 \pm 0.12$, $HCO_3/Na = 2 \pm 1$ (Gaillardet et al. 1999). The observed molar ratios of Ca/Na (2.02), Mg/Na (0.92) and HCO_3/Na (3.02) in the reservoir waters are much lower than those of the waters draining carbonate lithology and higher than that drain silicate rocks, indicating that the dissolved chemistry of the reservoirs is essentially controlled by two component mixing—silicates and carbonates.

Further, the ratios between HCO_3/H_4SiO_4 and $(Ca + Mg)/(Na + K)$ can also be used to infer the relative contribution of silicate and carbonate weathering. The observed average HCO_3/H_4SiO_4 ratio of 8.4 (4.8–17.0) is much higher as expected from silicate weathering (< 5.0), but it is lower than the expected from carbonate dissolution (> 10.0). The $(Ca + Mg)/(Na + K)$ molar abundance ratio in the silicates of the upper crust is generally 1.0 (Taylor and McLennan 1985), the observed $(Ca + Mg)/(Na + K)$ equivalent ratio of 2.6 in the analysed waters also suggests that the chemical composition of the reservoirs is under the combined influence of carbonate and silicate weathering. Estimation of bicarbonate contribution from the weathering of carbonate and silicate weathering shows that on an average 63% of the HCO_3 is contributed by carbonate weathering and

Fig. 7 US salinity diagram for classification of irrigation waters (after Richards 1954)



37% by silicate weathering in the studied reservoirs of Damodar River Basin (Raymahashay 1986).

The thermodynamic stability relationship of the water chemistry in the silicate system is an important way to establish the clay mineral assemblages, which would be consistent with water chemistry (Garrels and Christ 1965). Figure 5 shows the behaviour of reservoir water of Damodar River basin in the silicate system. The pH-log (H_4SiO_4) diagram shows that the plotted points fall in the kaolinite region, implying that the chemistry of the water favors kaolinite formation. This also agrees with the clay mineralogy of the suspended sediments of the basin (Table 4).

The computed partial pressure (PCO_2) for reservoir water is slightly higher or comparable ($10^{-2.1}$ – $10^{-3.6}$) with the atmospheric level ($10^{-3.5}$) indicating open-system weathering. The slightly higher value of PCO_2 of the river system is a global phenomenon trend indicating that the aquatic system is out of equilibrium with the atmosphere (Garrels and Mechazie 1971). The possible explanation for the slightly higher values of PCO_2 , could be (a) the river channel is supplied with the groundwater high in CO_2 and/or (b) the relatively higher rate of solubility in comparison to release of excess of CO_2 gas (Stumm and Morgan 1981). The equilibrium state of the water with respect to a mineral phase can be determined

by calculating a saturation index (SI) using analytical data. The plot of saturation index of calcite (SI_c) vs saturation index of dolomite (SI_d) demonstrates that most of the reservoir waters are undersaturated with respect to both calcite and dolomite; however, some samples of pre-monsoon season is supersaturated with respect to both (Fig. 6). The supersaturation shows the evaporation effects during the lean water level period of pre-monsoon and favouring the precipitation of carbonates (Hardie and Eugster 1970).

Quality assessment

The parameters such as sodium adsorption ratio (SAR), percent sodium (%Na) and residual sodium carbonate (RSC) were estimated to assess the suitability of water from the studied reservoirs for irrigation purpose. EC and sodium concentration are very important in classifying irrigation water. The total concentration of soluble salts in irrigation water can be expressed for the purpose of classification of irrigation water as low ($EC = < 250 \mu S cm^{-1}$), medium (250 – $750 \mu S cm^{-1}$), high (750 – $2,250 \mu S cm^{-1}$) and very high ($2,250$ – $5,000 \mu S cm^{-1}$) salinity zone (Richards 1954). While a high salt concentration (high EC) in water leads to for-

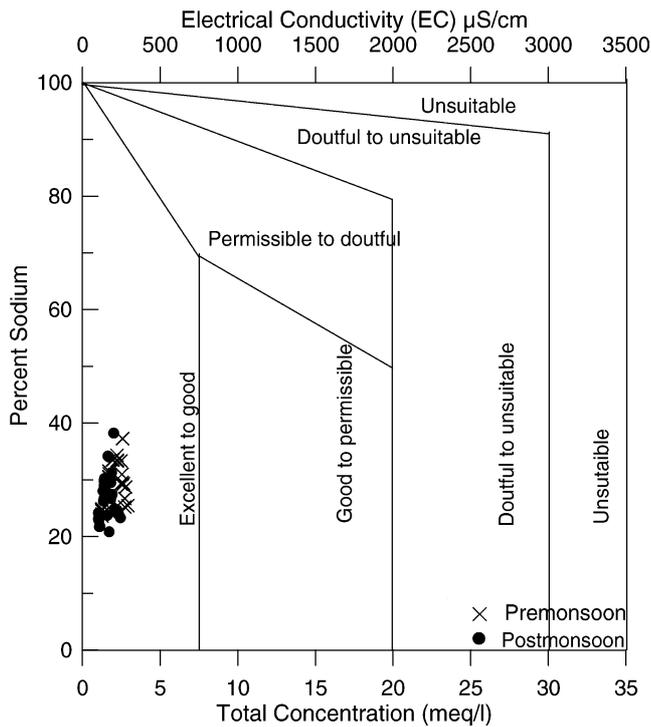


Fig. 8 Plot of sodium percent vs electrical conductivity (after Wilcox 1955)

mation of saline soil, a high sodium concentration leads to development of an alkaline soil. The sodium or alkali hazard in the use of water for irrigation is determined by the absolute and relative concentration of cations and is expressed in terms of SAR and it can be estimated by the formula:

$$\text{SAR} = \frac{\text{Na}}{[(\text{Ca} + \text{Mg})/2]^{0.5}}$$

There is a significant relationship between SAR values of irrigation water and the extent to which sodium is adsorbed by the soils. If water used for irrigation is high in sodium and low in calcium, the cation-exchange complex may become saturated with sodium. This can destroy the soil structure owing to dispersion of the clay particles. The calculated value of SAR in the study area ranges from 0.40 to 0.85 in the pre-monsoon and 0.35–0.90 in the post-monsoon season. The plot of data on the US salinity diagram, in which the EC is taken as salinity hazard and SAR as alkalinity hazard, shows that most of the surface water samples fall in the category C1S1 and a few samples in C2S1, indicating low to medium salinity and low sodium water which can be used for irrigation in most soil and crops with little danger of development of exchangeable sodium and salinity (Fig. 7).

The sodium percentage (%Na) in the study area ranges between 24% and 37% in pre-monsoon and 21–38% in post-monsoon water. As per the BIS (Bureau of

Indian Standard), maximum sodium of 60% is recommended for irrigation water. A plot of analytical data on the Wilcox (1955) diagram relating EC and sodium percent shows that the water is 'excellent to good quality' and can be used for irrigation purposes (Fig. 8). To quantify the effects of carbonate and bicarbonate, RSC has been computed. A high value of RSC in water value leads to an increase in the adsorption of sodium on soil (Eaton 1950). Irrigation waters having RSC values greater than 5 meq l⁻¹ have been considered harmful to the growth of plants, while waters with RSC values above 2.5 meq l⁻¹ is not considered suitable for irrigation purpose. The RSC values of the study area surface water samples varies between 0.45–1.29 meq l⁻¹ and 0.35–0.90 meq l⁻¹ in pre and post-monsoon, indicating that the water is safe for irrigation purpose.

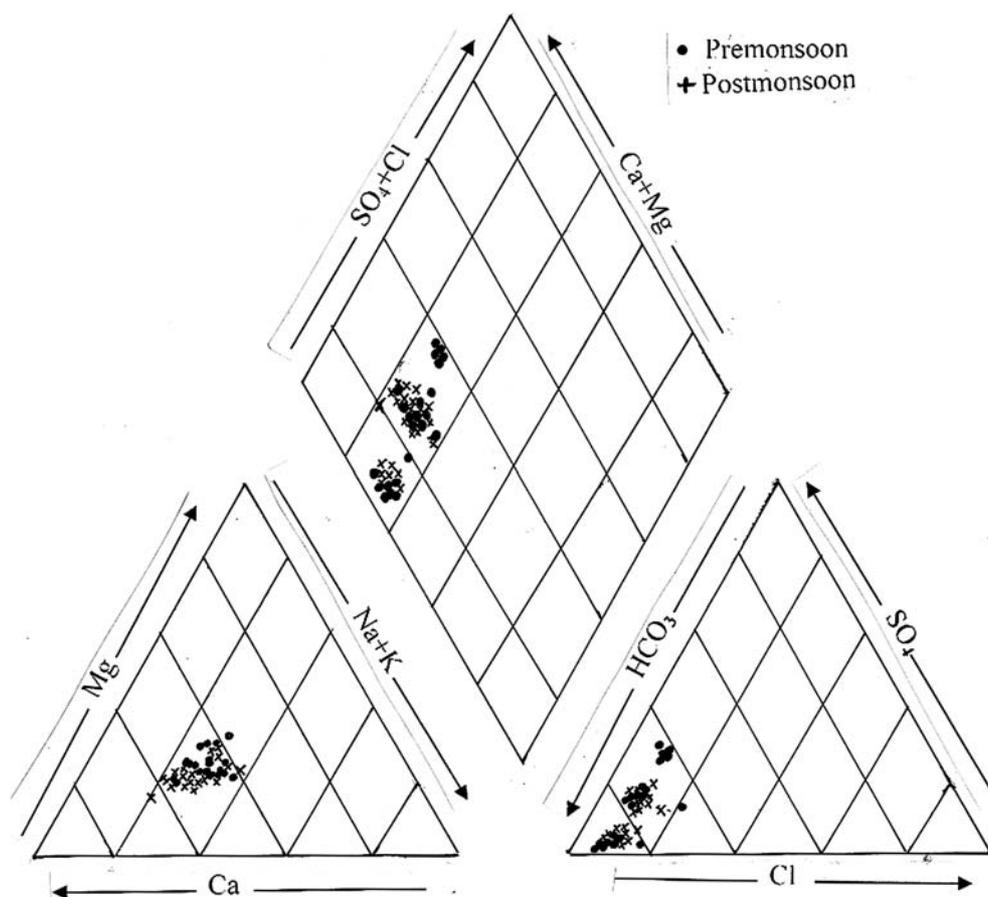
The evolution of water and relationship between rock types and water composition can be evaluated by the trilinear Piper diagram (Piper 1944). The piper diagram is an ingenious construction, which consists of two triangular diagrams at the lower left and lower right, describing the relative composition of cations and anions and an intervening diamond-shaped diagram that combines the composition of cations and anions. The plot of chemical data on trilinear diagram reveals that a majority of the reservoir water samples fall in the areas of 1, 3 and 5 suggesting that alkaline earth exceeds alkalis and weak acids exceed strong acids, respectively (Fig. 9). The ions representing carbonate hardness (secondary alkalinity) exceeds 50%, that is, the total hydrochemistry is dominated by alkaline earths and weak acids. The variations and distributions of hydrochemical facies of reservoir water show that Ca–Na–HCO₃, Ca–Na–HCO₃–Cl and Ca–Na–HCO₃–SO₄ are the dominant hydrochemical facies.

Factor analysis

Factor analysis is a useful explanatory tool in multivariate statistical analysis, and it can be applied to discover and interpret relations among variables or to test hypotheses (Davis 1986; Gupta and Subramanian 1998; Ballukraya and Ravi 1999; Reeder et al. 1972). The general purpose of the factor analysis is to find a way of condensing the information contained in a number of original variables into a smaller set of new composite dimensions with a minimum loss of information. An R-mode factor analysis has been used for extracting factors governing the water chemistry of the Damodar Basin reservoirs. The data matrix of 13 variables (pH, F, EC, Cl, NO₃, SO₄, HCO₃, H₄SiO₄, Ca, Mg, Na, K and TDS) and 60 observations has been used in the present factor analysis.

Three factors with eigen values >1 have been extracted from the principal factor matrix after varimax

Fig. 9 Plot of trilinear diagram (after Piper 1944)

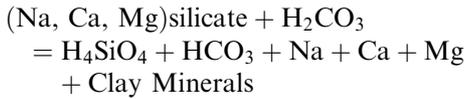


rotation (Table 5). Factor-I has high loading of HCO_3 , TDS, Na, EC, Ca and Mg. Factor-I may be treated as a bicarbonate factor and explains the dissolution of crystalline dolomitic limestones and Ca-Mg silicates as the dominant chemical processes in the Damodar River

basin. Orthoclase, Ca-plagioclase, amphiboles, pyroxene and biotite are the primary silicates present in the rock associated with the crystalline rocks of the area and the general reaction for the weathering of silicate rocks with carbonic acid can be written as:

Table 5 Principal and varimax rotated R-mode factor loading matrix ($n=60$)

| Variables | Principal factor matrix | | | | Varimax rotated factor matrix | | |
|--------------------------|-------------------------|------------|------------|-------------|-------------------------------|------------|------------|
| | Factor -I | Factor -II | Factor-III | Communality | Factor -I | Factor -II | Factor-III |
| PH | 0.321 | -0.501 | -0.545 | 0.651 | 0.335 | -0.068 | 0.731 |
| EC | 0.973 | 0.027 | 0.032 | 0.948 | 0.828 | 0.510 | 0.053 |
| F | 0.318 | 0.581 | -0.049 | 0.442 | 0.479 | -0.096 | -0.451 |
| Cl | 0.761 | 0.007 | 0.415 | 0.752 | 0.486 | 0.705 | -0.136 |
| NO_3 | -0.080 | 0.675 | 0.405 | 0.626 | -0.016 | 0.017 | -0.791 |
| HCO_3 | 0.808 | 0.285 | -0.417 | 0.909 | 0.952 | -0.020 | 0.033 |
| SO_4 | 0.761 | -0.233 | 0.246 | 0.694 | 0.477 | 0.666 | 0.155 |
| H_4SiO_4 | 0.153 | -0.738 | 0.227 | 0.620 | -0.198 | 0.533 | 0.545 |
| Ca | 0.814 | 0.269 | -0.058 | 0.738 | 0.806 | 0.267 | -0.128 |
| Mg | 0.933 | -0.175 | -0.073 | 0.906 | 0.772 | 0.484 | 0.276 |
| Na | 0.875 | 0.092 | -0.177 | 0.806 | 0.850 | 0.274 | 0.089 |
| K | 0.623 | -0.236 | 0.632 | 0.843 | 0.201 | 0.895 | -0.045 |
| TDS | 0.977 | 0.071 | -0.136 | 0.978 | 0.914 | 0.365 | 0.097 |
| Eigenvalue | | | | | 6.634 | 1.898 | 1.381 |
| Variance (%) | | | | | 51.0 | 14.6 | 10.6 |
| Cumulative (%) | | | | | 51.0 | 65.6 | 76.3 |



The HCO_3 along with corresponding cations Ca, Mg and Na are to a larger extent responsible for the conductivity of the reservoirs water. Factor-I accounts for 51% of the variance in the data matrix and dominate over the other factors in controlling the water chemistry. Factor-II accounts for 32% variance in the data matrix and consists of variables K, Cl, SO_4 and dissolved silica. K is the least dominated cations in the analysed samples. During the course of continental weathering, Na turns out to be more mobile than K and dominate the natural solution (Milliot 1970). Only 15% of the river transport of K is in the dissolved form (Berner and Berner 1987). The high loading of SO_4 and Cl may be attributed to anthropogenic input from the industrial discharge from coal-based industries and domestic sewage into the Damodar River. A high positive score of potassium and dissolved silica can be attributed to the weathering of feldspar/mica present in the silicate rocks of drainage basin:

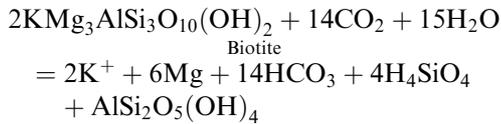
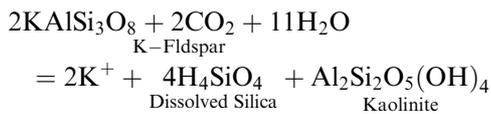
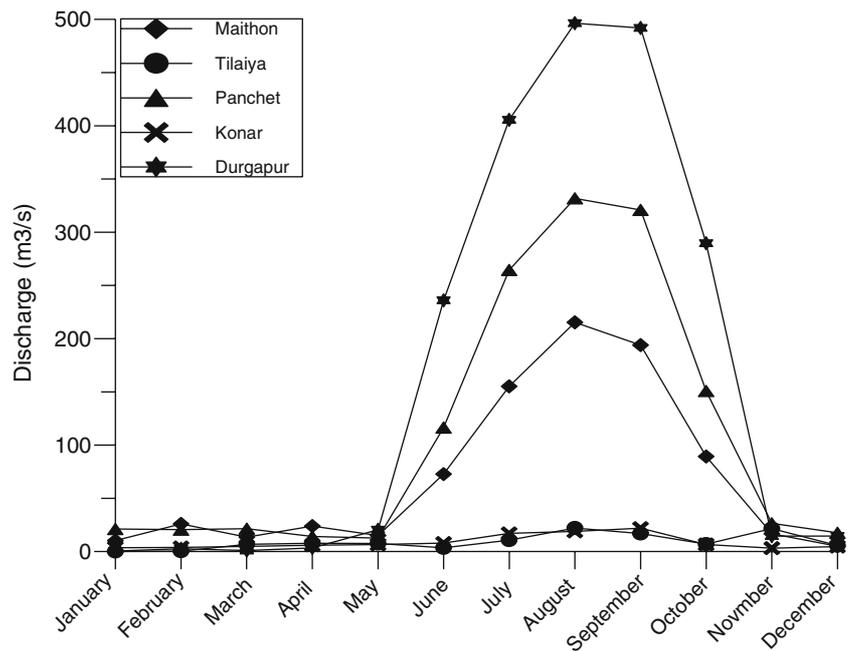


Fig. 10 Monthly variation in discharge from Dams/barrage of Damodar River basin



The factor-III is less significant and accounts for only 11% of the total variance. This factor is mainly represented by pH and shows negative loading of NO_3 . The nitrate ion has no significant lithological source in the area and it may be associated with surface run-off of nitrate fertiliser from the catchments or from atmospheric inputs. These three factors taken together explains about 76% of the total variance in the data matrix, indicating that the determined variables, which control the water chemistry are rock weathering with minor contribution from anthropogenic and atmospheric sources.

Discharge and solute flux

The reservoirs of Damodar River Basin show enormous variation in water discharge. Figure 10 shows the average monthly variation in discharge of dams/reservoirs constructed at Damodar River at Panchet and Durgapur, Barakar River at Tilaiya and Maithon and Konar River at Konar. It shows that 45–70% of the annual water discharge from the reservoirs occurs in just three monsoonal months (July to September) and only 1–12% during the lean flow period (January to March). The annual solute flux and chemical denudation rate of studied reservoirs were calculated from TDS contents, catchment area and water discharge and presented in Table 6. The Panchet reservoir annually delivers 691×10^3 tons of dissolved load and the chemical denudation rate of the Panchet catchment is 63 tons/km^2 .

Table 6 Solute flux and chemical denudation rate (CDR) at different sites

| Reservoirs | Catchment Area (km ²) | Discharge m ³ /sec. | TDS mg l ⁻¹ | Solute Flux X10 ³ Tons/Yr | CDR Ton/km ² /Yr |
|------------|-----------------------------------|--------------------------------|------------------------|--------------------------------------|-----------------------------|
| Panchet | 10,966 | 109.95 | 199.2 | 691 | 63 |
| Durgapur | – | 164.77 | 178.1 | 925 | – |
| Konar | 997 | 8.80 | 107.7 | 30 | 30 |
| Tilaiya | 984 | 9.23 | 162.4 | 47 | 48 |
| Maithon | 6,394 | 70.08 | 152.5 | 337 | 53 |

year. The dissolved load and water discharge increases at Durgapur Barrage. At Durgapur, the reservoir delivers 925×10^3 tons of dissolved load per year. The annual solute flux of the reservoirs Tilaiya (47×10^3 tons), Maithon (337×10^3 tons) and Konar (30×10^3 tons) are low as compared to the Panchet (691×10^3 tons) and Durgapur (925×10^3 tons). The chemical denudation rates of the Tilaiya, Maithon and Konar are 48, 53 and 30 tons/km²/years, respectively.

Conclusions

The reservoir water is alkaline in nature. Calcium and sodium are the dominant cations and bicarbonate and sulphate are the dominant anions. The water chemistry is largely controlled by rock weathering with minor contribution from atmospheric and anthropogenic sources. The high concentration of dissolved silica, low ratio of (Ca + Mg)/(Na + K), and relatively high contribution of (Na + K) to the total cations suggest significant contribution of dissolved ions from silicate weathering. High concentration of HCO₃ and (Ca + Mg) and ratios of Ca/Na, Mg/Na, HCO₃/Na,

and HCO₃/H₄SiO₄ suggest combined influence of carbonate and silicate weathering in controlling the water chemistry of the studied reservoirs. Seasonality in the ionic concentration is related to the water level and flow regime. Observed high concentration of sulphate and conductivity in reservoirs of Tenughat, Panchet and Durgapur indicate the input from the weathering of sulphide minerals in the catchment and anthropogenic contribution from coal washeries and other coal-based industries. The chemical composition of the river water demonstrates that it is in equilibrium with kaolinite. The water chemistry is largely undersaturated with respect to calcite and dolomite; however, some samples in pre-monsoon shows supersaturation with respect to both. The calculated parameters of SAR, %Na and RSC shows that water is excellent to good quality and can be used for irrigation without any hazard.

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