ENVIRONMENTAL GEOCHEMISTRY OF NARMADA RIVER BASIN

A THESIS

Submitted in partial fulfilment of the requirements for the award of the degree

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in

EARTH SCIENCES

By

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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled **ENVIRONMENTAL GEOCHEMISTRY OF NARMADA RIVER BASIN** in partial fulfilment of the requirements for the award of the Degree of **Doctor of Philosophy** and submitted in the **Department of Earth Sciences** of the **Indian Institute of Technology Roorkee, Roorkee** is an authentic record of my own work carried out during the period from January 2003 to July 2006 under the supervision of **Dr. G. J. Chakrapani**.

The matter presented in the thesis has not been submitted by me for the award of any other degree of this or any other University/Institute.

(HARISH GUPTA)

This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

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ABSTRACT

The Narmada river in India is a medium size river, which flows into the Arabian Sea and drains mostly over the volcanic rocks named as the 'Deccan Traps'. Mass transport and their important characteristics in the Narmada river have been studied by collection of various environmental samples such as, river water, groundwater, rain and spring water. All major dissolved chemical parameters, nutrients and strontium isotopic analysis were carried out to obtain information encrypted in the samples. Temporal and spatial variations in water flow and sediment loads in the Narmada river are inferred based on analysis of more than twenty years of data at various locations along the river and its tributaries. The monsoon rains control water flow in the river to a large extent, however groundwater discharge and dams/reservoirs also regulate water flow. A number of important factors and their influence on water and sediment transport variability have been identified, which include rainfall, relief, catchment area, basin geology, soil characteristics and presence of reservoirs/dams. Major ion chemistry of the river water covering the Narmada river and its tributaries were carried out from samples collected during 2003-04, during different time periods, to understand seasonal variability. Daily, seasonal, annual and decadal variations have also been interpreted. A comparative description of water chemistry of Narmada river with other rivers in the world, flowing over basaltic terrains have been presented. Physical and chemical weathering rates in the basin show excellent correlation, indicating their complement nature. Sediment flux by the Narmada river have been estimated based on long term data. The concentrations of dissolved inorganic nitrate, phosphate and silica and their loads at different locations on Narmada river and its tributaries have been studied, temporal and spatial variability observed and flux rate calculated. The influence of the presence of

dams on the retention of sediment load, chemical load, nutrient load and flux have been established. The thesis is structured and presented as follows:

Chapter 1 deals with an overall introduction of physical and chemical weathering processes, their regulating factors and the role of weathering processes in the global environment. Some recent and previous works on rivers flowing over volcanic provinces have been described. The importance of studying Narmada river is identified and objectives for the present work have been delineated. The introductory chapter is covered with 2 figures and 1 table.

Chapter 2 deals with the details of study area "The Narmada River Basin". Various features of the study area, including information on the drainage net work, prevailing climatic conditions, geology, soils, vegetation and land use have been described in detail and illustrated with 15 figures and 6 tables.

Chapter 3 deals with the information on time of collection of samples, hydrological parameters of sampling locations and methodology adopted for analytical details and described with 1 figure and 4 tables.

Chapter 4 presents the results with discussion. The chapter mainly concerns with (i) water and sediment characteristics, (ii) dissolved chemical compositions and (iii) nutrient flow patterns. The presented data are discussed with various interpretations. It focuses on major ion chemistry of the Narmada mainstream and major tributaries, by using water samples collected during the present work and the multi-annual data, from compositions of rain, spring water and ground water. Chemical and sediment flux are presented and their controlling factors established. Specific flux of strontium and nutrients have also been estimated. The methodology adopted for calculation of weathering rates and the coupling between various weathering parameters are discussed. The role of natural and anthropogenic processes involved in regulation of water and sediment flow are discussed and illustrated with 51 figures and 25 tables.

In addition, abstract, conclusion and references cited in the text are included in the thesis.

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Chapter 1

INTRODUCTION

The Narmada river at Amarkantak (Dudhdhara fall)

1.1 RIVERS - IMPORTANT GEOLOGIC AGENTS

Increased curiosity and implications of climatic changes and associated phenomena, have led to numerous studies to identify the causes and responses to short term and long term global climate. Climatic changes involve multiple and complex interactions between lithosphere, hydrosphere, atmosphere and biosphere. The global hydrologic cycle to a large extent regulates global surface temperature and associated atmospheric phenomena. Rivers are an integral part of the hydrologic cycle and are the major geologic agents, which erode the continents and transport, water and sediments to the oceans. Along with water and sediments, enormous amounts of chemical constituents are carried to the oceans, which play a significant role in the chemical composition of oceanic and marginal water bodies. Rivers are also the main pathways for biogeochemical cycling of elements. Sediment transfer from continents to oceans via rivers is one of the most vital processes regulating river bank stabilization, soil formation, crust evolution and pollutant migration. The two most important processes in river transport of materials, chemical and mechanical (physical) denudation, act complementarily and are governed by many natural and anthropogenic factors. To understand geochemical mass balance between land and oceans, appraisal of nature and estimation of mass transfer from continents to oceans is very essential. Each river has a characteristic finger-print of activities and products. Recent suggestions that creation of topography associated with orogeny can significantly affect rates of mechanical denudation and consequently chemical weathering, which perturb global carbon budget and hence climate, has reinforced the need for a clear understanding of factors controlling river dynamics.

In qualitative and quantitative estimations of the various river-borne materials to the oceans, it is essential to have precise information on river runoff, sources of water and the various controlling factors. Water discharge in a stream or river shows secular and seasonal variations, hence it is essential to consider a long term data of water discharge. On a global scale, fluvial erosion is the largest mechanism of continental transported materials to the oceans (Summerfield and Hulton, 1994; Hay, 1998; Hovius and Leeder, 1998). One of the most fundamental interests to study rivers is to estimate the concentration and flux of various river water constituents. A number of attempts have been made to estimate the suspended sediment and dissolved loads of world-rivers to oceans. Milliman and Syvitski (1992) estimated that the modern global sediment flux are at least 100% higher than 2000 years ago, when human impact was less, in concurrence with the estimates of Hay (1998) for the Holocene fluxes to marginal seas, which are typically 1.5-4 times higher than those for similar periods during the Pleistocene. Based on the flux data of 62 large rivers, Holeman (1968) estimated the first comprehensive global sediment flux of 18.3 billion tons yr^{-1}, which Holland (1981) later revised to 20 billion tons per year taking into account bed load transport. Milliman and Syvitski (1992) revised the estimate back to 18 billion tons yr^{-1}, using the flux data of 280 rivers that included small mountainous rivers. The estimated flux of dissolved loads is close to 5.6×10^9 tons yr^{-1} (Martin and Meybeck, 1979). However, despite numerous attempts, exact estimation and magnitude of global sediment and dissolved flux to the oceans are fraught with uncertainties, firstly due to lack of data from several medium and mountainous rivers and secondly, the estimates are frequently revised due to changes influenced by humans in river flow and its dynamics (Milliman and Syvitski, 1992).

Our understanding of nutrient flows in surface water systems have improved greatly during the past few decades (Nixon et al., 1986; Turner et al., 1998; Turner et al., 2003). In these studies, it has been shown that some areas are exposed to intense nutrient removal and others to nutrient accumulation. Turner et al. (2003) have given a detailed account of the global pattern of dissolved N, P and Si in large rivers. During the last century, the surface and groundwater resources have been subjected to large human perturbations in the form of intensive use of fertilizers in agriculture, changes in land use patterns, deforestation, fossil fuel burning, release of domestic, municipal and industrial waste etc. which led to the eutrophication of lake/river waters and of the coastal environments on a global scale. Over the past 50 years, the fluxes of natural and synthetic materials from the terrestrial environment to the coastal margin have increased by a factor of 1.5 to 2 because of human induced perturbation (Garrels et al., 1975; Meybeck, 1982; Meybeck and Ragu, 1995).

The river sediment flux to the oceans is not only an issue of sediment cycling; in addition, river sediments also play an important role in determining the quality of water. River sediments have primarily been derived from weathering of rocks and reworked sediments. In the process, they attain the nature and composition of the catchment rocks. However, sediments being finer in size, also act as source/sink for various toxic metals and radio-nuclides. The sediment-water interaction plays an important role in deciding the water quality in rivers. Hence, investigations on dissolved toxic elements in aquatic ecosystems have attained immense importance in environmental studies. Natural factors as well as anthropogenic, such as, urbanization, industrialization, mining, etc. in a river basin, enhance accumulation of pollutants in water.

1.2 RIVER CONSTITUENTS

The river water components play an important role in the geochemical evolution of the world's oceans and provide significant information on geochemical processes in operation in respective catchments. A large river encompassing large drainage basin area integrates the total information and thus allows us to assess the weathering processes on a global scale (Negrel et al. 1993; Gaillardet et al. 1995) whereas studies on small watersheds reveal the dominance and control of each and every factor over water and sediment composition and flux. Medium and minor size rivers, as well as many of the mountainous rivers, have not received as much attention as large rivers, although it has been long realized that global flux of materials are controlled significantly by medium/minor rivers. A number of natural and anthropogenic factors influence the sediment concentration and flux in a river system along its pathway. Some important key factors are area of drainage basin, relief, geology of basin, climate (temperature and rainfall), runoff, vegetation, tectonics, land use patterns and presence of reservoirs/dams. Any or all of these factors in combination can be important in a particular river system. A large number of factors have been identified, which control the rate and intensity of chemical weathering reactions on the Earth's surface, although their relative dominance is a matter of intriguing debate (Garrels and Mackenzie, 1971; Stallard and Edmond, 1983; Meybeck, 1986; Volk, 1987; Brady, 1991; Berner, 1992; Krishnaswami et al., 1992; Raymo and Rudimann, 1992; Negrel et al., 1993; Velbel, 1993; Bluth and Kump, 1994; Brady and Carroll, 1994; Drever, 1994; Amiotte-Suchet and Probst, 1995; Edmond et al., 1995; White and Blum, 1995; Gislason et al., 1996; Berner and Berner, 1997; Edmond and Huh, 1997; Gaillardet et al., 1999; Dessert et al., 2003, Das et al., 2005; Pokrovsky et al., 2005; Vigier et al., 2005 and Rad et al., 2006).

Weathering process is proposed as the principal moderator in controlling large fluctuations in global temperature and precipitation, through the greenhouse effects of CO_2 over geologic time (Berner and Berner, 1997). Pioneering studies by Garrels and Mackenzie (1971) and Berner et al. (1983) have suggested that chemical weathering of silicate rocks has an important influence on global atmospheric CO_2 consumption rates. Chemical weathering acts as a negative feed-back mechanism and hence maintains any major change in global atmospheric CO_2 levels (Ruddiman, 2001). During the last two decades, a lot of emphasis has been given to determine the chemical erosion rates and associated CO_2 consumption rates in various river basins. Meybeck (1986) and Amiotte-Suchet and Probst (1993) observed that basalts are more prone to weathering than other crystalline silicate rocks and thus, play an important role in evolution of climate. According to Taylor and Lasaga (1999) the large igneous provinces release enormous amounts of CO_2 into the atmosphere and the subsequent weathering of these basalts, could make them a net CO_2 sink on timescales of several million years. The present day exposed area of basalts on land is ~7 $\times 10^6$ km^2, constituting 5.2% of total continental area of 135 $\times 10^6$ km^2 (Amiotte-Suchet et al., 2003). The major exposures of basalts on the continents are the basalts of Siberian Traps, Deccan Traps, Columbia river, Ethiopia, Iceland and the Parana. The important role of basalt weathering on global climate has been emphasized recently (Gislason et al., 1996; Louvat and Allegre, 1997, 1998; Taylor and Lasaga, 1999; Dessert et al., 2001; Steffansson and Gislason, 2001; Benedetti et al., 2003; Dessert et al., 2003; Das et al., 2005; Pokrovsky et al., 2005; Vigier et al., 2005 and Rad et al., 2006).

1.3 RIVERS FLOWING OVER BASALTIC PROVINCES

Bluth and Kump (1994) studied the rivers draining Hawaii, Iceland and Columbia plateau region and other regions in the USA and concluded that, the optimum climatic conditions do not necessarily produce the highest rates of chemical denudation whereas the presence of abundant vegetation and tropical climate favor chemical dissolution. Louvat and Allegre (1997) observed that the tropical and the oceanic climate with high runoff, high relief, volcanic activity, and the basalt lithology favor very high chemical and mechanical erosion rates in the Reunion Islands. On the basis of studies of the rivers draining the Sao Miguel Island, Louvat and Allegre (1998) estimated the physical and chemical denudation rates and CO_2 consumption rates due to weathering of basalts. They identified relief, runoff and tectonics as aiding the basaltic weathering in the province. Studies on the Columbia river basalts by Taylor and Lasaga (1999) suggested that basalt weathering plays an important role in the carbon cycle whereas the rapid dissolution of the basaltic minerals and the volcanic glass can lead to significant strontium fluxes from basaltic terrains, influencing the strontium isotopic chemistry of the oceans. Dessert et al. (2001) studied rivers draining the North Deccan Trap and calculated chemical weathering rates and associated CO_2 consumption, leading them to suggest that, temperature and runoff are the major controlling factors for chemical weathering of the Traps. Their study indicated that, the rate of chemical weathering of the Deccan Traps (21-63 tons km^{-2} yr^{-1}) and associated CO_2 consumption (0.58-2.54 $\times$ 10^6 mol C km^{-2} yr^{-1}) are relatively high compared to those linked to other basaltic regions. They concluded that the Deccan Traps emplacement was responsible for a strong increase of atmospheric pCO_2 by 1050 ppmv followed by a new steady-state pCO_2 lower than that in Pre-Deccan times, implying that pre-industrial atmospheric pCO_2 would have been 20% higher in the absence of the Deccan basalts. Studies by Gislason et al. (1996) and Steffansson and Gislason (2001) on rivers draining Iceland basalts show that runoff, vegetation/glacial cover and age of basalts are the key factors regulating their chemical weathering. According to Benedetti et al. (2003) in the Mount Cameroon area, chemical weathering is the major driving force and the physical and biological disaggregation are apparently second-order rate processes in the weathering of fresh basalts. Das et al. (2005) have estimated the chemical weathering rates and associated CO_2 consumption rates for the Krishna river and the Western Ghat rivers draining the south

Deccan Traps. Pokrovsky et al. (2005) specified the quantitative characterization of chemical erosion of basic rocks in permafrost-dominated boreal regions of Central Siberia and observed that, the overall basin weathering fluxes are among the lowest in the world. Rad et al. (2006) emphasized that the chemical weathering of basalts and associated CO_2 consumption rates in Caribbean Islands are among the highest in the world but lower than those of tropical volcanic islands.

1.4 DECCAN TRAPS - THE NARMADA RIVER

The Indian sub-continent is endowed with vast fresh surface water resources. Studies on river systems in India, which show large variations in climate, lithology, land use, urbanization etc. offer great challenges for research and have immense implications on day to day life of millions living in the river basin. The major river basins in India are shown in Fig. 1.1 and detailed hydrological characteristics of these major river basins are presented in Table 1.1. With distinctive geology and physiography, the Indian subcontinent is divisible into three fundamental units, the Himalayas, the Indo-Gangetic Plains and the Peninsular India. The Deccan Traps occupy an important and vast part of the Indian Peninsula, others being the Central Highlands, Eastern Plateaus, Eastern Hills and the Western Hills. The Deccan Traps extend from the Satpura-Maikala Ranges in the north, through the Maharashtra Plateau, to the Telangana and the Karnataka Plateaus on the south. The Sahyadri forms the western extremity of Deccan Traps. Although the Deccan Traps are a stable mass, it has undergone considerable tectonic disturbances (Mathur, 1991).

The Deccan Traps are located in the central-western region (Fig. 1.2), which presently covers an area of about 0.5×10^6 km^2 with present-day volume of $\sim 10^6$ km^3 (Dessert et al., 2001). Courtillot et al. (1986) suggested that the total initial volume of lava may have reached $\sim 3 \times 10^6$ km^3. Since its eruption 65 million years ago, two-thirds of the initial basalts must have disappeared. On the basis of Ar-Ar isotopic studies, Courtillot et al. (1988) argued that age younger than ~55 Myr is due to argon loss resulting from alterations. They argued that, the bulk of Deccan eruptions occurred in a short time, between 65 and 69 Myr. On the basis of Re-Os isotopic studies, Allegre et al. (1999) have established an age of 65.6±0.3 Myr, which is in excellent agreement with the previous estimations (Courtillot et al., 1986, 1988; Duncan and Pyle, 1988; Vandamme et al., 1991; Baksi, 1994). According to Javoy and Michard (1989) during the eruption of Deccan basalts, $\sim 1.6 \times 10^{18}$ moles of CO_2 gassed out, which represent half of the total ocean content and might have played a crucial role in the mass extinctions of around ~ 65 Myr, commonly known as K-T extinctions (Courtillot et al., 1988).

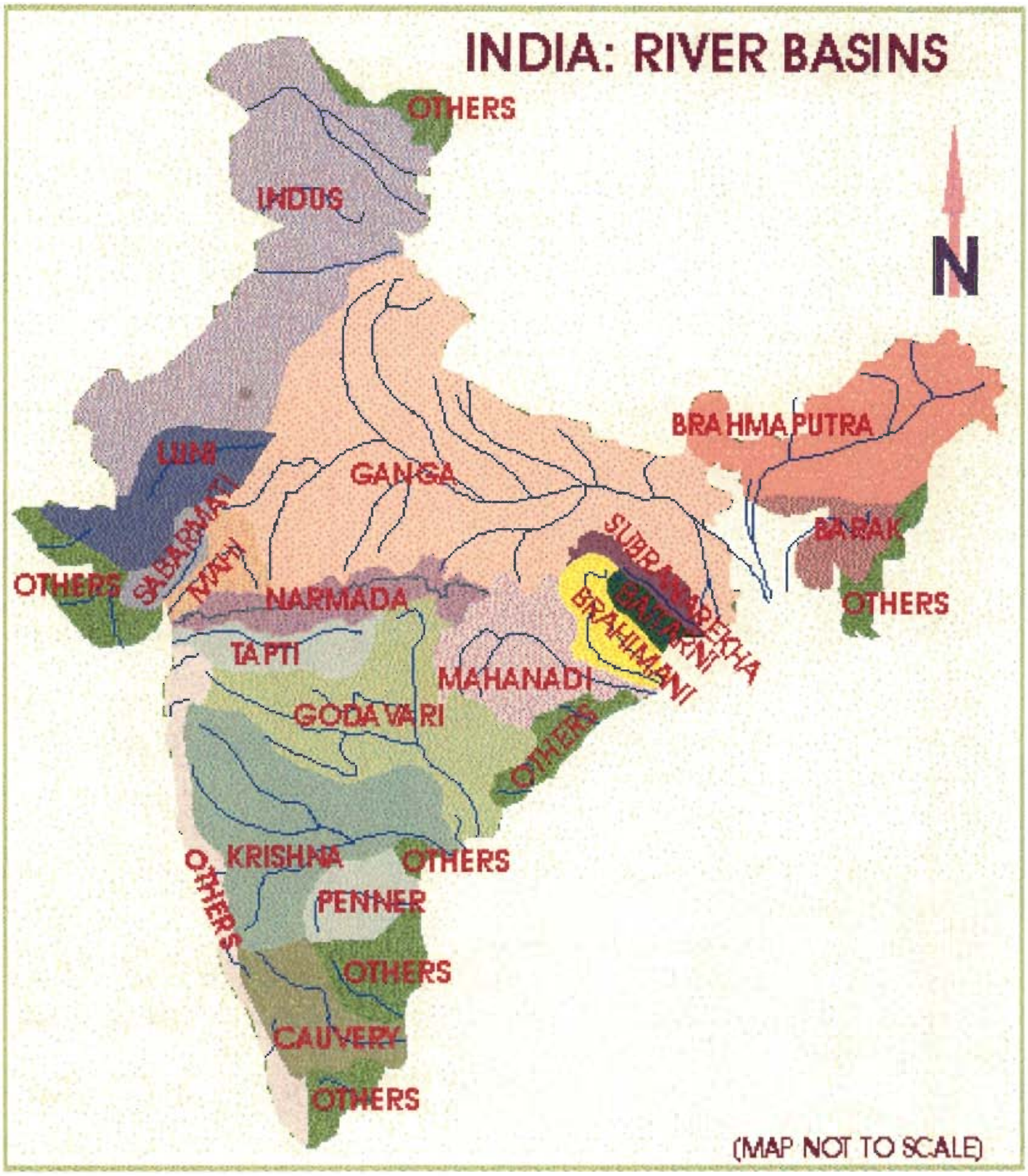


Fig. 1.1 River basins map of India (modified after http://www.wrmin.nic.in)

Table 1.1 Major river basins of India and their hydrologic characteristics (http://www.cwc.nic.in) (N/A: Data not available)

S. No	River	Source of River	Drainage Area (km^2)	Length of river in India (km)	Mean Basin Elevation (m from MSL)	Average Annual Discharge (km^3)	Per Capita Availability of Water ($m^3\ yr^{-1}$)
Rivers Flowing to Bay of Bengal							
1	Ganga	Gangotri Glacier	861,452	2525	3000	525.02	16859
2	Brahmaputra (including Barak)	Glaciers of Kailash Range	194,413	916	5000	585.60	1471
3	Indus	Glaciers of Kailash Range	321,289	1114	2500	73.31	1749
4	Godavari	Sahyadri Range	312,812	1465	400	110.54	2048
5	Krishna	Satpura Range (Western Ghats)	258,948	1401	420	78.12	1285
6	Mahanadi	Maikala Range	141,589	851	500	66.88	2513
7	Cauvery	Sahyadri Range	81,155	800	630	21.36	728
8	Mahi	Aravalli Range	34,842	583	N/A	11.02	1052
9	Brahmani	Ranchi Plateau	39,033	799	28.48	28.48	2915
10	Baitarni	Ranchi Plateau	N/A	N/A	N/A		
11	Penner	Chennakeshva Hills	55,822	N/A	N/A	6.32	651
12	Subernarekha	Ranchi Plateau	N/A	N/A	N/A	12.37	1307
Rivers Flowing to Arabian Sea							
13	Narmada	Maikala Range	98,976	1312	760	45.64	3109
14	Tapti	Satpura Range	65,145	724	740	14.88	1007
15	Sabarmati	Aravalli Range	21674	N/A	N/A	3.81	360
Others (Inland Drainage)							
16	Luni	Aravalli Range	N/A	N/A	N/A	15.10	683

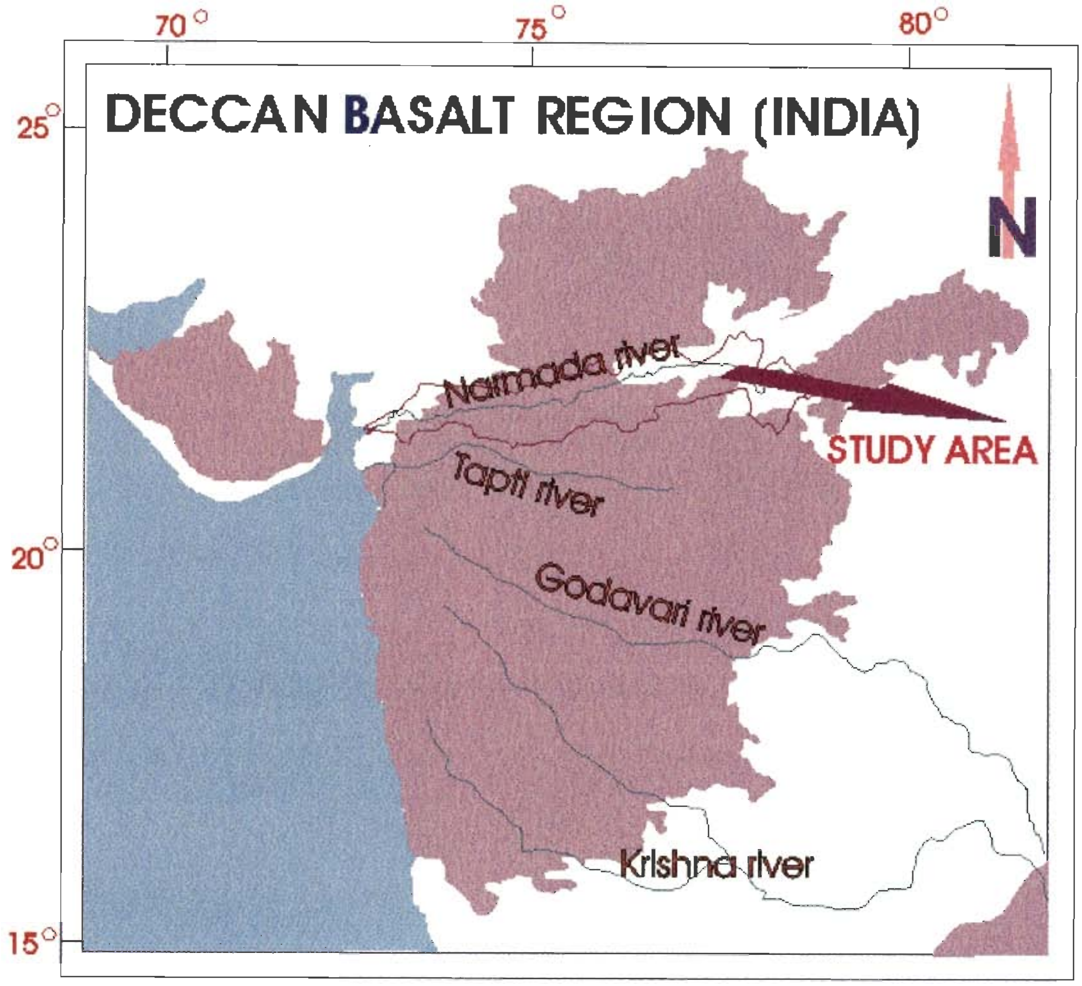


Fig. 1.2 Location of study area and extent of Deccan basaltic region in western India (modified after Courtillot et al. 1988)

The Godavari, Krishna, Narmada and the Tapti rivers are the major rives, which flow through the Deccan Traps. In contrast to the Godavari and the Krishna rivers, which drain their water into the Bay of Bengal, the Narmada along with the Tapti river, flow into the Arabian sea. A few small streams, which originate from the Western Ghats also drain their water into the Arabian sea. According to Subramanian (2000) all of these rivers account for a total annual discharge of ~ 250 km^3. Although of medium in size, the Narmada river is the largest river in India, flowing into the Arabian Sea. Dessert et al. (2001) carried out detailed study in parts of the Narmada river, Tapti river and the Wainganga (a tributary of the Godavari river) draining the northern Deccan Traps. The study quantified the multiple effects of the Deccan Trap emplacement on the global environment, which is responsible for about 20% reduction of atmospheric pCO_2, accompanied by a global cooling of 0.55 $^{\circ}C$, and has therefore produced a net CO_2 sink on geological time scales. In a recent study Das et al. (2005) calculated the chemical and silicate weathering rates (3-60 tons km^2 yr^{-1}) along with CO_2 consumption rates (3.6×10^5 mol C km^2 yr^{-1}) associated with silicate weathering for the Krishna river and other west flowing rivers. The calculated chemical and silicate weathering rates of the west flowing rivers of the Deccan are ~ 4 times higher than the east flowing rivers, suggesting that the differences may be due to comparatively higher rainfall and runoff in the western regions.

The significance of the Deccan Traps on the Earth's surface and the flow of the Narmada river over these Trap rocks, along with the significance of the river to the millions of people living in the basin, inspired me to under take the present study on **"Environmental Geochemistry of Narmada River Basin"**.

1.5 OBJECTIVES

The main objectives for the present study are, (i) to understand the effects of natural and anthropogenic processes on the chemical and sediment loads in the Narmada river, and (ii) to quantify water and sediment flux from the Narmada river to the Arabian Sea.

The objectives are accomplished by:

- Studies on temporal and spatial variations in water discharge, suspended and dissolved loads.
- Generation of baseline information on the dissolved major ion compositions.
- Studies on strontium isotopic compositions in water.
- Estimation of temporal and spatial variations in dissolved inorganic nutrients (DIN, DIP and DSi) and flux to the Arabian Sea.
- Estimation of temporal and spatial variations in physical and chemical weathering rates in the basin and flux to the Arabian Sea.
- Assessment of the role of natural and anthropogenic factors in materials transport and flux of the Narmada river.

Chapter 2

STUDY AREA

The Narmada river at Bheraghat, Jabalpur (Dhuandhar fall)

2.1 THE NARMADA RIVER BASIN

The Narmada river is the largest west flowing river and ranks seventh in terms of water discharge and drainage area in India. It originates from Amarkantak in the Maikala Hills in Anuppur District of Madhya Pradesh. Thereafter, the river flows mostly through the Deccan Traps, separating the Vindhyan and the Satpura range of hills on both sides and joins the Arabian Sea at about 10 km north of Bharuch via the Gulf of Cambay (Fig. 2.1).

Fig. 2.1 Location map of Narmada river basin, India (source: http://www.googleearth.com)

The Narmada river basin is situated between 72° 32' E and 81° 45' E longitudes and between 21° 20' N and 23° 45' N latitudes. The basin has an elongated shape with a maximum length of 953 km. from east to west and a maximum width of 234 km from north to south (CWC, 1997-98). The Narmada river flows along the ENE-WSW trending Narmada-Son Fault (NSF), a well-known seismo-tectonic feature. The NSF is laterally traceable for more than 1000 km. and parallels the Satpura orogenic belt (Biswas, 1987). It demarcates the peninsular India, into two geographically distinct provinces, the Vindhyan-Bundelkhand province to the north and the Deccan province to the south. The Narmada and the Tapti rivers throughout their course follow these tectonic trends. The Narmada basin evolved in Cretaceous during drift of the subcontinent (CRUMANSONATA, 1995).

The Narmada river rises as groundwater seepage, from Narmada Kund at an elevation of 1057 m at Amarkantak, on the eastern fringe of the Maikala Plateau. At 8 km from its source, the river drops to 21 m at Kapildhara fall and then 0.4 km further downstream, it drops by about 4.6 m at Dudhdhara fall. After Dudhdhara fall, the Narmada river meanders upto Mandla, over a rejuvenated peneplain. Flowing in a generally south-west direction in a narrow and deep valley, the river takes pin-head turn at places and slopes down to Jabalpur. Close to Jabalpur, 404 km from the source, the river cascades 15 m into gorge to form Dhuandhar fall. Subsequently it flows through a narrow channel through marble rocks for a small distance. From the marble rocks, the river turns west near Mangeli village (Jabalpur) and enters the plains. Downstream of Jabalpur, the Narmada river flows along the northern edge of an asymmetrical valley through alluvial tracks alternating with rocky gorges, enclosed by the Vindhyan range on the north and the Satpura range on the south. The Tawa river originates from the south and joins the mainstream of the Narmada river at Hoshangabad (676 km. from the source). The river valley shows a gradual broadening from Jabalpur in the east to Hoshangabad in the west with a drop of 60 m in elevation for a distance of about 300 km. At Hoshangabad the Narmada river attains its maximum width (700 m). Further downstream of Hoshangabad, after traversing through the plains initially, the Narmada river flows over the Vindhyan Sandstone. Emerging from the trap rocks of the Dhar Upland, it runs in a straight course for 130 km through the open alluvial plain of Mandleshwar. At 966 km from the source, nearly 6.4 km downstream of Maheshwar, the Narmada river, plunges by about 6.7 m at the Sahasradhara fall. Flowing further west, the river passes through the lower hilly regions and enters a narrow gorge of the Deccan Trap at Murakta. A 113 km long gorge is formed by the convergence of the Vindhyan range from the north and the Satpura range (rising over 1,000 m in the Arkhrani Hills) from the south towards the river. Emerging finally from the hills near Garudeshwar, the Narmada river meanders in broad curves through an alluvial plain till it reaches Broach. At Broach, it opens into the Gulf of Khambhat on the Arabian sea after traversing 1,312 km from its source. A few islands have been formed by the deposition of alluvium along the 30 km stretch estuary of Narmada river, of which Aliabet is the largest (CWC, 1997-98).

The Narmada river drains an area of 98,796 km^2 encompassing the administrative states of Madhya Pradesh, Maharashtra, Gujarat and Chhattisgarh. Out of total length of 1,312 km, for the initial 1,079 km it flows through Madhya Pradesh followed by 35 km stretch along the boundaries of Madhya Pradesh and Maharashtra, 39 km along Maharashtra and Gujarat and the remaining 159 km of the river stretches in the state of Gujarat (CWC, 1997-98). The state wise distribution of the basin area is presented in Table 2.1 and Fig. 2.2 displays the spatial distribution.

Table 2.1 State-wise distribution in drainage area of Narmada river basin

Administrative State	Basin Area	
	Km^2	Percentage of total
Madhya Pradesh	85,148	86.18
Maharashtra	1,538	1.50
Gujarat	11,399	11.60
Chhattisgarh	711	0.72
Total	98,796	100.00

Fig. 2.2 Administrative divisions of drainage area

2.2 CLIMATE

The Narmada river basin enjoys humid tropical climate. The 'Tropic of Cancer' passes through the Narmada river basin in the upper plains and a major part of the basin lies below this latitude.

2.2.1 Temperature

The difference between maximum and minimum temperatures is pronounced in different parts of the basin. Maximum temperature is observed during the month of May (40-42 ^{0}C) and minimum in the month of January (8-13 ^{0}C). In general, the upper Narmada basin shows lower temperature as compared to the middle part of the basin. In the lower part of the basin, the influence of Arabian sea is prominent in lowering of temperature (CWC, 1997-98). Fig. 2.3 A shows, the monthly variations in minimum and maximum temperature at three different locations, upstream (Dindori), midstream (Hoshangabad) and downstream (Rajghat) during 1998-99, whereas, Fig. 2.3 B shows, variations in the minimum and the maximum temperature at Rajghat (downstream) during 25 water-years (1979-2004).

2.2.2 Rainfall

A major portion of the precipitation in the basin takes place during the southwest monsoon season, which accounts for about 85-95% of the total precipitation. The post-monsoon season accounts for approximately 9% of the precipitation, whereas the winter and pre-monsoon seasons, together account for less than 10% of total precipitation. About 60% of the annual rainfall is received during the peak monsoon months of July and August. The average annual rainfall in the basin is about 1178 mm. Rainfall distribution is not uniform through out the basin and varies between 600 and 1800 mm. Maximum rainfall (approx 1800 mm.) occurs in Panchmarhi in the middle reaches of the basin whereas, the lower reaches of Barwani receive less than 650 mm. The rainfall is higher in the upper and lower basins, as compared to the middle part of the basin. The general rainfall in the basin shows increase in rainfall from west to east. The most intense rains occur in the southern parts of the upper Narmada basin, where it rains more than 360 mm in a continuous 24 hour rainfall

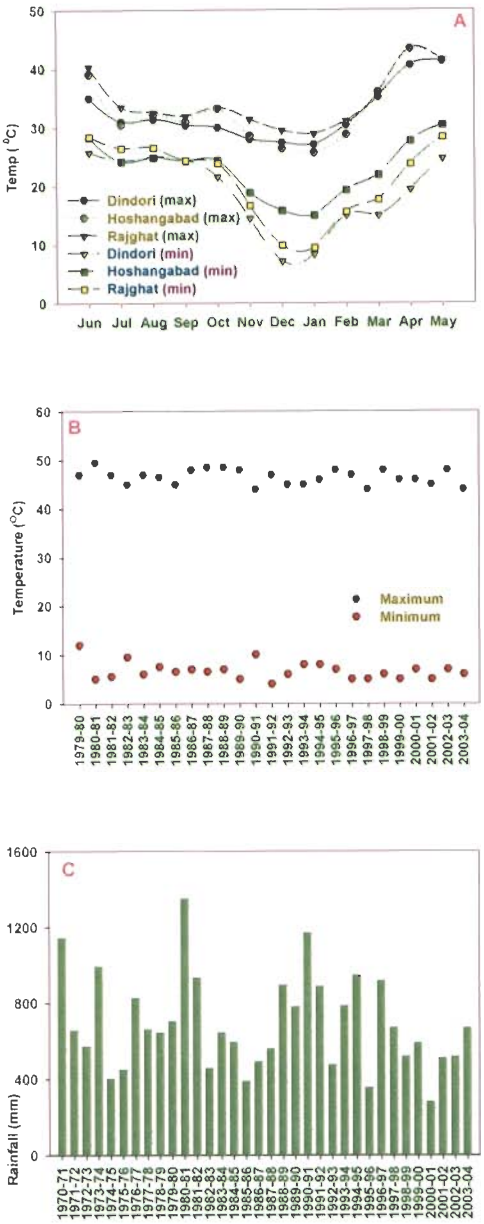


Fig. 2.3 Variations in climatic (temperature and rainfall) parameters in the basin; (A) Monthly minimum (mean) and maximum (mean) temperature during 1998-99 at three stations (up-, mid- and downstream), (B) Annual (1979 - 2004) minimum (mean) and maximum (mean) temperature at Rajghat and (C) Annual (1970 - 2004) rainfall at Rajghat

period, whereas in Jhabua and Dhar, a continuous 24 hour rainfall yields not more than 260 mm (CWC 1997-98). Fig. 2.3 C shows the average annual rainfall during the last 33 years

(1970-71 to 2003-04) at Rajghat and Fig. 2.4 represents the annual rainfall (isohyets) in the basin.

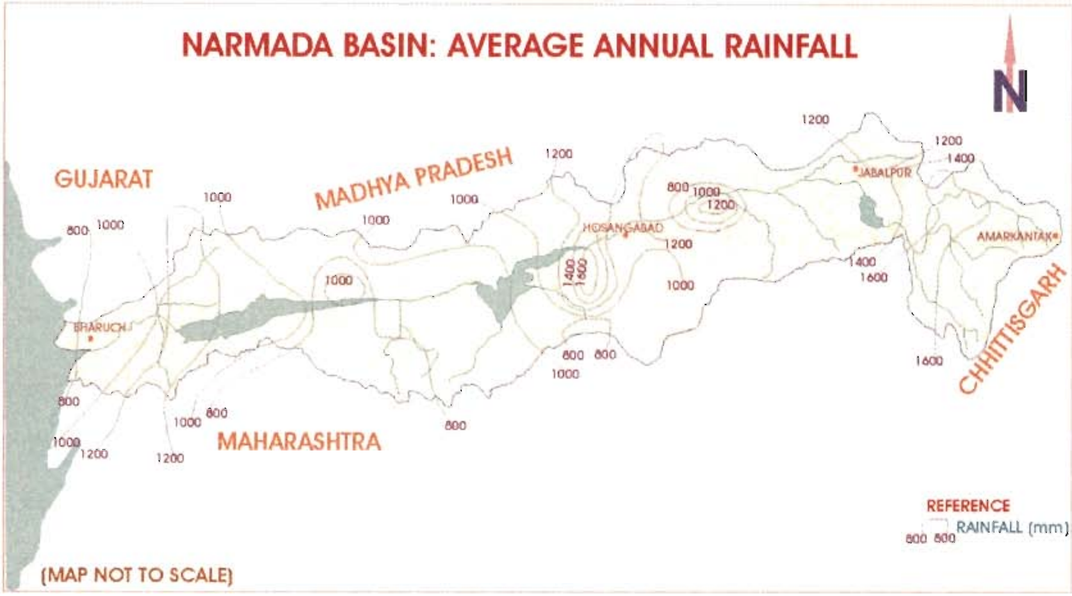


Fig. 2.4 Annual rainfall distribution in the Narmada river basin (redrawn from CWC, 1997-98)

2.2.3 Wind Direction

The average monthly wind speed in the basin varies between 3 km hr^{-1} and 16 km hr^{-1}. The minimum and maximum wind speed occurs at Hoshangabad and Khandwa. In the pre-monsoon and post-monsoon seasons, the wind speed is generally higher. The wind direction is mostly towards NW followed by SW and W (CWC, 1997-98).

2.2.4 Evaporation

In summer, evaporation loss in the upper Narmada basin is between 6 and 10 mm. In the middle part, evaporation loss is less (4-7 mm). In the lower part, evaporation loss is high and is between 12-28 mm. In the winter, evaporation loss is less in the upper and middle parts of the basin (1-3 mm). In lower Narmada basin, evaporation loss is between 6-9 mm. in the winter season. (CWC, 1997-98).

2.2.5 Humidity

The morning relative humidity in the basin varies between 27 and 92% and the evening humidity is 15-88% depending upon the season. The humidity levels are maximum during the monsoon months (80-90%) and in winter months of December and January, the relative humidity decreases to ~30%. The variation in relative humidity between upper, middle and lower parts of the basin is not very pronounced (CWC, 1997-98).

2.3 DRAINAGE NETWORK

During most of its flow path, the Narmada river, flows through a narrow valley confined at places by ridges and hills. The right bank of the Narmada mainstream receives only two significant streams, while on the left bank, a few large streams drain into it from the Satpura range. All along its course, the Narmada river is fed by forty-one tributaries of which, twenty-two are left bank and nineteen are right bank tributaries (Fig. 2.5). Out of these forty-one tributaries, the Burhner, Banjar, Hiran, Tawa, Chota-Tawa, Kundi and the Orsang river are the major tributaries, having catchment area of more than 3500 km^2. The remaining tributaries have catchment area ranging from 500 to 2500 km^2. The streams from the north are, the Hiran and the Orsang, which flow along the base of the Bhanrer hill into the Narmada river. Vital information of all the tributaries draining to the Narmada mainstream and other physiographic parameters are presented in Table 2.2.

2.3.1 Left Bank Tributaries

The Burhner river rises from the Maikala range, south east of Gwara village in the Mandla district of Madhya Pradesh at an elevation of about 900 m at 22° 32' N and 81° 22' E. It flows along west for a length of 177 km to join the Narmada river near Manot. The

Burhner river is the fourth largest tributary in terms of catchment area with a total area of 4,118 km^2. The confluence occurs at 248 km from the source of the Narmada river.

The Banjar river originates in the Satpura range in the Durg district of Madhya Pradesh near Rampur village at an elevation of 600 m at 21° 42' N and 80° 50' E. It flows along north-west for a total length of 184 km and joins the Narmada mainstream near Mandla. The Banjar river drains a total area of 3626 km^2. The confluence occurs at 287 km from the source of the Narmada river.

The Sher river rises from the Satpura range near Patan in the Seoni district of Madhya Pradesh at an elevation of 600 m at 22° 31' N and 79° 25' E. It flows north-west for a total length of 129 km before its confluence with the Narmada mainstream near Brahmand. The Sher river drains a total area of 2,901 km^2. The confluence occurs at 497 km from the origin of Narmada river.

The Shakkar river also rises from the Satpura range in the Chhindwara district of Madhya Pradesh, west of Chhindi village at an elevation of 600 m at 22° 23' N and 78° 52' E. It flows north-west for a total length of 161 km and joins the Narmada river at Paloha village. The Shakkar river drains a total area of 2,292 km^2. The confluence occurs at 546 km from the source of the Narmada river.

The Tawa river is the largest among all left bank tributaries and longest tributary of the Narmada river. It originates from the Mahadeo hills of the Satpura in the Chhindwara district of Madhya Pradesh, near Cherkathari village at an elevation of 900 m at 22° 13' N and 78° 23' E. It flows along north-west for a total length of 172 km to join the Narmada from the left, at Bandrabhan. The confluence is 676 km from the source of the Narmada river. The Denwa is the main tributary of Tawa river. The Tawa river is the largest tributary in terms of catchment area (6,333 km^2). The Tawa dam and reservoir were constructed on the Tawa river at Hoshangabad.

The Dudhi river rises in the Mahadeo hills of the Satpura in the Chhindwara district of Madhya Pradesh, at an elevation of 900 m at 22° 23'N and 78° 45' E. It flows north-west upto Sainkheda and afterwards towards west for a total length of 129 km and joins the Narmada on the left bank. The confluence is 575 km from the source of the Narmada river. The Dudhi river drains a total area of 1,541 km^2.

The Ganjal river originates in the Satpura in the Betul district of Madhya Pradesh, north of Bhimpur village at an elevation of 800 m at 22° 00' N and 77° 30' E. It flows for a total length of 89 km in north-west direction to join the Narmada from the left, near Chhipaner village. The confluence is 757 km from the source of the Narmada river. The Ganjal river drains a total area of 1,930 km^2.

The Chota-Tawa river originates in the Satpura in the West Nimar district of Madhya Pradesh, near Kakora village at an elevation of 600 m at 21° 30' N and 75° 50' E. It flows for a total length of 169 km north to join the Narmada from the left bank, at Purni village. The Chhota-Tawa is next in size to the Tawa among the tributaries and drains a total area of 5051 km^2. The confluence of Chhota-Tawa river occurs at 829 km from the source of the Narmada river.

The Kundi river rises in the Satpura range in the West Nimar district of Madhaya Pradesh, near Tinshemali village at an elevation of 600 m at 21° 25' N and 75° 45' E. It flows for a total distance of 121 km along north to join the Narmada river from the left near Mandleshwar. The Kundi river drains a total area of 3,820 km^2. The confluence of the Kundi river occurs at 943 km from the source of the Narmada river.

The Goi river rises in the Satpura range in the West Nimar district of Madhaya Pradesh, near Dhavdi village at an elevation of 600 m at 21° 40' N and 75° 23' E. It flows for a total distance of 129 km in a north-west direction to join the Narmada river on the left bank at Barwani. The Kundi drains a total area of 1,891 km^2. The confluence of the Kundi river occurs at 1038 km from the source of the Narmada river.

The Karjan river rises in the Satpura range in the Surat District of Gujarat, south of Nana village at an elevation of 300 m at 21° 23' N and 73° 35' E. It flows for a total length of 93 km in north-west direction to join the Narmada river on the left bank at Sinor village. It drains a total area of 1,489 km^2.

2.3.2 Right Bank Tributaries

The Hiran river rises in the Bhamer range in the Jabalpur district of Madhya Pradesh near Kundar village at an elevation of 600 m at 23° 12' N and 80° 27' E. It flows south-west for a total length of 188 km to join the Narmada river on the right bank near Sankal village. The Hiran river, the biggest right bank tributary of the Narmada river drains a total area of 4,792 km^2.

The Barna river rises in the Vindhyan range in the Raisen district of Madhya Pradesh, east of Barkhera village at an elevation of 450 m at 22° 55' N and 77° 44' E. It flows for a total length of 105 km in south-east direction to join the Narmada river on the right bank, near Dimaria village. It drains a total area of 1,787 km^2.

The Kolar river rises in the Vindhyan range in the Sehore district of Madhya Pradesh, near Bilquisganj village at an elevation of 450 m at 23° 07' N and 77° 17' E. It flows for a total length of 101 km in a south-west direction to join the Narmada river on the right bank, south of Nasrullahganj. The Kolar river drains a total area of 1,347 km^2.

The Man river rises in the Vindhyan range in the Dhar district of Madhya Pradesh near Dhar town at an elevation of 500 m at 22° 33' N and 75° 18' E. It flows for a total length of 89 km along south to join the Narmada river from the right bank at Talwara Deb village. It drains a total area of 1,528 km^2.

The Uri river rises in the Vindhyan range in the Jhabua district in Madhya Pradesh, near Kalmore village at an elevation of 450 m at 22° 36' N and 74° 47' E. It flows for a total length 74 km in a southerly direction to join the Narmada river from the right near Nisarpur village. It drains a total area of 1,813 km^2.

The Hatni river rises in the Vindhyan range in the Jhabua district of Madhya Pradesh, at Kanas village at an elevation of 450 m, at 22° 32' N and 74° 40' E. It flows for a total length of 81 km along south direction to join the Narmada river from the right, near Kakrana village. It drains a total area of 1,943 km^2.

The Orsang river rises in the Vindhyan range of the Jhabua district of Madhya Pradesh, near Bhabra village at an elevation of 300 m, at 22° 30' N and 74° 18' E. It flows for a total length of 101 km along south-west direction to join the Narmada river on the right bank, near Chandod village. It drains a total area of 4,079 km^2.

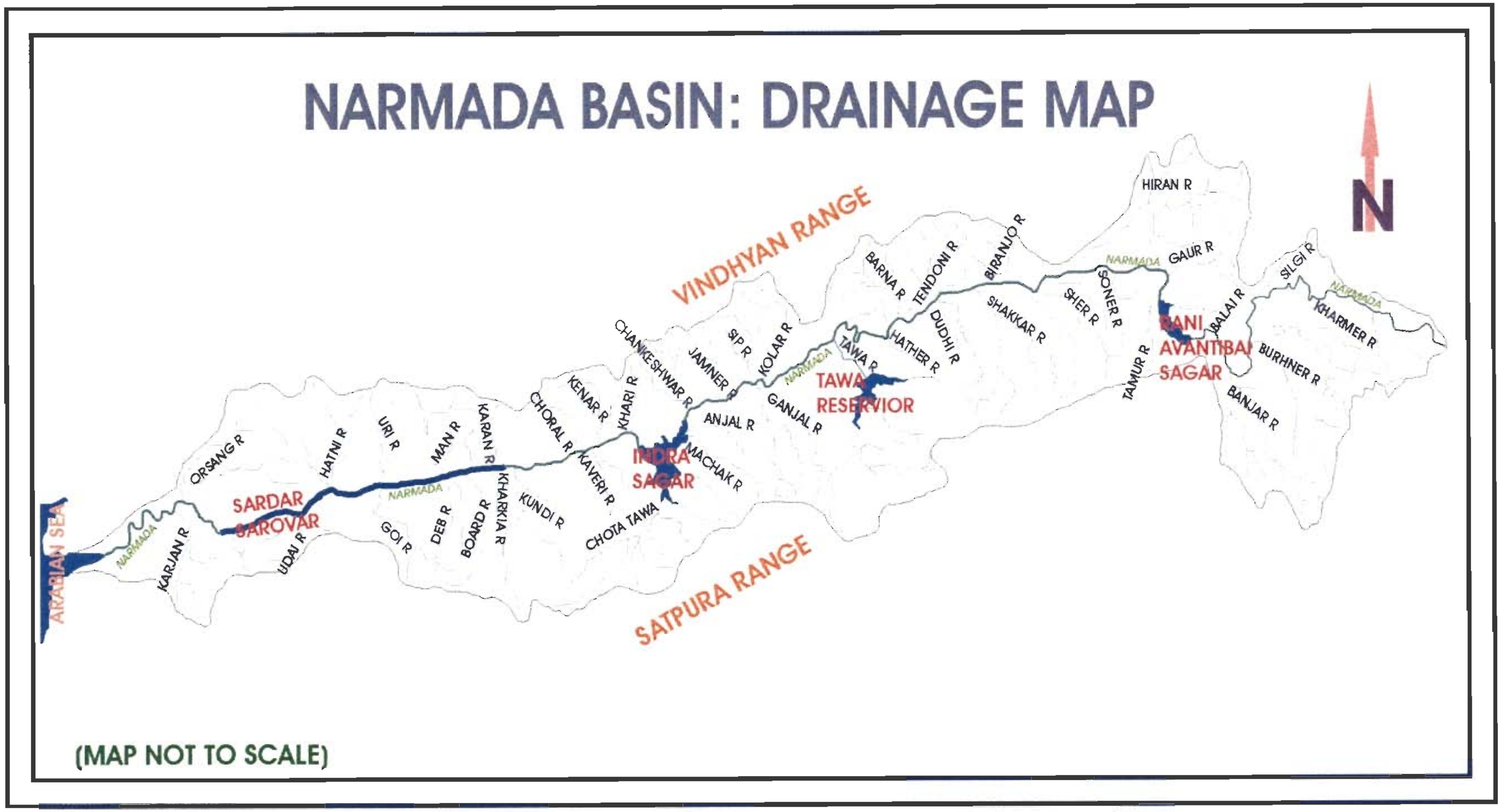


Fig. 2.5 Drainage map of the Narmada river (redrawn from NCA, 2003)

Table 2.2 Physiographic features of the tributaries of the Narmada river (CWC, 1997-98; N/A: Data not available)

S. No.	Tributary	Bank of confluence	Elevation of source above MSL (m)	Catchment area (km^2)	Total length from source (km)
1	Kharmer	Left	N/A	557	64
2	Silgi	Right	N/A	531	65
3	Burhner	Left	900	4228	177
4	Banjar	Left	600	3282	183
5	Balai	Right	N/A	531	46
6	Temur	Left	550	892	54
7	Gaur	Right	690	1107	79.5
8	Soner	Left	N/A	581	51
9	Hiran	Right	500	4795	188
10	Sher	Left	650	2903	129
11	Biranjo	Right	N/A	1172	62
12	Shakkar	Left	900	2294	161
13	Dudhi	Left	900	1542	129
14	Sukhri	Left	N/A	609	39
15	Tendoni	Right	500	1633	177
16	Barna	Right	450	1789	105
17	Tawa	Left	600	6338	172
18	Hather	Left	N/A	645	37.5
19	Kolar	Right	600	1348	101
20	Ganjal	Left	700	1931	89
21	Sip	Right	N/A	879	45
22	Jamner	Right	470	671	30
23	Chankesher	Right	600	1249	30
24	Anjal	Left	N/A	1203	62.5
25	Machak	Left	550	1112	87.5
26	Chhota Tawa	Left	400	5055	169
27	Khari	Right	N/A	754	41
28	Kenar	Right	N/A	1581	62.5
29	Kaveri	Left	N/A	954	32.5
30	Choral	Right	N/A	601	55
31	Kharkia	Left	N/A	1099	24
32	Kundi	Left	900	3973	120
33	Karan	Right	N/A	858	45
34	Board	Left	N/A	866	62.5
35	Man	Right	550	1529	89
36	Deb	Left	650	969	82.5
37	Uri	Right	450	2004	74
38	Goi	Left	800	1892	129
39	Hatni	Right	350	1944	30
40	Orsang	Right	300	3946	101
41	Karjan	Left	200	1490	93

2.4 PHYSIOGRAPHY

The Narmada river basin is bounded on the north by the Vindhyan range, on the east by the Maikala range, on the south by the Satpura range and on the west by the Arabian sea. The Vindhyan and the Satpura range are the two east-west ranges of hills in Central India, which geographically separate the Indian Subcontinent into northern India (the Indo-Gangetic Plain of northern India and Pakistan) and Southern India (Deccan Plateau). The Satpura range parallels the Vindhyan range to the north. The Satpura range rises in eastern Gujarat state near the Arabian sea coast, running east through Maharashtra and Madhya Pradesh to Chhattisgarh. The Satpura consists of three hill groups rising on an average to 900 m. Pajpipla hills in the west, Mahadeo hills in the centre and the Maikala range in the east. The Maikala range is an east facing escarpment. The Narmada river runs along the depression between the Satpura and Vindhyan ranges, draining the northern slope of the Satpura range and running west towards the Arabian sea.

The Narmada river basin can be divided in to four major physiographic units (Fig.2.6) following the divisions given by Central Pollution Control Board (2001), on the basis of elevation above mean sea level. These units are based on area between the elevation above mean sea level, (i) 600-1350 m, (ii) 300-600 m, (iii) 150-300 m and (iv) 0-150 m. Small parts of the basin in the Satpura range have an elevation more than 600 m. The location of origin of the Narmada river at Amarkantak and a small area around Pachmarhi are at a height of more than 1000 m above mean sea level. Most parts of basin posses an elevation of 300-600 m, followed by large areas with elevation of 150 and 300 m. Mean basin elevation is 760 m above mean sea level whereas, most of the basin is at an elevation of less than 500 m above mean sea level.

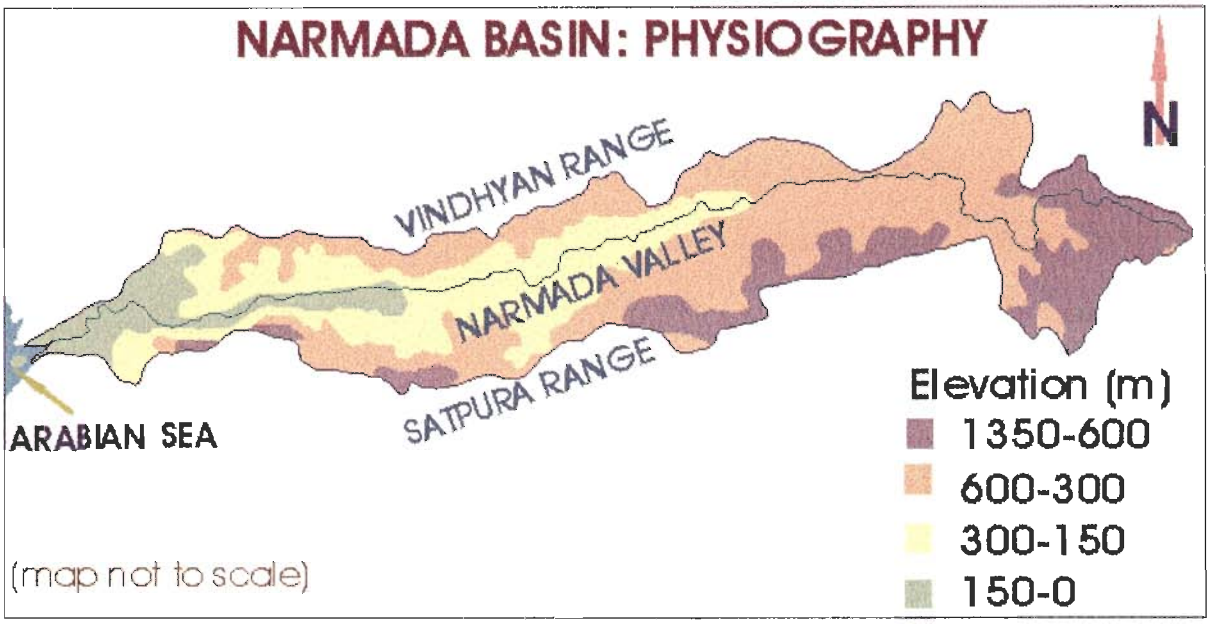


Fig. 2.6 Physiography of Narmada river basin (modified after CPCB, 2001)

2.5 VEGETATION

According to the studies of CPCB (2001), the natural vegetation in the basin can be classified in to three groups, (i) tropical dry deciduous, (ii) tropical moist deciduous and (iii) littoral and swamp vegetation. Tropical dry deciduous vegetation occupies nearly the entire basin, followed by tropical moist deciduous vegetation, whereas littoral and swamp vegetation is dominant along coasts (Fig. 2.7). Large parts of the tropical dry and the moist deciduous vegetations have forest cover. The hilly regions in the Narmada basin are well forested. A significant proportion of the forest cover in the upper reaches of the basin has vanished due to mining activities. Similarly the Satpura range was formerly heavily forested, most of the forests have been cleared, but some of the parts of the Satpura range still have significant growth of forests. The eastern portion of the Satpura range receives more rainfall than the western part and constitutes the moist deciduous forest eco-region. The seasonally dry western portion of the range, together with the Narmada valley and the western Vindhyan range are within the Narmada valley dry deciduous forest eco-region. In the Narmada basin, the density of the natural vegetation increases eastward. A number of National parks and Sanctuaries are present in the basin (CPCB, 2001).

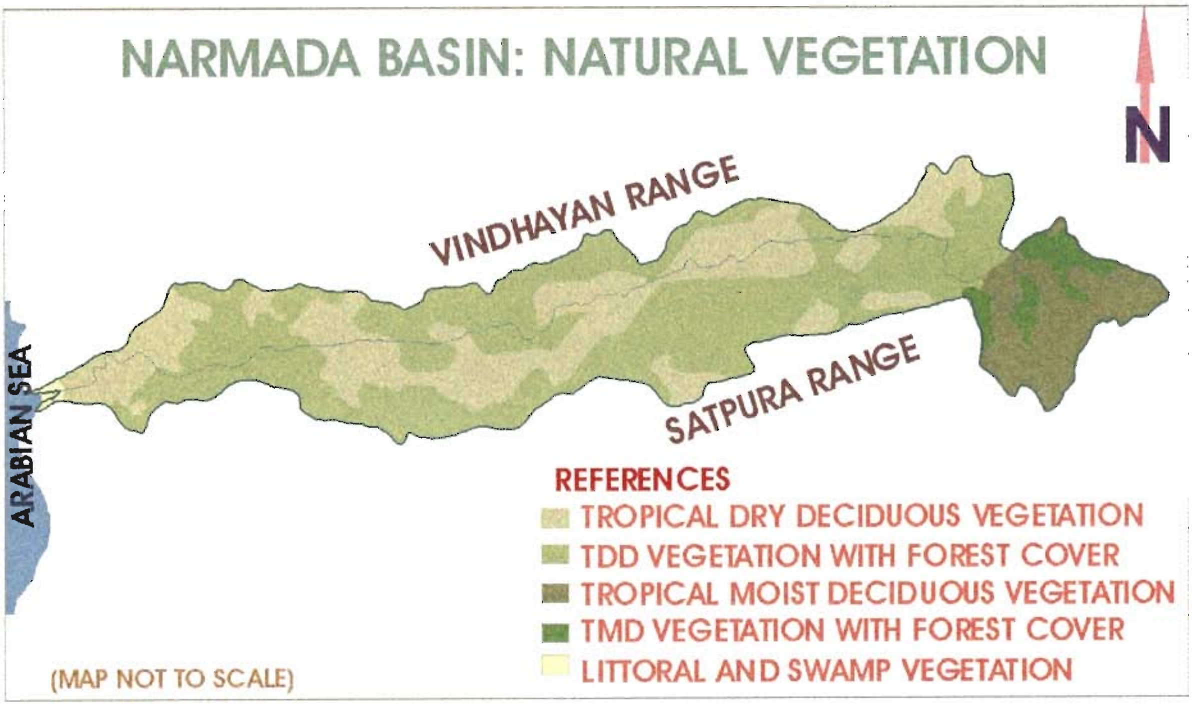


Fig. 2.7 Type and extent of natural vegetation in the Narmada river basin (modified after CPCB, 2001)

2.6 LAND USE

The Narmada basin can be divided into three broad classes - two as major (arable land and forests) with irregular distribution and the less abundant scrub and grasses (Fig. 2.8). Approximately, 35, 60 and 5% of the basin are under forest cover, arable land and scrub and grassland respectively. The hill slopes with thin soil cover and dissected plateaus are main areas under forest cover. The upper, middle and the lower plains are broad and fertile and well suited for cultivation. The area covered by scrub and grass are very limited and exist in the areas of the lower-middle parts (Dhar and Barwani districts of Madhya Pradesh) of the basin with scanty rainfall and thin soil cover (CPCB, 2001)

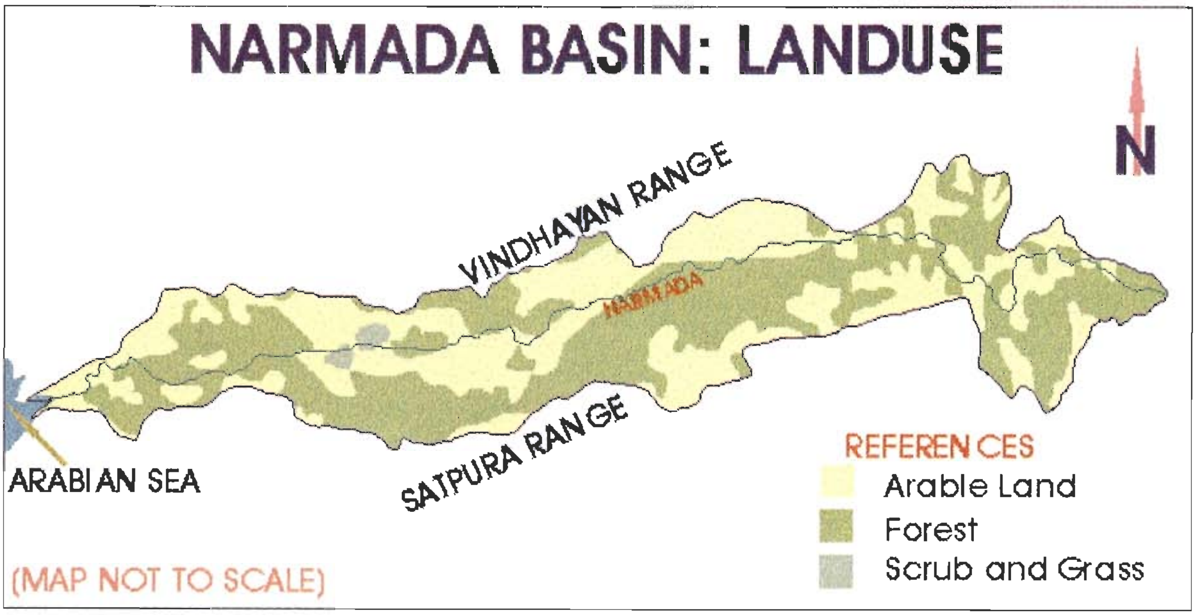


Fig. 2.8 Land use in the Narmada river basin (modified after CPCB, 2001)

2.7 MINERAL RESOURCES

Some of the important mineral resources in the basin area are bauxite, clay, coal, dolomite, graphite, iron ore, manganese ore, talc and limestone etc (CPCB, 2001)

2.8 GROUNDWATER RESOURCES

The groundwater map (Fig. 2.9) shows potential groundwater resources (per thousand persons, unit - 10^6 m^3) in different parts of the Narmada river basin. Groundwater availability in the Narmada basin varies from 200 to >1400 $\times 10^6$ m^3. The occurrence of ground water generally depends upon rainfall, drainage, topography and geological conditions. Groundwater in upper, middle and, lower basin occurs in distinct horizons with characteristic aquifers (CPCB, 2001).

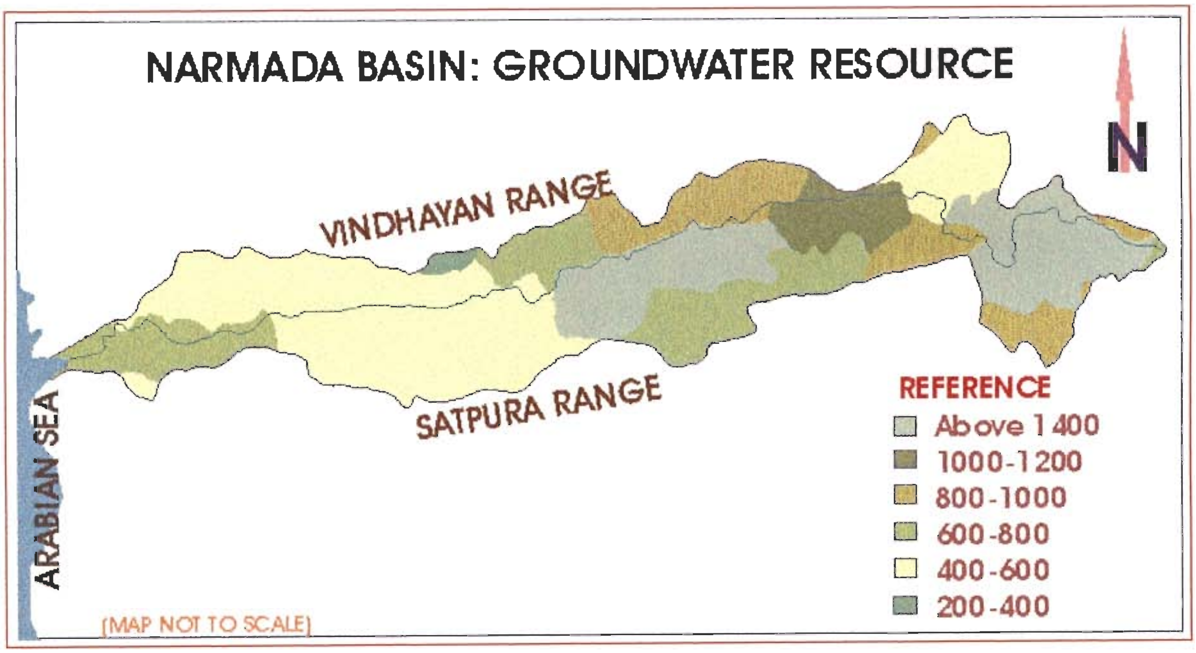


Fig. 2.9 Ground water resources ($\times$ 10^6 m^3) in the Narmada river basin (modified after CPCB, 2001)

In the upper part of the basin, the geological formations are mainly the older rocks belonging to the Archaeans and Vindhyans and are characterized by good water potential. Ground water within part of the basin occurs mainly in the weathered zones of the rocks. In the middle part of the basin, where Gondwana rocks are predominant, ground water occurs in varied quantities in the pores of sandstones. In the coarse grained rocks, the ground water availability is substantial. However, in sections of the basin, where the trap rocks are exposed, the ground water conditions are rather erratic. Similar to the Deccan basalts of west-central India (Kulkarni et al. 2000), basalts in the Narmada river basin are hydrogeologically inhomogeneous. A significant part of the lower basin is occupied by trap basalts, where ground water occurs in patchy aquifers. However, near the mouth of the river, the coastal alluviums are predominant. The coastal alluviums contain highly permeable aquifers with good quantities of water. Their yield is generally excellent, and with good recharges characteristics. Ground water in this area occurs mainly in unconfined aquifers at varying depths. However, ground water in alluvial plains is susceptible to seasonal water table fluctuations (http://www.cgwbmp.nic.in)

A number of small springs occur along the course of Narmada river between Jabalpur and Narsimhapur. The origin of these springs may be attributed predominantly to tectonic movements. Concurrence of availability of water at shallow depths and presence of faults due to tectonic disturbances may be the reason for occurrence of a number of springs in between Jabalpur and Narsimhapur. Naik et al. (2002) reported the presence of springs in the Western Ghats and suggested that geologic control, particularly the physiographic/geomorphic setting, is the important factor in the origin of these springs.

2.9 SOILS

Due to diversity of parent rock materials, variation in the climatic condition and soil forming processes, soils in the Narmada basin show diverse characters (Table 2.3). Fig. 2.10 shows the spatial distribution of these different soils in the basin (CPCB, 2001).

Table 2.3 Soil types and characteristics in the Narmada river basin

Soil	Soil Characteristics
Black soils (average depth: 100-300 cm)	Erosional products of the trap basalts, cover a large portion of the basin, dark in colour due to high contents of humus, calcium, magnesium carbonates and iron oxides and are rich in smectite clays having a high water holding capacity,
Lateritic soils (average depth: below 25 cm)	Contain ferruginous aluminous elements, formed in regions of heavy seasonal rainfall accompanied by high temperature conditions, result of intense chemical leaching of basalts, poor in phosphorus, potassium, calcium and nitrogen, reddish in colour due to presence of iron oxides, intense leaching due to good drainage, lack in nutrients
Red soil (average depth: 25-50 cm)	Red soils, formed by weathering of the ancient crystalline and metamorphic rocks, found in areas of low rainfall and high temperature, less leached, red colour due to high iron content, poor in nutrients and calcium content.
Alluvial soils (average depth: above 300 cm)	Formed through the process of deposition of sand, silt and clay etc. in layers, abundant in the upper-middle and coastal part of the basin,

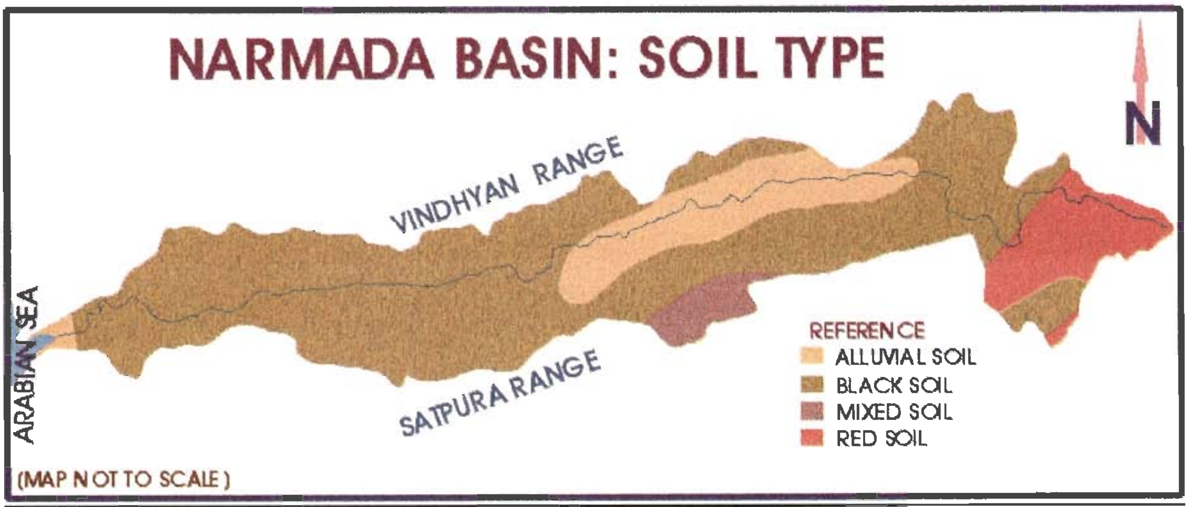


Fig. 2.10 Spatial distributions of various soils in the Narmada river basin (modified from CPCB, 2001)

2.10 GEOLOGY

The rocks in the Narmada basin range in age from Archaean to Recent and can be divided into three following broad divisions, (i) Pre-collision rocks, (ii) Post-collision rocks and (iii) Suites of younger rocks. The spatial distribution of the litho-units is shown in the geological map of the Narmada basin, India (Fig. 2.11).

The pre-collision rocks of the northern tectonic block of the Narmada basin include the Basement Gneisses, Geenstone Belts, Aravalli Supergroup, Bijawar Group and Susar Group, whereas the pre-collision rocks of the southern tectonic block consist of Amgaon gneisses, Malanjkhand pluton, Sakoli Group, Nandgaon volcanics, and Chilpi group of rocks. The post-collision rocks of the area include the Vindhyan sediments of the northern tectonic block. The suites of younger rocks include Gondwana rocks and Deccan basalts and Quaternary Alluvial. A significant portion of the Narmada basin is composed of Quaternary Alluvial, which occur in two separate regions, in the upper-middle Narmada valley (Great Plains) and, (ii) alluvial reach in the lower Narmada valley (Coastal Plains). Table 2.4 presents a brief description of these rock formations.

The stratigraphy of the Narmada basin, worked out from the stratigraphic sequence of Son-Narmada-Tapti Zone, is presented in Table 2.5. The stratigraphic sequence of the Son-Narmada-Tapti Zone has been established on the basis of field relationships, tectonic setting of the basins and available geo-chronological data (CURMANSONATA, 1995).

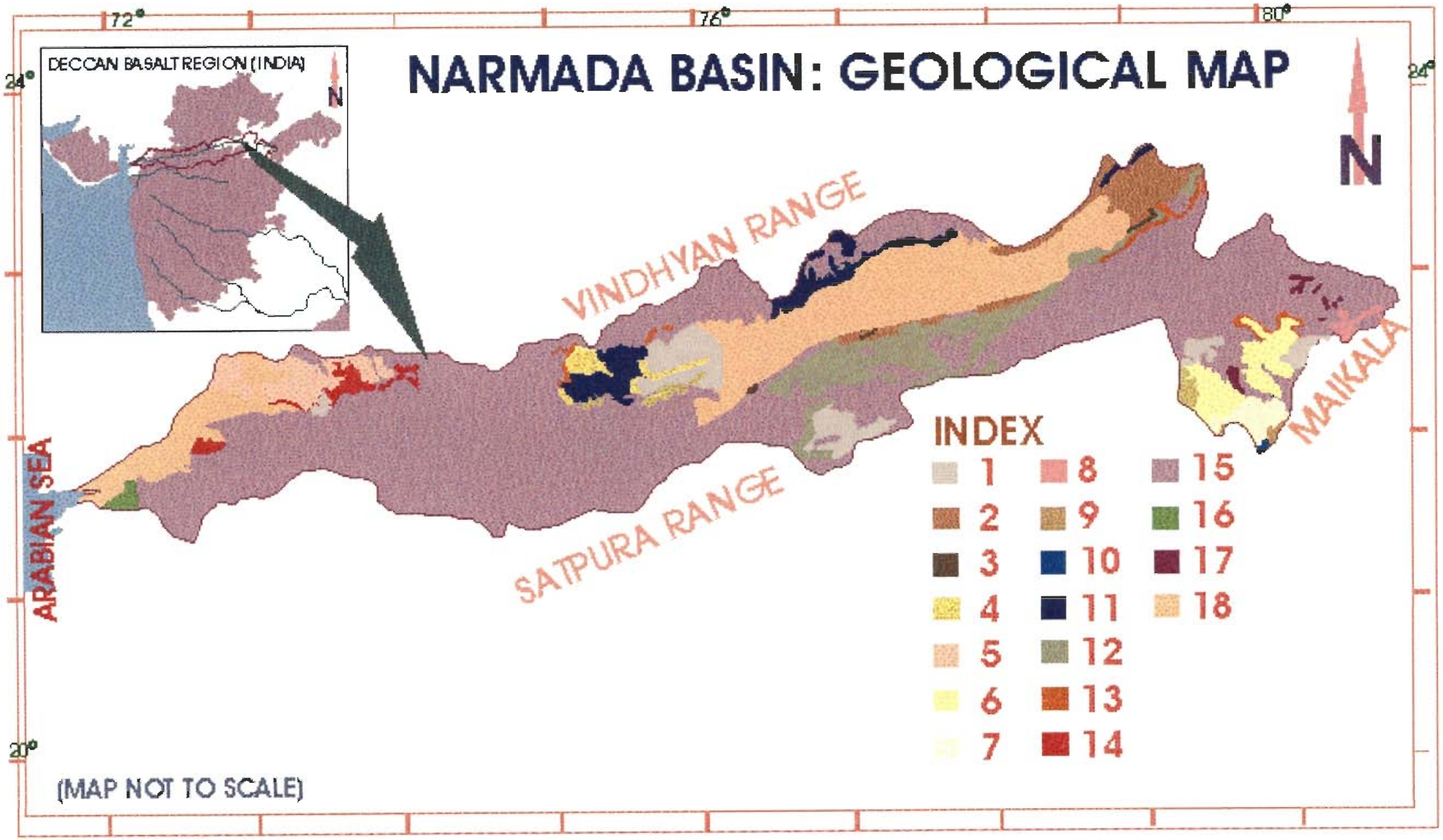


Fig. 2.11 Lithological map of Narmada river basin

Description of Index-(1) Unclassified gneiss and granites (2) Mahakoshal Group (3) Madanmahal and equivalent granites (4) Bijawar Group (5) Aravallis of Jhabua area (6) Sausar Group (7) Malanjkhand granite and equivalent (8) Nandgaon Group (9) Chilpi Group (10) Nandgaon Group (11) Vindhyan Supergroup (12) Gondwana Supergroup (13) Lameta Sediments (14) Bagh Sediments (15) Deccan Basalt (16) Tertiary Rocks (17) Laterite and Bauxite (18) Quaternary Alluvium

Table 2.4 Description of various litho units in Narmada basin (CURMANSONATA, 1995)

Rock formations	Lithology and important features
Unclassified Gneisses and Granitoids	Shows difference in composition, nature and occurrence, considered as the oldest formation, undifferentiated granitic gneiss may be remnants of primitive sialic crust
Mahakoshal Greenstone Belt	Characterized by basic metavolcanics, pyroclastics, clastics and chemical precipitates, with several post-tectonic granitic plugs, syenite bodies, ultramafic plugs and a wide variety of alkaline intrusives. greenstone association of typical continental rift set-up.
Madanmahal and Equivalent Granites	Occur as granite (stocks and bosses) intrusions
Bijawar Group	Mainly consist of quartzite, sandstone and conglomerate
Aravallis of Jhabua area	Characterized by wide variety of lithologies including hornblende gneisses, carbonaceous phyllite, chlorite phyllite and schist, marble, dolomite and calc-silicate rocks, banded magnetite quartzite/quartzite, interbedded metabasic rocks, ultramafic intrusives.
Sausar Group	Largely of sedimentary origin, subsequently metamorphosed and invaded by acid and basic plutonic rocks. Hornblende granulites, manganiferous marbles, gondites, calciphyres, quartzite and quartz schists are the dominant rocks
Malanjkhand Granite and Equivalent	Occurs as major granitoid batholith exposed for over 1400 km^2 in the central part of the Son-Narmada-Tapti Zone, almost juxtaposed with the Central Indian Suture Zone.
Nandgaon Volcanics	Volcanic and volcanoclastic rocks represented by tuffaceous conglomerate, agglomerate, crystal tuffs, andesitic basalt and rhyolites.
Chilpi Group	Include volcanic, volcanoclastic sequence comprises mainly chlorite phyllites and chlorite-sericite phyllites with banded jaspathic cherts.
Amgaon Gneiss:	Migmatitic gneisses (granodioritic in composition comprising mainly quartz, feldspar and biotite) and carry enclaves of metasediments interbedded with metabasalts
Vindhyan Supergroup of rocks	Vindhyan Supergroup consists of thick sedimentary pile comprising sequence of sandstone and shale in almost equal proportion with subordinate limestone.
Gondwana Rocks	Represented by thick series of shallow water, fluviatile and lacustrine sediments. Main rock types are sandstones, shales, clays, conglomerates and coal seams.
Lameta Sediments	Lameta beds of fresh water origin, consisting of limestones, sandstones, clay and shales.
Bagh Sediments	Marine Cretaceous deposits, lithology differs, in different outcrops, generally it starts with a gritty-sandstone which grades to calcareous sandstone.
Deccan Basalt	Tholeiitic nature of the lavas, markedly oversaturated to marginally under-saturated character. Along with the quartz-normative composition, a number of the flows are also olivine normative.
Tertiary Rocks	Characterized by various types of fossiliferous limestone, sandstones, clays and characteristic agate conglomerate beds.
Laterite Formations	Weathered products of basalt and formed due to the leaching of silica, alkalies and alkaline earth whereas alumina, iron, manganese and titanium remains as residue.
Quaternary Alluvium	Composed chiefly of reddish, brownish and yellowish clay with numerous intercalated bands of silt, sand and gravels.

Table: 2.5 Stratigraphic formations in the Narmada river basin (CURMANSONATA, 1995)

PHANEROZOIC			Quaternary/Recent Alluvium	
			Laterite	
			Deccan Traps and associated intrusives	
			Lameta Group	
			Bagh Group	
		Gondwana Supergroup	Jabalpur Formation	
			Mahadeva Formation	
			Lamprophyre	
			Damuda Group	
PROTEROZOIC	UPPER / MIDDLE	Vindhyan Supergroup	Bhander Group	
			Rewa Group	Acid intusives (Satpura region)
			Kaimur Group	
			Northern Tectonic Block	**Southern Tectonic Block**
			Intrusive granites (Satpura region)	Chilpi Group Malanjkhand and equivalent granitoids; Nandgaon Group
			Aravalli Supergroup	
	LOWER		Sausar Group, Bijawar Group, Madan Mahal and equivalent granites of Mahakoshal Belt	Sakoli Group
			Mahakoshal Group	
ARCHAEAN			Unclassified gneisses and granitoids	Amgaon Group (gneisses, meta-sediments and metavolcanics)

2.11 DAMS

A number of dams have been constructed on the Narmada river and its tributaries, mainly for the purpose of electric power generation, irrigation and for controlling floods in the basin. More than 4000 water related projects of various scales and purposes have been planned to be constructed in the basin. Bargi (Rani Avantibai Sagar), Barna, Indra Sagar, Kolar, Omakareshwar, Maheshwar, Bhagwant Sagar, Tawa and Sardar Sarovar dams are some of the major projects in the basin. Among the 30 large dams planned for the Narmada river basin, the Sardar Sarovar dam is the largest with a proposed height of 110.64 m and with a reservoir capacity of $3{,}700 \times 10^6$ m^3. The dam will be the third highest concrete dam (163 meters) in India. The other details of the Sardar Sarovar Reservoir/Dam are presented in Table 2.6 (http://www.sardarsarowardam.org).

Table 2.6 Key features of Sardar Sarovar Reservoir/Dam

◊	Length	214 km
◊	Full Reservoir Level (FRL)	138.68 m
◊	Minimum Draw Down Level	110.63 m
◊	Gross Storage	9500×10^6 m^3
◊	Live Storage	5800×10^6 m^3
◊	Annual Evaporation Loss	616×10^6 m^3
◊	Submergence at FRL	348.4 km^2
◊	Average width	1.77 km

2.12 POPULATION

The population density in the Narmada basin varies between 100-500 persons km^{-2}. Average population density in the basin is between 100-200 persons km^{-2}. Only a small part of the basin has a population density of more than 200 person km^{-2} (Fig. 2.12). Average population density in the basin is significantly lower than the Indian national population average of 324 person km^{-2}. Physiographic features and absence of large industries and metropolitan cities seems to be the main reason for low population density (CPCB, 2001).

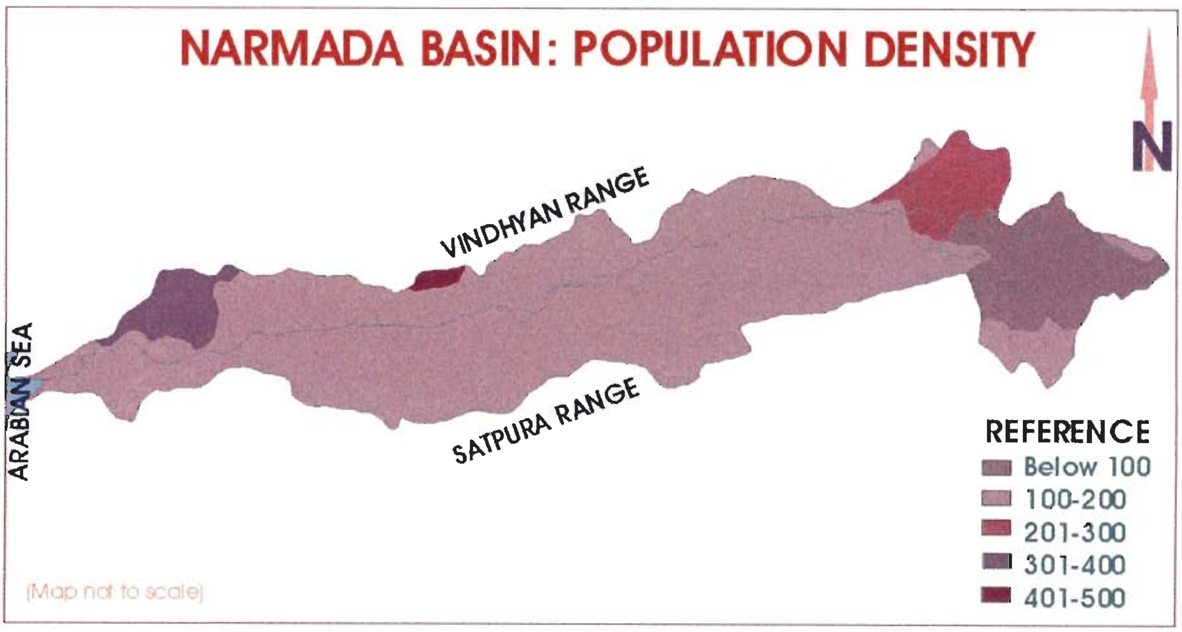


Fig. 2.12 Distribution of population density in the Narmada river basin (modified from CPCB, 2001)

2.13 FERTILIZER APPLICATION

The use of nitrogen, phosphorus and potassium (NPK) fertilizers in the Narmada river basin show large variations and vary between < 25 t and > 150 kg hectare^{-1} (Fig. 2.13). The fertilizer application in per unit area in the basin is lower than national average. In the hill regions, fertilizer application is least (< 25 kg hectare^{-1}), whereas in large parts of the basin, it varies from 25 to 75 kg hectare^{-1}. Only in a small part of the basin (in Gujarat/ Maharashtra) fertilizer application is more than 150 kg hectare^{-1} (CPCB, 2001). Approximately 86% area of the basin lies within the political boundaries of Madhya Pradesh. Fertilizer consumption in Madhya Pradesh during 1990-2001 is shown in Fig. 2.14. Fertilizer utilization has increased several folds since 1950, attaining peak consumption during 1997-2000, followed by a gradual decline (http://www.mp.nic.in/agriculture).

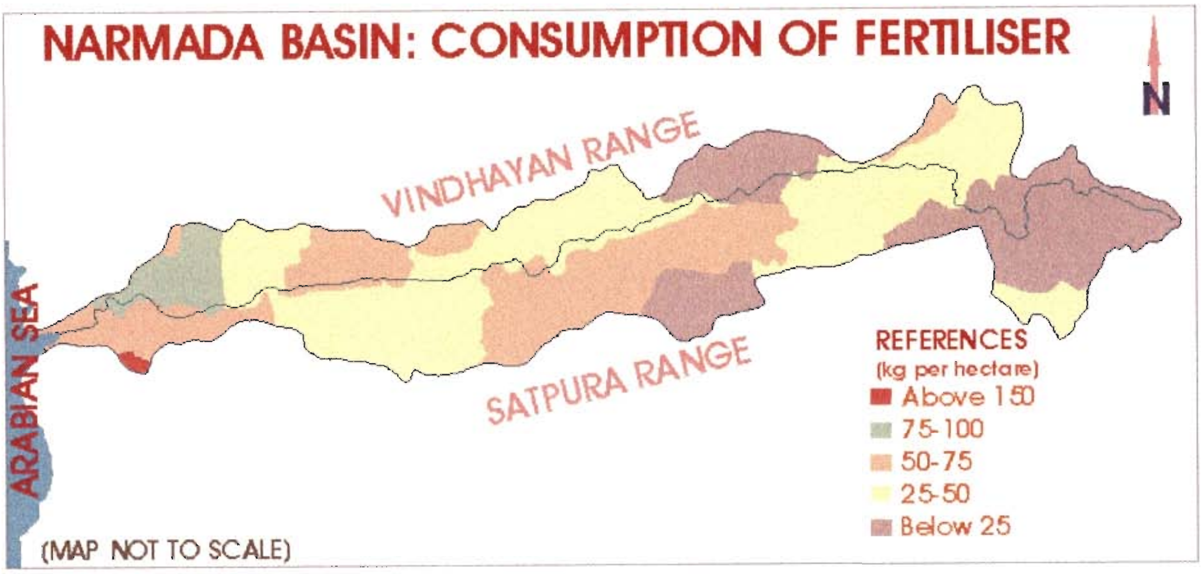


Fig. 2.13 Application of fertilizers in the Narmada river basin (modified from CPCB, 2001)

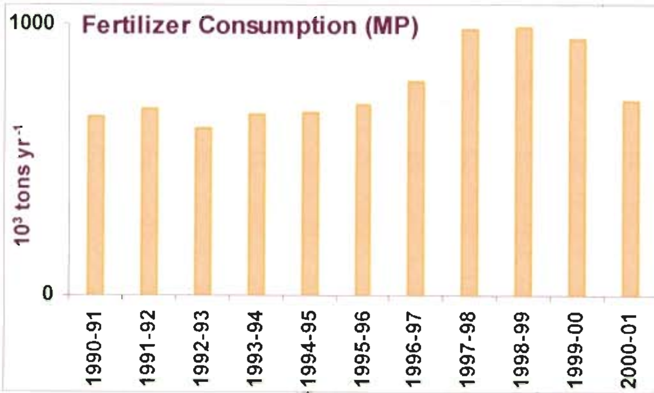


Fig. 2.14 Fertilizer (NPK) utilization in the administrative state of Madhya Pradesh (1990-91 to 2000-01) (http://www.mp.nic.in/agriculture)

2.14 SOIL DEGRADATION

The hilly regions (Vindhyan and Satpura range) of the basin are represented as stable terrain, whereas a large part of the basin is affected by the erosion due to running water, which causes moderate loss in top soil cover (CPCB,2001). The upper reaches of middle basin are characterized by the abundance of quaternary soils (Fig. 2.15), which are severely affected by the water erosion and lose a significant proportion of top soils during monsoon season. A significant proportion of the lower section of the middle basin (Hoshangabad to close to Punasa) is chemically deteriorated due to salinization of soils (CPCB, 2001).

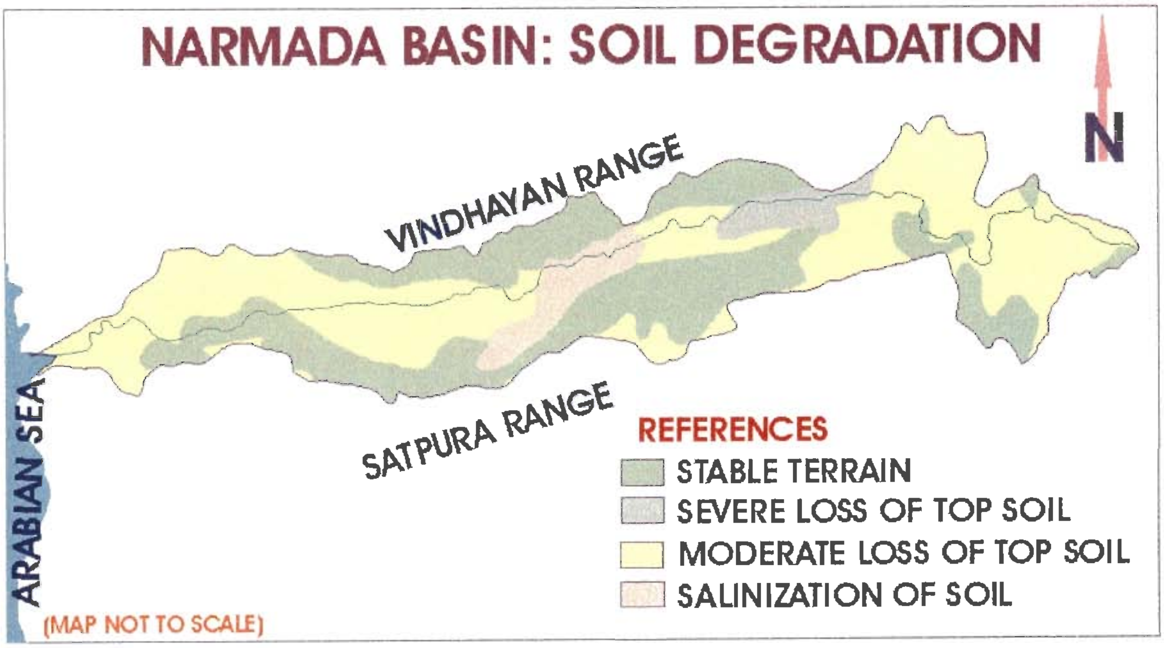


Fig. 2.15 Spatial distribution of degraded soils in the Narmada river basin (modified from CPCB, 2001)

Chapter 3

METHODOLOGY

Ion Chromatograph (Metrohm 792 Basic IC)

3.1 SAMPLING

Samples of river water, rain water and spring water and groundwater were collected from various locations along the Narmada river and its tributaries, covering various seasons. The samples were analyzed for various chemical parameters. To understand the water discharge and sediment load estimations, multiannual data for different locations were collected from Central Water Commission (CWC).

The river water samples were collected in four phases covering pre-monsoon season (May 2004), monsoon (August 2003 and September 2004) and post-monsoon seasons (January 2004). The sampling locations and details of seasonal samples collected during four phases are presented in Table 3.1. A total of seventy-three river water samples were collected, out of which, forty-five samples were from the Narmada mainstream and the remaining twenty-eight samples were from the tributaries.

Along with river water, a few spring water and ground water samples were also collected. During monsoon 2003 and 2004, thirty-six rain water samples were collected in pre-cleaned open buckets. Out of the thirty-six rainwater samples, six were collected during August 2003 and the remaining during June - September 2004. Rainwater samples during monsoon 2004 were collected with the help of CWC officials. These samples were collected in pre-cleaned polypropylene treys and collected rainwater samples were filled in cleaned polypropylene bottles of 100 ml capacity and stored in refrigerators. The analysis of rainwater samples for major ions was completed during the last week of September 2004 at Roorkee.

Table 3.1 Details of sample collection phases

S. No.	Sampling Location	Location Code	Collection of Samples (Yes-√ and No-×)			
			Aug 2003	Jan 2004	May 2004	Sept 2004
Narmada mainstream						
1	Amarkantak	N0	×	√	√	×
2	Dindori	N1	√	√	√	√
3	Manot	N2	√	√	√	√
4	Jabalpur SG	N3	×	×	√	√
5	Jabalpur BG	N3^	×	×	√	×
6	Barmanghat	N4	√	√	√	√
7	Sandia	N5	√	√	√	√
8	Hoshangabad	N6	√	√	√	√
9	Handia	N7	√	√	√	√
10	Mortakka	N8	√	√	√	√
11	Mandleshwar	N9	√	√	√	√
12	Rajghat	N10	√	√	√	√
13	Garudeshwar	N11	√	√	√	√
Major tributaries						
14	Mohgaon	T1	√	√	√	√
15	Bamni	T2	√	√	√	√
16	Patan	T3	√	√	√	√
17	Belkheri	T4	√	√	×	√
18	Gadarwara	T5	√	×	√	√
19	Chhidgaon	T6	√	√	√	√
20	Kogaon	T8	√	√	√	√
21	Chandwara	T9	√	×	×	√

^ water sample collected from upstream of marble rocks (Jabalpur BG)

The river water samples were collected from an approximate depth of 0.6 m from surface level. Mostly water sampling was done from mid-stream of the river with the help of boats or from bridges to avoid local heterogeneity and possible human influences near the river banks. Water samples were collected in pre-cleaned plastic (high density polypropylene) bottles of 1liter capacity and the bottles were copiously rinsed with the ambient river water before collection of samples. Enough care was taken to fill the sample containers completely to avoid any gas exchange. pH and alkalinity measurements were done just after the sample collection. The water samples were filtered within 24 hours of the sampling, through 0.45 μm Cellulose

Nitrate Membrane Filters (Sartorius) using manual operated Sartorius D-3400 SM 16510 filtering apparatus having a capacity of filter 250 ml. The filtered samples were divided in two separate aliquots. One aliquot (250 ml) was kept un-acidified to measure anions, major cations and dissolved silica whereas rest of the filtered sample was acidified (1% of high purity HNO_3) to measure strontium and its isotopic compositions. pH and alkalinity were measured in the field immediately after collection of samples and major cations and anions were analyzed within two-three weeks of collection of water samples. All the water samples were kept at refrigerated condition (4 ^{0}C) before analysis and were equilibrated with ambient temperatures prior to analysis.

3.2 ANALYSIS

Table 3.2 presents the details of analysis, including instruments and standards used. pH was measured in the field by a portable pH meter. The electrode was calibrated using buffer solutions. The accuracy of the pH measurement was ± 0.1 units. Titrations for measurement of alkalinity was carried out in the field wherever possible, by using micropipettes for addition of diluted HCl and by successive addition of HCl till the pH in the sample was reduced to 3.5. Alkalinity was calculated from Gran plots of acid consumption and pH change. A simple schematic flow chart of water analysis is shown in Fig. 3.1. A brief description of analytical methodologies is as follows:

3.2.1 Dissolved Silica: Silica in the river water was measured by using UV Spectrophotometer (GENESYS^{TM} 10 UV) using ammonium molybdate reagent at 410 nm wavelength (APHA, 1998). The duplicate analysis shows a precision of 2%.

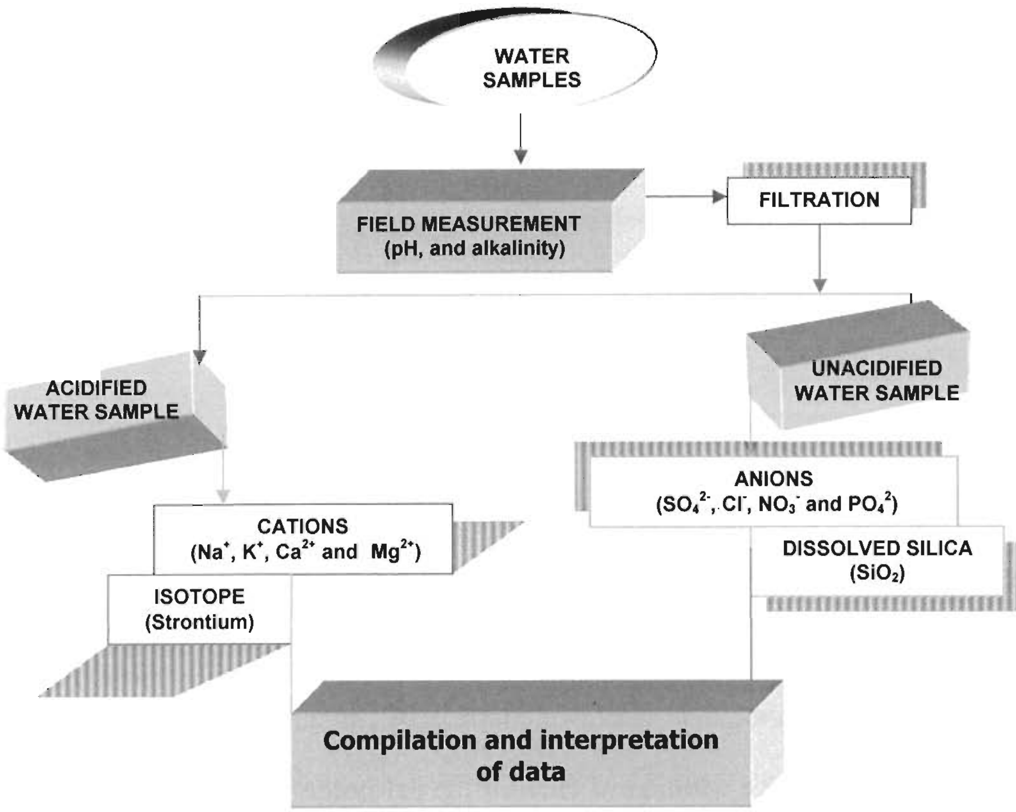


Fig 3.1 Simplified flow chart of analysis of water samples

3.2.2 Cations: The major cations (Na^+, K^+, Ca^{2+} and Mg^{2+}) in the samples collected during first two phases (August-2003 and January 2004) were analyzed using GBC Avanta Atomic Absorption Spectrophotometer (ASS). The accuracy of the measurement was checked by measuring freshly prepared standards of known concentrations made from analytical grade reagents. The water samples collected during last two phases were analyzed by Ion Chromatograph (Metrohm792 Basic IC with suppressor module). The system was calibrated using multi-element MDML standards (Metrohm). The eluent for cation analysis was prepared by adding 0.6 gm of tartaric acid with 0.167 gm of dipiclonic acid and dilute to 1000 ml. All of the analysis (ASS and IC) were replicated to check the precision in measurement and the precision was better than 5% in all of the cases.

3.2.3 Anions: The filter samples were analyzed for Cl^-, SO_4^{2-}, PO_4^{2-} and NO_3^-. For first two phases of sampling, Cl^- was measured by **mercuric nitrate** titration whereas $SO4^{2-}$, PO_4^{2-} and NO_3^- were measured by Spectrophotometeric method (APHA, 1998). For the samples of the last two phases of sampling, Ion Chromatograph was used to measure Cl^-, SO_4^{2-} and NO_3^-. The eluent for anion analysis was prepared by adding 0.3392 gm of sodium bicarbonate (Na_2CO_3), with 0.085 gm of sodium bicarbonate (Na_2HCO_3) and dilute to 1000 ml. The system was calibrated using multi-element standards prepared from analytical grade reagents. Internal check standards of different concentrations were run during analyses to check the accuracy of the measurement. Based on replicate analyses of different samples, the precision of measurement for anions were found to be better than 5%.

3.2.4 Strontium Isotopic Ratios: $^{87}Sr/^{86}Sr$ isotopic ratios were measured on Thermal Ionization Mass Spectrometric method (TIMS) by isotopic dilution. About 100 ml of filtered, acidified river water was taken in pre-cleaned FEP beakers and evaporated to near dryness. To the residue, about ~1 ml of HNO_3 acid was added and dried completely. The residue was converted to chloride-form with HCl and dissolved in 1.5 ml of 2N HCl. The solution was centrifuged in 1.5 ml tubes and 1 ml of the clear supernatant was loaded on the resin column. Sr was separated from the other interfering elements and Rb, by ion exchange chromatography. Separation was carried out in 6 mm ID silica glass columns containing Bio-Rad AG 50X8 (200-400 mesh) H^+ form cation exchange resin. Chemical separation was performed using HCl acid eluents. Samples were elueted with 2N HCL (29 to 42 ml). The extracted pure and concentrated Sr fraction was dried and thereafter dissolved in a few μl volume of 0.5N HNO_3. Typical sample loads were less the 500 ng of Sr on a single degassed filament with 1 μl of TaF_5 solution having 1% Ta in the solution. Methodology given by Choudhary et al. (2004) was followed in the whole procedure. Sr isotopes were measured in water samples using fully automatic variable collector mass spectrometer (TRITON T1), at Institute Instrumentation Center, IIT Roorkee. During the measurements, the Sr standard (SRM 987) was run repeatedly to check for accuracy and reproducibility. The ^{84}Sr (82.5%) solution was calibrated using gravimetric solutions prepared from NIST SRM 987 $SrCO_3$.

The concentrations of Sr in river, spring/groundwater and rain water samples were measured by inductively coupled plasma - mass spectrometer (ICP- MS) at IIC, IIT Roorkee. The instrument was calibrated with single-element standard solution prepared from analytical grade Sr $(NO3)_2$.

Table 3.2 Analytical details of water samples

Parameter	Instrument	Lab	Standard	Accuracy and Precision
pH	Ion Selective Electrode	In Field	Buffer Solution	With in 1%
Na^+, K^+, Ca^{2+} and Mg^{2+}	AAS	IIC,IITR	Lab Standard	Better than 5%
	Ion Chromatography (Metrohm792 Basic)	ES, IIT R	MDML Standards (Metrohm)	Better than 2%
Alkalinity	Ion Selective Electrode	In Field	----	Better than 1%
Cl^-	Titration	ES, IIT R	Lab Standards	Better than 5%
SO_4^{2-}, NO_3^- and PO_4^{2-}	Spectrophotometer	ES, IIT R	Lab Standards	Better than 2%
Cl^-, SO_4^{2-}, NO_3^- and PO_4^{2-}	Ion Chromatography	ES, IIT R	Lab Standards	Better than 2%
SiO_2	UV-Spectrophotometer	ES, IIT R	Lab Standards	Better than 2%
Sr concentration	ICP MS	IIC IITR	Lab standards	Better than 1%
$^{87}Sr/^{86}Sr$ isotopic ratios	TIMS	IIC IITR	NIST SRM 987	0.1% for Sr

(IITR: Indian Institute of Technology Roorkee, IIC: Institute Instrumentation Centre, ES: Earth Sciences Department)

3.3 MULTIANNUAL DATA COLLECTION

The multiannual data used in this study was obtained from Central Water Commission (CWC), an organization of the Ministry of Water Resources, Government of India. CWC has a large number of monitoring stations along Narmada river and its major tributaries for hydrological studies (Table 3.3). The details of the observation stations, procedures dealing with the sampling and analysis are given in CWC working manuals (CWC, 2000). All of the water quality data used show normalized charge balance (NICB) within ±5%.

Daily water discharge for three consecutive water-years (1996-1999) and daily sediment concentration/load data for 10 years (CWC 1990-2000) and annual water discharge and sediment load data for over 20 years (CWC 1978-2000) of Narmada basin were obtained from Narmada Basin Organization, Bhopal and Surat. In addition daily meteorological data for three water-years 1996-1999 and annual rainfall data of 33 water-years (1970-2004) and 10 water-years (1990-2000) for Rajghat and Mandleshwar respectively were also obtained. Similarly fortnight water quality data for eleven water-years (1990-2001) was collected. Sample locations with coded numbers and related information for both the sample collected during field trips and multi-annual data are presented in Table 3.4.

Table 3.3 Details of multiannual data

S. No	Locations	River	Multiannual data used in Present Study					
			water discharge		Sediment		Water Quality (fortnight)	Meteorological data
			Daily	Annual	Daily	Annual		
1	Dindori	Narmada	1996-97 to 1998-99	N/A	N/A	N/A	1990-91 to 2000-01	1996-97 to 1998-99
2	Manot	Narmada	1996-97 to 1998-99	1990-91 to 1999-2000	1990-91 to 1999-2000	1980-81 to 1999-2000	1990-91 to 2000-01	1996-97 to 1998-99
3	Jamtara	Narmada	1996-97 to 1998-99	1990-91 to 1999-2000	1990-91 to 1999-2000	1980-81 to 1999-2000	1990-91 to 2000-01	1996-97 to 1998-99
4	Barmanghat	Narmada	1996-97 to 1998-99	1990-91 to 1999-2000	1990-91 to 1999-2000	1980-81 to 1999-2000	1990-91 to 2000-01	1996-97 to 1998-99
5	Sandia	Narmada	1996-97 to 1998-99	1990-91 to 1999-2000	1990-91 to 1999-2000	1980-81 to 1999-2000	1990-91 to 2000-01	1996-97 to 1998-99
6	Hoshangabad	Narmada	1996-97 to 1998-99	1990-91 to 1999-2000	1990-91 to 1999-2000	1980-81 to 1999-2000	1990-91 to 2000-01	1996-97 to 1998-99
7	Handia	Narmada	1996-97 to 1998-99	1990-91 to 1999-2000	1990-91 to 1999-2000	1980-81 to 1999-2000	1990-91 to 2000-01	1996-97 to 1998-99
8	Mandleshwar	Narmada	1996-97 to 1998-99	1990-91 to 1999-2000	1990-91 to 1999-2000	1980-81 to 1999-2000	1990-91 to 2000-01	1996-97 to 1998-99
9	Rajghat	Narmada	1996-97 to 1998-99	1990-91 to 1999-2000	1990-91 to 1999-2000	1980-81 to 1999-2000	1990-91 to 2000-01	1996-97 to 1998-99
10	Garudeshwar	Narmada	1996-97 to 1998-99	1990-91 to 1999-2000	1990-91 to 1999-2000	1980-81 to 1999-2000	1990-91 to 2000-01	N/A
11	Mohgaon	Burhner	1996-97 to 1998-99	1992-93 to 1999-2000	1992-93 to 1999-2000	1992-93 to 1999-2000	1990-91 to 2000-01	1996-97 to 1998-99
12	Hirdaynagar	Banjar	1996-97 to 1998-99	1992-93 to 1999-2000	1992-93 to 1999-2000	1992-93 to 1999-2000	1990-91 to 2000-01	1996-97 to 1998-99
13	Patan	Hiran	1996-97 to 1998-99	N/A	N/A	N/A	1990-91 to 2000-01	1996-97 to 1998-99
14	Belkheri	Sher	1996-97 to 1998-99	N/A	N/A	N/A	1990-91 to 2000-01	1996-97 to 1998-99
15	Gadarwara	Shakkar	1996-97 to 1998-99	1990-91 to 1999-2000	1990-91 to 1999-2000	1980-81 to 1999-2000	1990-91 to 2000-01	1996-97 to 1998-99
16	Chhidgaon	Ganjal	1996-97 to 1998-99	N/A	N/A	N/A	1990-91 to 2000-01	1996-97 to 1998-99
17	Ginnore	Chota-Tawa	1996-97 to 1998-99	1990-91 to 1998-99	1990-91 to 1998-99	1986-87 to 1996-97	1990-91 to 1998-99	1996-97 to 1998-99
18	Kogaon	Kundi	1996-97 to 1998-99	N/A	N/A	N/A	1990-91 to 2000-01	1996-97 to 1998-99
19	Chandwara	Orsang	1996-97 to 1998-99	1990-91 to 1999-2000	1990-91 to 1999-2000	1988-89 to 1999-2000	1990-91 to 2000-01	N/A

Table 3.4 Hydrological parameters of sampling locations

S. No.	Station Code	Sampling Location	River/ Tributary	Latitude	Longitude	Elevation of station (m from MSL)	Drainage Area upto station (km^2)	Length of river upto station (km)	Rainfall (mm)	Temperature (mean, °C)
Narmada mainstream										
1	N0#	Amarkantak	Narmada	22°42'	81°42'	1057	N/A	8	N/A	N/A
2	N1	Dindori	Narmada	22°57'	81°05'	666.1	2,292	95	1493	23.0
3	N2	Manot	Narmada	22°44'	80°31'	451.6	4,467	218	1517	25.1
4	N3*	Jamtara	Narmada	23°05'	79°57'	371.5	17,157	389	1397	25.3
5	N3#	Jabalpur	Narmada	23°07'	79°48'	352.0	18,200	404	1397	25.3
6	N4	Barmanghat	Narmada	23°01'	79°00'	319.1	26,453	504	1241	25.3
7	N5	Sandia	Narmada	22°50'	78°21'	308.6	33,954	594	1150	25.3
8	N6	Hoshangabad	Narmada	22°46'	77°43'	292.1	44,548	676	1302	26.1
9	N7	Handia	Narmada	27°29'	77°00'	270.2	54,027	747	1124	27.9
10	N8#	Mortakka	Narmada	22°21'	76°02'	165	67,184	894	965	27.5
11	N9	Mandleshwar	Narmada	22°10'	75°39'	153.5	72,809	940	820	27.2
12	N10	Rajghat	Narmada	22°04'	74°51'	128.0	77,674	1015	636	26.9
13	N11	Garudeshwar	Narmada	21°53'	73°39'	31.2	87,892	1169	1123	27.0
Major Tributaries										
14	T1	Mohgaon	Burhner	22°45'	80°37'	447	4,090	177	1517	25.7
15	T2*	Hirdaynagar	Banjar	22°32'	80°23'	436	3,133	183	1528	24.1
16	T2#	Bamni	Banjar	22°29'	80°22'	N/A	1864	160	1528	24.1
17	T3	Patan	Hiren	23°18'	79°39'	500	4,795	188	1280	26.4
18	T4	Belkheri	Sher	22°54'	79°20'	650	2,903	129	1241	25.0
19	T5	Gadarwara	Shakkar	22°54'	78°54'	321	2,270	161	1268	27.8
20	T6	Chhidgaon	Ganjal	22°25'	77°20'	700	1,931	89	1148	29.1
21	T7*	Ginnore	Chota Tawa	22°10'	76°39'	218	4,816	169	987	27.8
22	T8	Kogaon	Kundi	22°06'	75°41'	900	3,973	120	820	25.9
23	T9	Chandwara	Orsang	22°01'	73°25'	18	3,846	101	631	27.0

* River water samples are not collected, only multiannual data is used for present work
# River water samples collected, multiannual data is not available; N/A Data not available

Chapter 4

RESULTS AND DISCUSSION

Tawa river (Largest tributary of the Narmada river) before confluence

4.1 WATER FLOW CHARACTERISTICS

The water flow characteristics of the Narmada river discussed in the succeeding sections are based on multi-annual data between 1980-2000 at nineteen locations (Fig. 4.1). The annual flux at different locations are estimated based on the multi-annual data of more than twenty water-years (21-29 years) for the Narmada mainstream (except Dindori; N1). The mean annual river runoff (per unit area) at a particular location is calculated from the mean annual flux and the catchment area upto location for the Narmada mainstream and tributaries whereas the runoff ratio is calculated from the mean annual river runoff and the average rainfall of the location. The mean monthly water discharge is calculated from the daily water discharge of three consecutive water-years (1996-1999). The mean discharge (monsoon (high flow), non-monsoon (low flow) and annual and monsoon contributions are calculated from data of ten water-years.

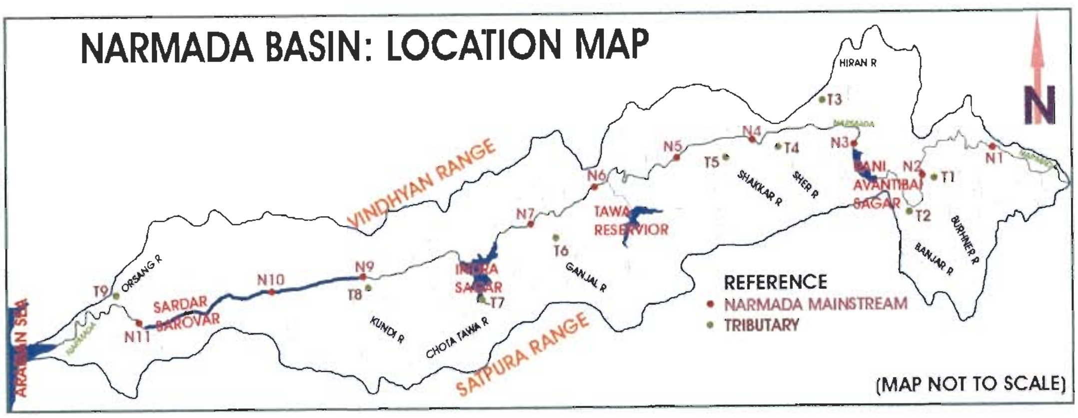


Fig. 4.1 Study locations on Narmada mainstream (N1 to N11) and tributaries (T1 to T9)

Time series of three consecutive water years (1996-1999) of daily water discharge at ten locations on the Narmada mainstream and nine locations on the tributaries are presented in Fig. 4.2 (A) and Fig. 4.2 (B) respectively. There is a significant temporal and spatial variation in water discharge, during different time periods in the Narmada river. Water discharge during five months of monsoon (June to October) show high peaks, as compared to discharge during non-monsoon, although a number of discrete peaks are also observed during non-monsoon. These discrete peaks are due to rains during retreat of monsoon and winter monsoon (locally known as 'mawath'). Similar to discrete peaks during non-monsoon, a large number of distinct plummet in monsoon season are also observed. Peaks and dips in water discharge show spatial variations among the different locations, depending upon rainfall distribution patterns and other local catchment characteristics (catchment area, soil properties, topography and vegetation cover). Lowest water flow in the river is observed during peak summer months of April, May and June. Time series plots of three consecutive years also demarcate the temporal discrepancy in water discharge patterns in the river flow. Rainfall in the basin is a major source of water to the river and hence it is a key controlling factor for water discharge. Depending on the amount of annual rainfall received in the basin, drought, flood or normal conditions prevail. The water-year 1997-98 observed good rains whereas, in the year 1996-97 rainfall was less, giving rise to high and low water discharge respectively. Discrepancies in rainfall periodicity, intensity and its distribution in the basin are other important aspects of monsoon rains, which consequently control water discharge patterns in the Narmada mainstream and its tributaries. Water discharge patterns at Jamtara (N3) are exceptionally regular as compared to upstream and downstream locations. This controlled flow indicates the influence of the presence of reservoir/dam over natural flow pattern of water. These controlled flows of water not only modify the seasonal water discharge, but they also amend the daily water flows. The time series plots in Fig. 4.2 (A), show continuous flow and indicate the perennial feature of the Narmada mainstream while time series plots for the tributaries (Fig. 4.2 B) are rather short, indicate the ephemeral nature of the tributaries, in which water flow is mainly confined to monsoon seasons.

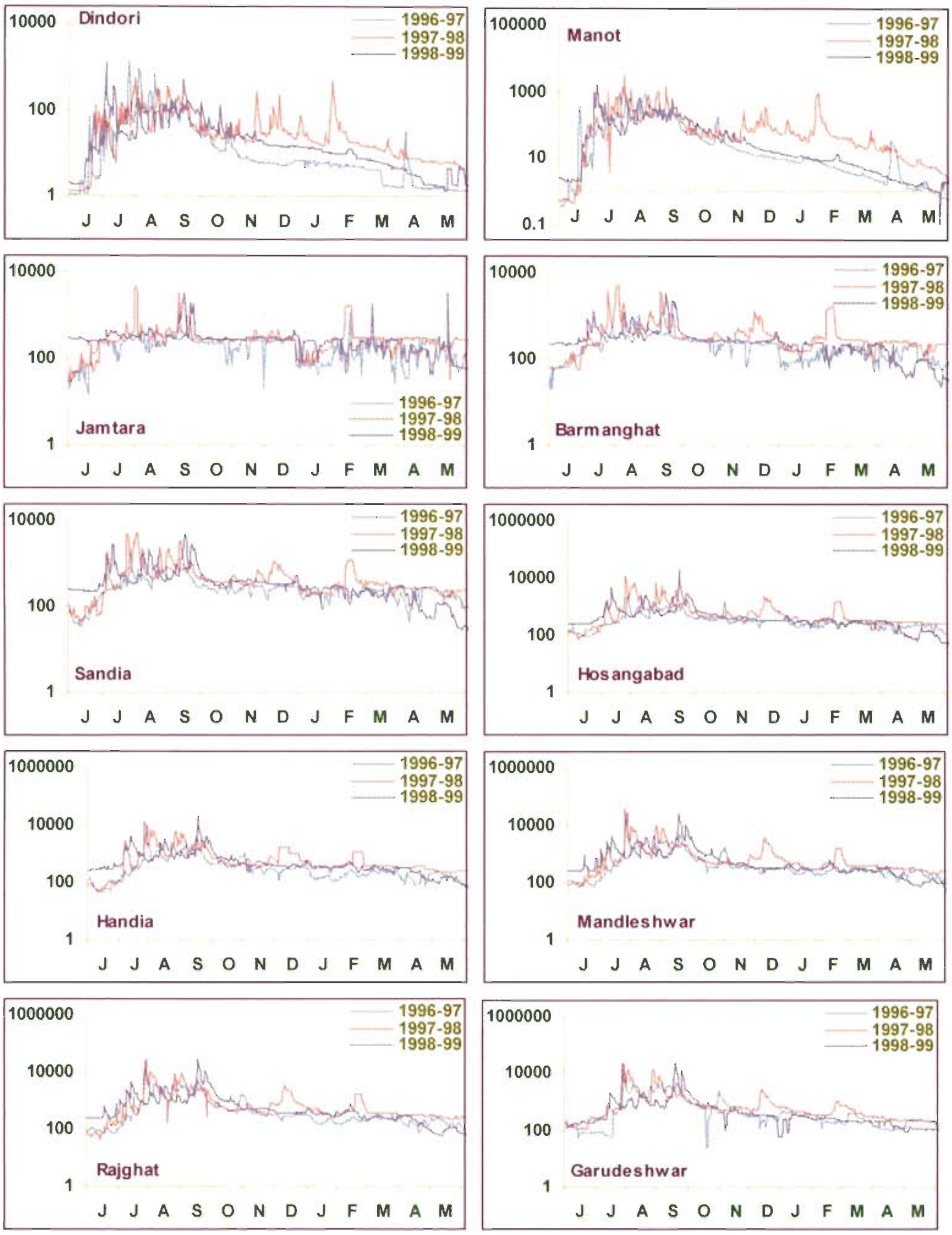


Fig. 4.2 (A) Daily water discharge plots of three consecutive water years (1996-99) for different locations on the Narmada mainstream (along downstream)

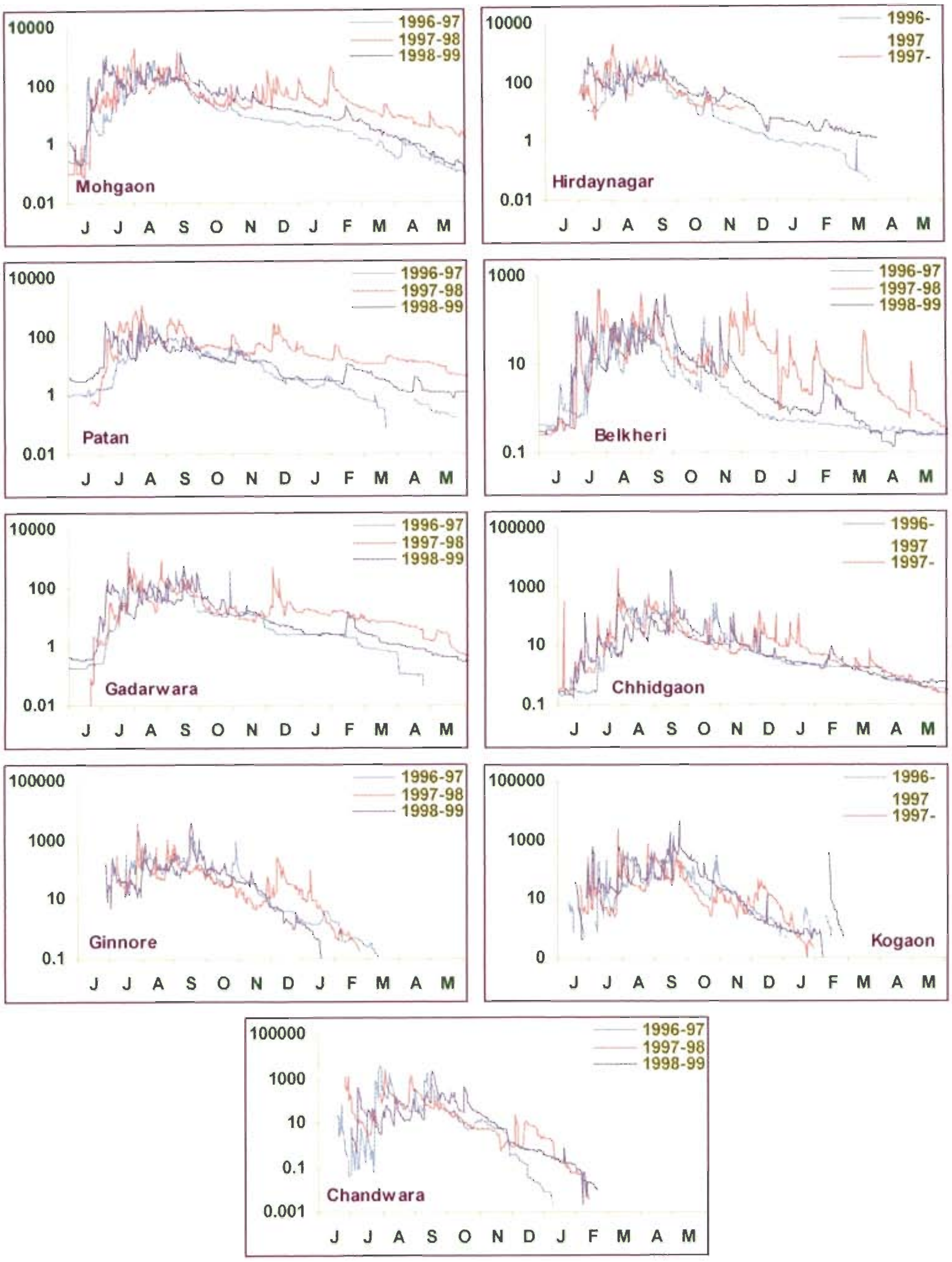


Fig. 4.2 (B) Daily water discharge plots of three consecutive water years (1996-99) for different locations on major tributaries (along downstream)

Temporal and spatial variations in water discharge in the basin span >1 order of magnitude. In a difference of a day, water discharge may vary more than hundred times. A few days of the monsoon season lead to huge water flows, which account for a significant amount of the annual water flow. Among the three water-years (1996-99) discussed here, highest water discharge is observed at Mandleshwar (N9) which is about 36000 m^3s^{-1} on 27 July 1997 and the day accounted for > 9% of annual water flux at the location. The maximum water discharge in the basin during last twenty-eight water-years (1973-2000) was observed at Garudeshwar, on 7 September 1994 with a flow of 60642 $m^3 s^{-1}$ (CWC, 1997-98). From ten water-years (1990-2000) data on daily water discharge of monsoon months suggest that, approximately 30 days of monsoon season make up about half of total annual water flow, especially in the upstream locations and the tributaries. Due to presence of large dams and their control over water flow, significance of a few days in high water flow becomes less noteworthy at the downstream locations. The role of a few days in water flow becomes significant in tributaries, because of their inability to store large quantity of water in small catchment areas.

Fig. 4.3 (A-D) shows the mean monthly water discharge in the river at four locations, representing upstream (Manot-N2), midstream (Hoshangabad-N6), downstream (Garudeshwar-N11) and one tributary (Shakkar river at Gadarwara-T5) from the middle of the basin. It is evident from Fig. 4.3 that water discharge is considerably high during July, August and September in contrast to other months and these patterns remain alike throughout the basin, suggesting that the monsoon discharge make the bulk of annual discharge (60 - 80%) and water discharge is influenced mostly by rainfall during monsoon months.

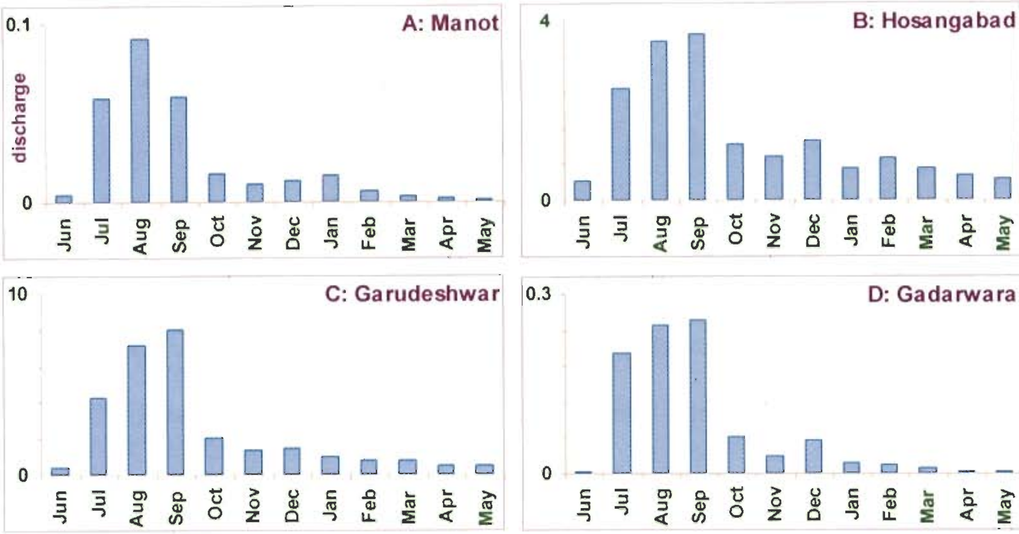


Fig. 4.3 Mean monthly water discharge (km^3) at four locations on the Narmada river

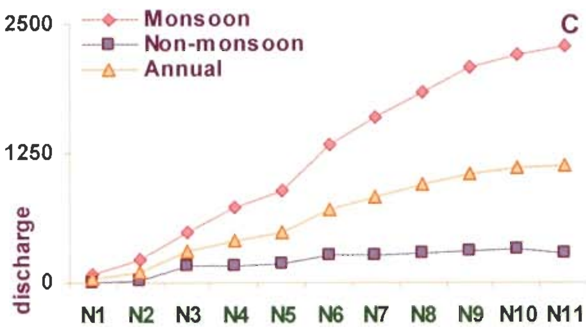


Fig. 4.4 Mean water discharge (monsoon, non-monsoon and annual) at different locations on the Narmada mainstream

Table 4.1 presents data of monsoon (high flow), non-monsoon (low flow) and annual water discharge and Fig. 4.4 shows a comparison of water flows at all locations on the Narmada mainstream. Water discharge (monsoon, non-monsoon and annual) shows temporal and spatial variations. Water discharge is considerably higher at upstream locations. The monsoon water flows are 12 (Dindori-N1) to 16 (Manot-N2) times more than the non-monsoon water flows. High ratios of monsoon to non-monsoon discharge at upstream locations indicate the influence of topography (basin relief) over water discharge. Average monsoon and non-monsoon flows are about 84 m^3 $s^{-1}$and 7 m^3 $s^{-1}$for upstream location Dindori (N1) and 2279 m^3 s^{-1} and 290 m^3 s^{-1} for downstream location Garudeshwar (N11). The water discharge ratio of monsoon to non-monsoon show large variations and vary from ~10 to over 100.

Table 4.1 Water discharge characteristics of the Narmada mainstream and major tributaries at different locations

Location	Daily Water Discharge (m^3 s^{-1})			Monsoon Contribution (% of annual water flux)	Flux (km^3 yr^{-1})	Runoff ratio	Runoff (mm)
	High Flow	Low Flow	Annual Mean				
Narmada mainstream							
N1-Dindori	84	7	1.24	90	0.64	39	540
N2-Manot	231	14	3.31	92	0.49	105	742
N3-Jamtara	491	152	9.27	70	0.39	294	540
N4-Barmanghat	722	165	12.6	76	0.38	398	475
N5-Sandia	887	191	15.2	77	0.39	483	448
N6-Hoshangabad	1330	255	22.2	79	0.38	706	499
N7-Handia	1603	271	26.2	81	0.43	829	484
N8-Mortakka	1841	292	29.7	82	0.46	941	442
N9-Mandleshwar	2085	308	33.2	83	0.56	1053	456
N10-Rajghat	2189	324	34.9	83	0.71	1106	449
N11-Garudeshwar	2279	290	35.4	85	0.36	1124	403
Tributaries							
T1-Mohgaon	156	8	2.20	93	0.39	70	538
T2-Hirdayangar	116	4	1.60	95	0.43	51	511
T3-Patan	104	11	1.58	87	0.26	50	329
T4-Belkheri	50	3	0.72	92	0.20	23	247
T5-Gadarwara	92	5	1.30	93	0.54	42	573
T6-Chhidgaon	70	4	1.00	93	0.45	32	518
T7-Ginnore	154	3	2.13	97	0.45	67	442
T8-kogaon	79	2	1.08	97	0.33	34	271
T9-Chandwara	109	1	1.50	99	0.64	46	391

4.2 WATER FLUX

Fig. 4.5 illustrates the water flux of the Narmada mainstream at different locations and contribution of the major tributaries. The details of the water flux at different locations on the Narmada mainstream are given in Table 4.1. The mean water flux in the Narmada mainstream varies between 1.2 $km^3\ yr^{-1}$ at Dindori (N1) to 35.4 $km^3\ yr^{-1}$ at Garudeshwar (N11) whereas individual contribution of the nine major tributaries discussed in the present study vary between 0.7 and 2.2 $km^3\ yr^{-1}$. The final flux (mean discharge) of the Narmada river to the Arabian sea is approximately 37 $km^3\ yr^{-1}$. The largest tributary in terms of water discharge is the Burhner river (with average water discharge of 2.2 $km^3\ yr^{-1}$). Other important tributaries are the Chota-Tawa river (2.1 $km^3\ yr^{-1}$), Hiran river (1.6 $km^3\ yr^{-1}$), Banjar river (1.6 $km^3\ yr^{-1}$), Orsang river (1.5 $km^3\ yr^{-1}$) and the Shakkar river (1.3 $km^3\ yr^{-1}$). Both the Chota-Tawa river and the Burhner river, originate from the Satpura range on the left bank of the mainstream of the Narmada River. The Satpuras, act as the main source of water to the river in its initial stages. The Narmada mainstream show a strong downstream increase in water flux, with significant contributions from the major and the minor tributaries throughout its journey to the Arabian sea (Fig. 4.1). Amongst the total of forty-one tributaries, nine major tributaries contribute nearly 40% of water flux of the Narmada river, while the other tributaries contribute 30% of water flux. Table 4.2 presents the water flux (km^3) of some of the tributaries during the water year 1999-2000 (NCA, 2003). Other important source of water is direct runoff from catchment area on either sides of mainstream at the time of rainfall.

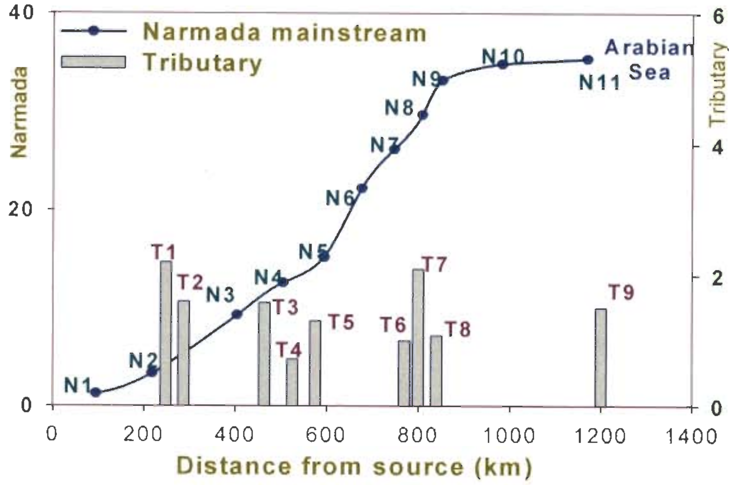


Fig. 4.5 Water flux (km^3 yr^{-1}) in the Narmada mainstream at different locations (primary Y- axis; N1 to N11) and contribution from the major tributaries (secondary Y-axis; T1 to T9)

Table 4.2 Water discharge by the tributaries during 1999-2000

River	Location	Water Flux (km^3)
Burhner	Mohgaon	2.94
Banjar	Hridayanagar	2.93
Hiran	Patan	2.98
Sher	Belkheri	1.50
Shakkar	Gadarwara	3.29
Tendoni	Maheshwar	1.43
Barna	Bareli	3.81
Ganjal	Chhidgaon	1.56
Jamer	Sandalpur	0.38
Ajnal	Hardakhas	0.28
Machak	Mandla	0.72
Choral	Choral dam	0.02
Kundi	Kogaon	0.72
Man	Ajandiman	0.44
Uri	Dhulsar	0.02
Goi	Pati	0.15
Udai	Dhadgaon	0.09

Fig. 4.6 shows the distribution of water flux during the monsoon and non-monsoon periods. It is evident from the figure that, the discharge during monsoon periods makes up bulk of annual flux. The southwest monsoon, prevailing mostly over June, July, August, September and October is the dominant source of water in the Narmada river basin. As a result, the annual flow pattern of the Narmada river is intimately tied to the southwest monsoon system. These observations are also true for other Indian rivers, such as the Brahmaputra river, Krishna, Cauvery, Godavari and the Mahanadi river (Gupta and Chakrapani, 2005). Discharge during the monsoon varies from 70 - 99% of total annual flow at different locations in the basin. The monsoon contributions for the Narmada mainstream vary between 70 - 92% (Fig. 4.6) whereas it varies between 87 - 99% for the tributaries. A large number of tributaries in the basin show either low flow or no flow conditions during dry periods. During a few days of non-monsoon season, the tributaries show sufficient discharge, due to the occasional rains and contributions from groundwater. The upstream locations (Dindori and Manot) on the Narmada mainstream show highest contributions during monsoon months, whereas Jamtara shows the least contribution. Jamtara (N3) shows highest non-monsoon flow, may be due to the presence of a big dam (Bargi dam) which controls release of water from the dam for irrigation and other purposes, and hence causes shift in natural water flow patterns. Similar to Bargi Dam, presence of a large number of dams across the Narmada mainstream and other tributaries control water flow during different time periods.

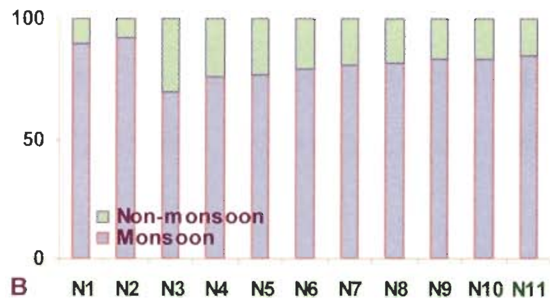


Fig. 4.6 Distribution of water flow among the monsoon and the non-monsoon periods (percentage of the annual flux) at different locations on the Narmada mainstream

The Narmada river shows large variations in the annual water flux. Fig. 4.7 shows annual water flux at nine locations (upstream to downstream) during twenty water years (1980-2000). Minimum, maximum and the average values of water flux show large variations. Large fluctuations are also observed between the different locations and different years. At Garudeshwar (N11), water flow was 73.5 km^3 (maximum discharge recorded with the existing data) in the years 1994-95, because of the high rainfall. In contrast to 1994-95, water flux in the year 1987-88 it was very low (15.0 km^3).

Runoff ratio represents the ratio of average river runoff (per unit area) to average rainfall (per unit area). According to Berner and Berner (1987) the world average value of runoff ratio is about 0.46, suggesting that about 50% of rainwater that reaches the ground is returned directly to the atmosphere by evaporation and never arrive at rivers. However, there is considerable variation in the runoff ratio for different continents, from a high of 0.54 in Asia to a low of 0.28 in Africa. Geographical location of the basin, local climate (temporal and spatial distribution of rains and temperature) and basin area are the important controlling factors. The Narmada river shows large spatial variations in runoff ratios (Table 4.1) at different locations. Runoff ratios at different locations on the Narmada mainstream vary between 0.36 and 0.71, whereas for catchment area of major tributaries it varies between 0.20 and 0.64. The runoff in the Narmada river varies between 247 mm to 742 mm. The highest runoff in the basin is observed at Manot (N2), whereas lowest runoff is observed at Belkheri (T4).

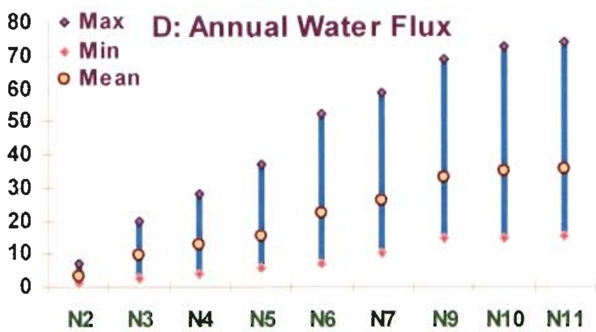


Fig. 4.7 Variations in the annual water flux (maximum, minimum and mean) at different locations on the Narmada mainstream

Although rainfall is the primary source of water to the Narmada river and its tributaries, the contributions from ground water can not be ignored. The Narmada river originates as a ground water seepage and many of the perennial flowing tributaries may also have their source from ground water. Hence, the contribution from groundwater may be the other potential source of water to the river particularly during the dry seasons. The seasonal variations in depth of groundwater and the availability of groundwater at shallow depths during monsoon season is an important contributing factor to the river water flow.

4.3 VARIATIONS IN SEDIMENT LOAD

Sediment transport characteristics in the Narmada river are investigated on the basis of daily sediment concentrations of ten water-years and annual sediment load data of 12 - 21 water-years depending on data availability, at nine gauging locations on the Narmada mainstream and five locations on five major tributaries. The study locations are shown in Fig. 4.8.

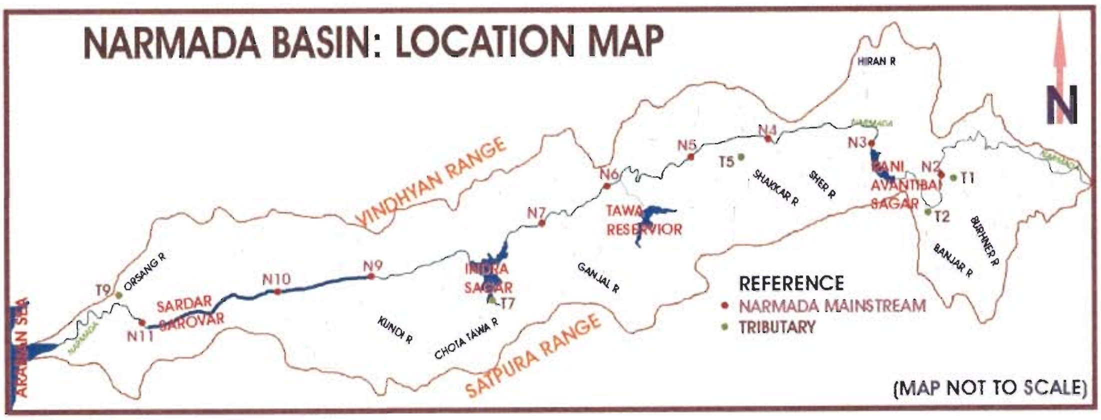


Fig. 4.8 Study locations for sediment load distribution

The mean annual sediment concentrations are calculated from the annual suspended sediment concentrations data of twenty water-years for the Narmada mainstream and maximum available data for tributaries. To observe temporal changes in the sediment concentrations during last two decades, sediment concentrations during 1980-2000 were calculated. To understand the role of monsoon rains in sediment transportations, the annual sediment data of ten water-years were used and average monsoon concentrations were estimated for all locations. Role of "a few days" in sediment transportations were understood from daily sediment concentration and load data of 8-10 water-years. To understand the influence of water discharge on sediment transportation (concentration and load), daily water discharge and sediment data of the water-year 1997-98 were used.

4.3.1 Daily Variations

The Narmada river shows large temporal and spatial variations in daily sediment concentrations and the variations are predominantly significant for monsoon period. Plot between daily water discharge and sediment concentration (water-year 1997-98), suggest that the sediment concentrations in the basin are intimately coupled with water discharge patterns (Fig. 4.9 A and B). It is observed that one fold increase in water discharge leads to 2-3 fold increase in sediment concentrations. The coarse and medium sized particles get transported during high water flow. The daily sediment concentrations in the basin during monsoon season for water-year 1997-98 range between almost nothing to 6513 mg l^{-1}. The lowest sediment concentrations are observed for the tributaries. The maximum sediment concentration (6513 mg l^{-1}) in the Narmada mainstream was observed at Handia (N7) on September 10th 1997, whereas among the major tributaries, the Shakkar river at Gadarwara (T5) observed highest sediment concentration (5000 mg l^{-1}) on July 30th 1997, followed by the Burhner river at Mohgaon (4311mg l^{-1}) on July 18th 1997. It is also observed that only "a few days" carry sediment concentrations of more than 1000 mg l^{-1}. The total number of days in a year, which show sediment concentrations > 1000 mg l^{-1} varies between 1 day to 40 days for different locations. Upstream locations Manot (N1) and Mohgaon (T1) are the two locations, which show higher number of days with high sediment concentrations and reflect the role of topography over sediment transport. In the middle part of the basin, the Narmada river drains over quaternary soils and shows an average of 20 days carrying >1000 mg l^{-1} sediment concentration annually. The maximum suspended sediment concentrations during the monsoon months in the river are observed during July, August and September and lowest suspended sediment values are observed during the months of February, March, April and May.

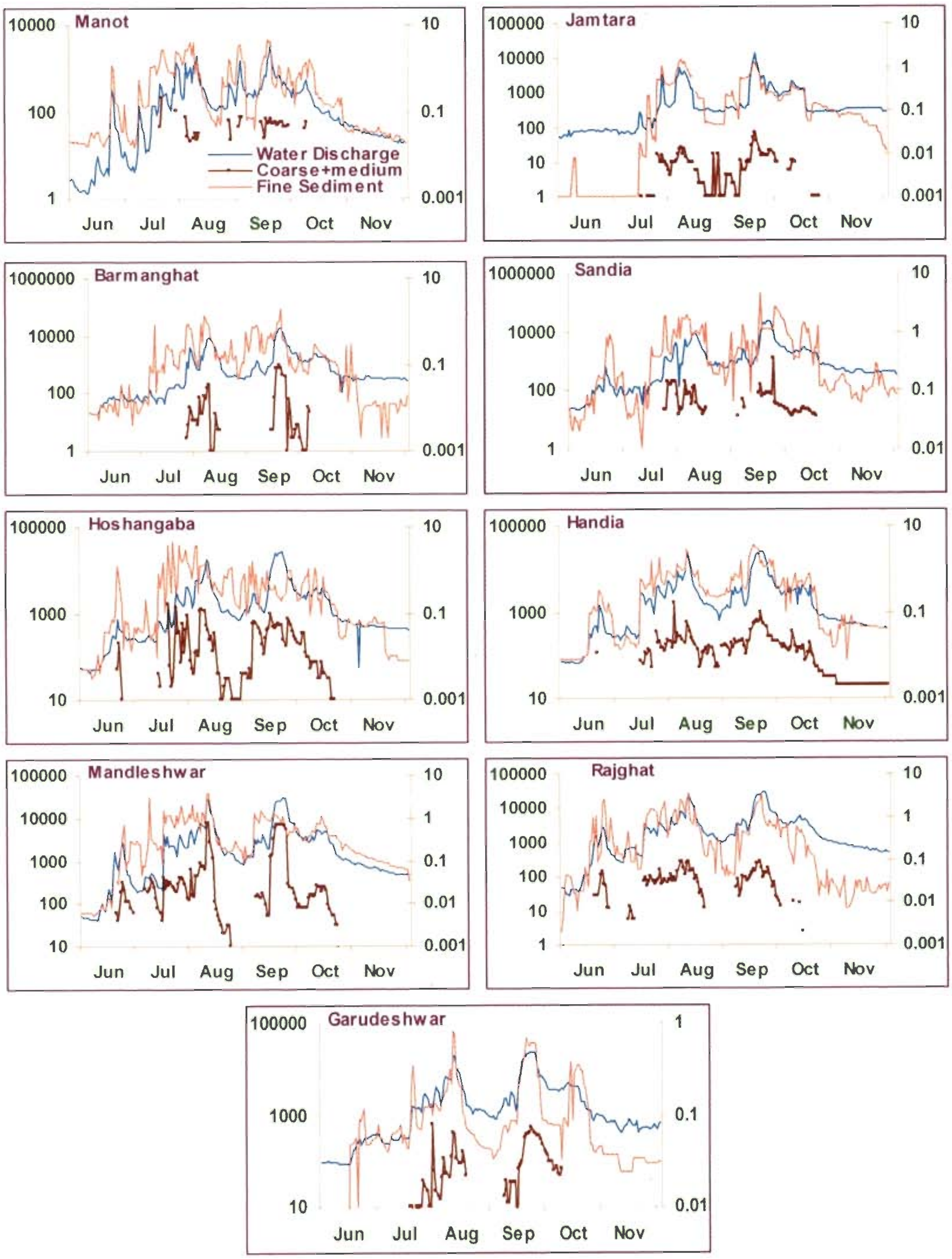


Fig. 4.9 A. Water discharge ($m^3 s^{-1}$) and associated sediment concentration ($gm l^{-1}$) during monsoon period at different locations on the Narmada mainstream (Water discharge-primary X- axis and sediment concentration-secondary Y- axis)

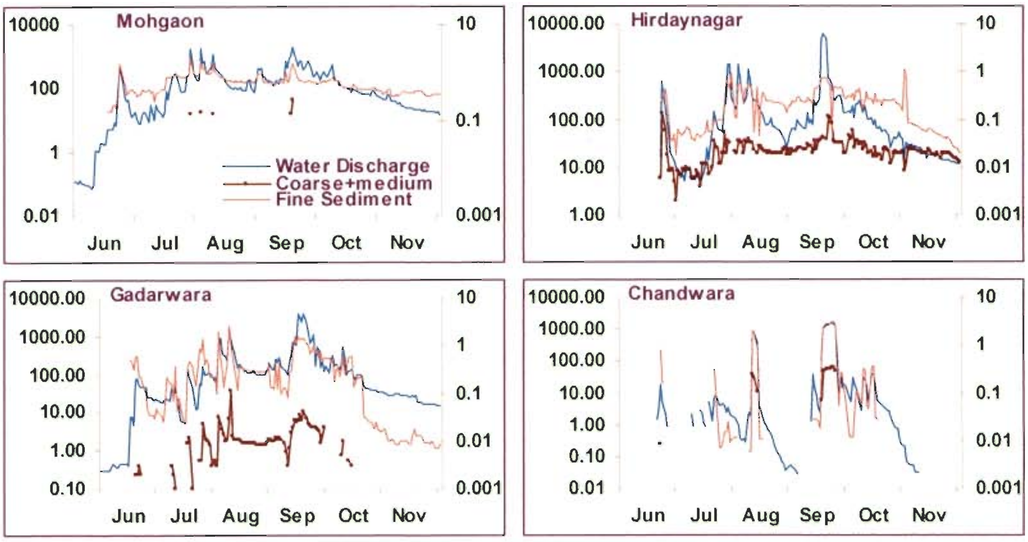


Fig. 4.9 B. Water discharge ($m^3 s^{-1}$) and associated sediment concentration ($gm\ l^{-1}$) during monsoon period at different locations on the tributaries (Water discharge-primary X-axis and sediment concentration-secondary Y- axis)

4.3.2 Decadal, Annual and Seasonal Variations

The "long term" sediment concentrations presents the average annual sediment concentrations over two decades and show conspicuous difference as sediment concentrations in the last decade reduced significantly compared to the decade 1980-90. The analysis of data of two decades (1980-2000) shows 6-50% changes. The mean concentration during last decade (1990-2000) varied between 215 -1703 mg l^{-1} for the Narmada basin. Mean concentrations vary between 215 and 1444 mg l^{-1} for the Narmada mainstream and between 534 and 1703 mg l^{-1} for the major tributaries. The highest sediment concentrations in the Narmada mainstream (1444 mg l^{-1}) are observed at upstream location Manot (N2), while downstream location (N3) shows the least sediment concentration (215 mg l^{-1}), due to trapping of sediments in Bargi reservoir/dam. The mid-stream locations (Barmanghat; N4) show appreciable increase in sediment concentrations (1000 mg l^{-1}). Afterwards upto

Handia (N7), the Narmada river shows, low sediment concentrations. From Jabalpur upto Handia, the river flows through quaternary sediments (Great Plains) of Hirdepur formation. The Hirdepur formation comprises grey homogenous calcareous silt, inter-layered sequence of grey calcareous silt and sand, coarse sand, gravel and conglomerates. This formation is characterized by abundance of silt and sand fractions and lacks in finer clay contents. (Tiwari and Bhai, 1997). Pre-quaternary laterite formations are also present in abundance in the middle portion of the basin. The laterites characterized by hydrous oxides of iron and aluminium become hard when exposed to air. Thus, it is not easily available for transportation by runoff. At Handia, the Narmada river shows an increase in suspended sediment concentration (1199 mgl^{-1}). The average suspended sediment concentration of the Narmada river (downstream to Garudeshwar) to Arabian Sea is 502 $mg\ l^{-1}$. Four tributaries, the Burhner, Shakkar, Chota-Tawa and the Orsang rivers, show relatively high sediment concentration (>1000 mgl^{-1}) whereas the Banjar river shows relatively low (534 $mg\ l^{-1}$) sediment concentration. Many of the tributaries are characterized by the dominance of easily erodible soils and rocks as compared to the resistant trap rocks. For example, the Burhner river drains red soils and lithology other than basalts, and the Chota-Tawa river drains rocks of Gondwana group and quaternary soils.

More than 90% annual sediment loads in the Narmada basin are transported during the monsoon season. Table 4.3 presents the mean monsoonal sediment concentrations of 1990-2000. The average monsoon sediment concentration at all fourteen locations are calculated using water discharge and sediment concentration data of monsoon periods of ten years (1990-2000). In locations downstream to dams, significantly higher concentrations during monsoon season are observed, due to release of large amount of water during high flood events associated with heavy rainstorms.

Table 4.3 Variations in sediment concentrations at different locations in the Narmada river (N/A: Data not available)

Code	Location	Mean Annual Sediment Concentration (mg l^{-1})			
		Long term	1980-1990	1990-2000	Monsoon (1990-2000)
Narmada mainstream					
N2	Manot	1756	1938	1444	1549
N3	Jamtara	359	399	215	493
N4	Barman	951	1159	1000	1220
N5	Sandia	766	970	892	973
N6	Hoshangabad	1050	1201	772	1288
N7	Handia	1189	1278	1199	1448
N9	Mandleshwar	1094	1250	1135	1309
N10	Rajghat	1191	1422	1088	1431
N11	Garudeshwar	817	979	502	935
Tributary					
T1	Mohgaon	N/A	N/A	1703	1765
T2	Hirdaynagar	N/A	N/A	534	479
T5	Gadarwara	1280	1215	1488	1261
T7	Ginnore	N/A	1253	1079	1348
T9	Chandwara	N/A	1076	1052	1082

Most of rivers in India are fed by the monsoon rainfall, which show that monsoon rains control the sediment discharge patterns of these rivers. During the six months (June to November) covering four months of monsoon period (June to September) July, August and September months observe bulk transport of sediment loads. The sediment discharge on 26th July 1997 at Hoshangabad (N6) was 23.01% of total annual loads, with the highest sediment concentrations (3749 mg l^{-1}) of season, whereas the on 25th and 27th July, it was 4.0 and 1.8% of total annual loads. Almost 70% of total sediment load during 1997-98 were carried only in seventeen days (July 25th to Aug 10th). Total sediment load of July, August and September 1997 accounted for 44.6, 38.9 and 6.2%, with a total of about 90% of annual loads. It is observed that "a few days" in the year carry > 1% of the annual sediment loads.

Table 4.4 presents the number of days with sediment loads of 1 - 10% and >10% of total annual loads for thirteen locations based on decadal data. The number of days with sediment loads 1 - 10% vary between 11 and 23 days and account for 34 - 65% of annual sediment loads, whereas the days with sediment load > 10% vary between 1 and 3 and account for 13 - 15% of the annual loads. Approximately, 70 - 90% of annual loads in the Narmada river are transported during 14 - 24 days. All of these days with high sediment loads correspond to monsoon season. It is interesting to note that, on some instances, high sediment loads do not coincide with the days with sediment concentrations > 1000 mg l^{-1}. It is possible the days with low sediment concentrations and with high water discharge account for higher sediment loads. This observation is also true for some of the peninsular rivers such as, the Godavari (Biksham and Subramanian, 1988) and the Mahanadi rivers (Chakrapani and Subramanian, 1990) river basins. Meade and Parker (1985) observed in many rivers of the United States, that a large proportion of the sediment load is transported in only 'a few days", and calculated that more than one half of the annual sediment load is transported in only 5 or 6 days.

Table 4.4 Role of "a few days" in sediment transportation (load) in the Narmada basin

Code	Location	1-10% of annual loads		>10% of annual loads		Total		Total monsoon loads (%)
		Sediment load (%)	Days	Sediment load (%)	Days	Sediment load (%)	Days	
N2	Manot	56	18	23	1	79	19	94.5
N3	Jamtara	47	16	26	1	73	17	89.8
N4	Barman	64	23	18	1	81	24	93.9
N5	Sandia	65	22	17	1	82	23	94.6
N6	Hoshangabad	65	23	13	1	79	24	93.2
N7	Handia	56	21	21	2	78	22	96.72
N9	Mandleshwar	51	19	27	1	79	21	99.6
N10	Rajghat	52	19	27	1	79	21	98.7
N11	Garudeshwar	48	17	31	2	79	19	98.8
T1	Mohgaon	56	23	15	1	71	23	94.0
T2	Hirdaynagar	50	21	32	2	82	22	99.4
T5	Gadarwara	36	12	48	3	84	15	96.9
T9	Chandwara	34	11	57	3	90	14	100

4.3.3 Grain size of sediments

The relative contribution (in percentage) of different size fractions to the annual loads in the Narmada basin were calculated from the data of ten years (1990-2000) and presented in Table 4.5. Transport of coarse and medium size sediments (diameter above 0.075 mm) is more pronounced during monsoon season as compared to the non-monsoon, although >90% sediments are carried in finer sizes (< 0.075 mm). It is evident from Fig. 4.9 A and 4.9 B that the coarse and medium size particles are predominant during high water flow. Daily sediment concentration data of ten years, suggest that mostly days with sediment concentrations more than 1000 mg l^{-1} carry bulk of the annual loads are coarse and medium size. The tributaries seem to carry particles of higher grain size, which may be because of the high gradient. Average gradient in some important sub-basins are higher (Burhner - 0.0025, Banjar - 0.0085, Sakkar - 0.0036, Kundi - 0.0061 and Orsang - 0.0027) as compared to the mainstream (0.00072). This might be having an effect on erosion rates in the Narmada river basin. Two tributaries namely, the Banjar and the Chota-Tawa rivers contribute very high amount of medium (about 10%) and coarse (about 4%) sediments. In upper reaches, concentrations of coarse (about 2%) and medium (4%) size sediments are higher. The Chota-Tawa river is the largest tributary of the Narmada river and drains the easily erodible soils of quaternary origin and carries high sediment loads to mainstream. This is evidenced by the presence of maximum coarse (about 2%) and medium (about 3.84%) size sediments at Mandleshwar (downstream to confluence of the Chota-Tawa river) on the Narmada mainstream.

Table 4.5 Relative proportion (%) of various size fractions of suspended sediments in annual sediment loads and average annual sediment load at different locations in the Narmada river basin

Locations	Size fractions of sediments (%)			Avg. Annual Sediment Load ($\times 10^6$ tons)
	Fine (<0.075 mm)	Medium (0.075-0.2 mm)	Coarse (>0.2 mm)	
Narmada mainstream				
N2-Manot	94.8	3.5	1.7	5.9
N3-Jamtara	96.9	2.5	0.5	3.6
N4-Barman	94.9	4.0	0.9	12.0
N5-Sandia	96.1	2.6	1.2	12.8
N6-Hoshangabad	95.0	3.9	1.1	23.6
N7-Handia	96.5	2.9	0.6	32.5
N9-Mandleshwar	93.2	4.8	2.0	38.1
N10-Rajghat	95.9	2.4	1.8	42.6
N11-Garudeshwar	95.1	3.8	1.1	28.3
Tributaries				
T1- Mohgaon	95.9	2.8	1.3	3.8
T2-Hirdaynaga	84.4	10.9	4.8	0.9
T5-Gadarwara	93.5	5.7	0.8	1.7
T7-Ginnore	86.7	10.2	3.1	2.6
T9-Chandwara	97.6	1.6	0.8	1.6

4.3.4 Average sediment load

The annual sediment loads of the Narmada river vary from 3.33×10^6 tons to 41.5×10^6 tons, at different locations in the basin. The mean annual sediment loads at upstream location (Manot) are close to 5.83×10^6 tons whereas, it is about 28.9 $x10^6$ tons at Garudeshwar, location closest to the Arabian sea. The lowest and highest sediment loads are observed at Jamtara (3.33×10^6 tons) and Rajghat (41.5×10^6 tons). The arithmetic mean of total suspended sediment (TSS) for the past 20 years is shown in Table 4.5. Sediment loads from upstream to downstream show a significant increase, except at a few locations. The tributaries contribute significant amount of the TSS to the river throughout its course. In terms of annual loads, the Burhner river carries higher loads (3.8×10^6) followed by the Chota-Tawa river.

4.3.5 Coupling between water flow and sediment load

Logarithm of daily water discharge (m^3 s^{-1}) and daily sediment concentration (gm l^{-1}) data of ten years (monsoon season-June to Nov) at ten location on the Narmada mainstream shows a good linear relation (Fig. 4.10), indicating water discharge to be a major factor in the transport of sediments in the river. Several non-linear/linear relationships have been proposed to connect the two parameters. Woolhiser and Todorovic (1974) suggested that a linear relation exists between the logarithm of sediment load and the logarithm of peak discharge of the runoff from each rainstorm and that relation can be used to estimate annual sediment discharge for a basin. Singh and Chen (1982) developed a linear relation between the logarithms of sediment load and the logarithms of volume of direct runoff. It is apparent that a long-term data is needed to observe relations in water discharge and sediment load. For many rivers, functional relations between these two do not exist, because the sediment discharge is affected more by the supply of materials for transport than by the capacity of flow to transport it (Nordin, 1985). Goswami (1985) observed for the Brahmaputra river that suspended sediment loads increase more rapidly than water discharge, indicating increased concentration at higher flow. In Narmada river, increase in water discharge resulted in distinct increase in sediment load. For example, the water and sediment discharge on 28 July 1996 at Rajghat was 11.7% and 47.4% of the total annual discharges, whereas the water and sediment discharge on 27 and 29 July 1996 were 3.2% and 4.8% and 3.4% and 4.7%, respectively. A three-fold increase in water discharge resulted in ten-fold increase in sediment loads. A probable reason for the increase in high suspended sediments could arise because, once the water has been able to scour the channel, the sediments are in re-suspension stage for a considerable length of time and are not easily settled down because of the high sediment concentrations in water, which act as barriers for easy settlement of particles.

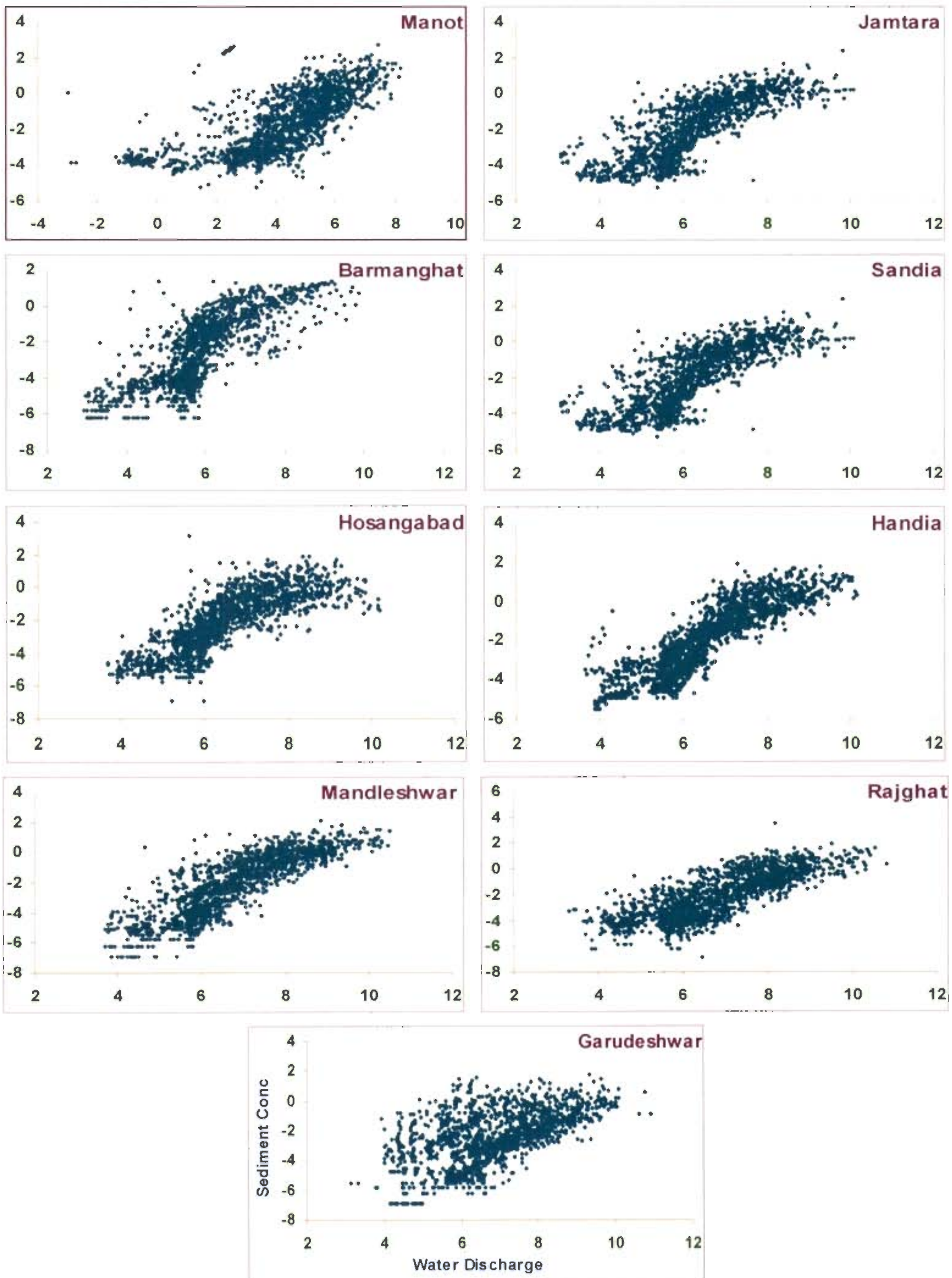
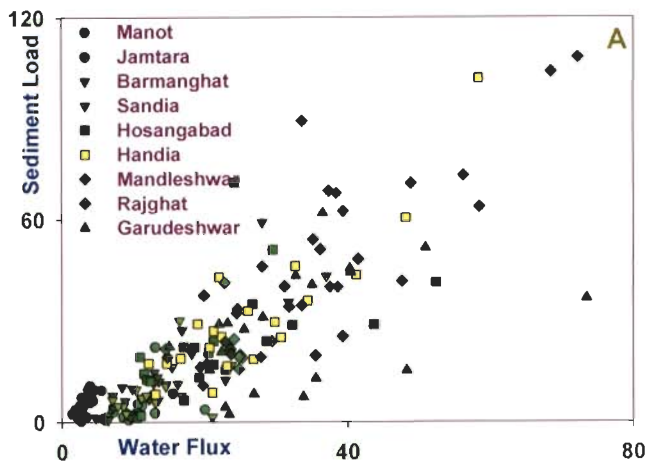


Fig. 4.10 Linear relationship between daily water discharge ($m^3\ s^{-1}$) and sediment concentration ($gm\ l^{-1}$) in the Narmada mainstream

Fig. 4.11 A and 4.11 B show the relationship between the annual water flux and the sediment loads for the Narmada mainstream and the tributaries respectively. The sediment discharge of the Narmada river and its tributaries are time dependent. The relation between sediment discharge and water flow changes from year to year, depending upon the monsoon patterns. Along with climatic factors, physical factors also modify the typical relationship. However, a good correlation is observed for the entire Narmada river, regardless of the differences in relief, geology, geographical location and climatic factors.



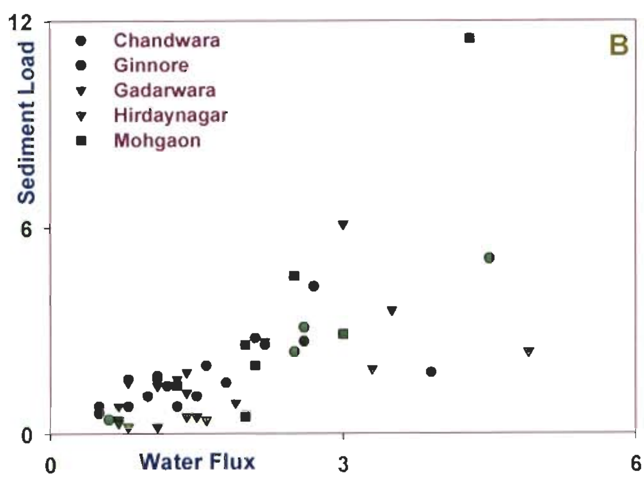


Fig. 4.11 Linear relationship between annual water flow (km^3) and sediment load (10^6 tons) at different locations; A-Narmada mainstream and B-Tributaries

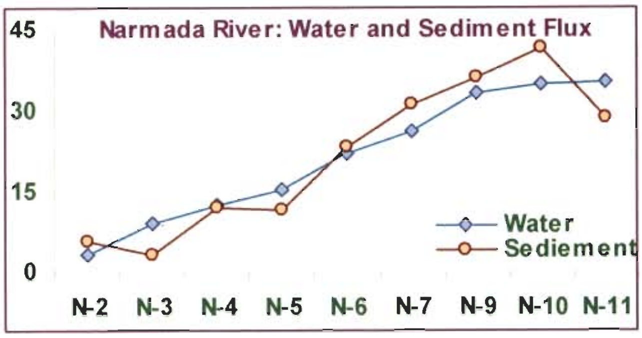


Fig. 4.12 Coupling between annual water flow and sediment load at different locations on the Narmada mainstream

It is evident that the relations between water and associated sediment flux are well defined and stable, though it shows slight deviation from linearity. According to Nordin (1985) for most of the large rivers, the relations between stage and discharge and between flow and sediment load usually show a good deal of scatter. Similar to association of water discharge and sediment concentration, water flux and sediment loads also show good relation throughout the basin (Fig. 4.12), although sediment loads in the basin are more prone to alteration due to natural and anthropogenic factors.

4.4 FACTORS CONTROLLING WATER FLOW AND SEDIMENT LOAD

4.4.1. Rainfall

Precipitation has been widely understood to have a predominant influence on river water flow and sediment discharge. The flow regime of Indian rivers is directly dependent on the precipitation patterns in their watersheds. According to Sinha et al. (2002) high sediment production in the Himalayan region is favored by monsoon rains in the source areas. Heavy and intense rainfall upto 11,000 mm yr^{-1} triggers extensive catchment erosion, thereby introducing high amounts of sediments. The reported percentage of sediment transport during monsoon season exceeds 97% in some studies of the Hindu-Kush

Himalayan rivers (Ferguson, 1982). Similar to the Himalayan region, the water flow and sediment transportation in the Narmada river is precipitation dependent.

Water discharge and sediment loads in Narmada river are essentially confined to monsoon season and is directly dependent upon rainfall in the catchment area. Monsoon season extends for five months (June to Oct). On an average the basin gets rain only for 50-70 days and a few days during the monsoon make up the bulk of the rainfall by receiving rainfall more than 10 mm. Annual rainfalls shows large variations in the basin. This is one of the main reasons for the variation in annual water flow and sediment loads. Heavy and excessive rainfall in the basin, triggers high water discharge and sediment loads. Likewise uneven distribution of rains, its intensity and periodicity, cause irregular water discharge and sediment load patterns at various locations.

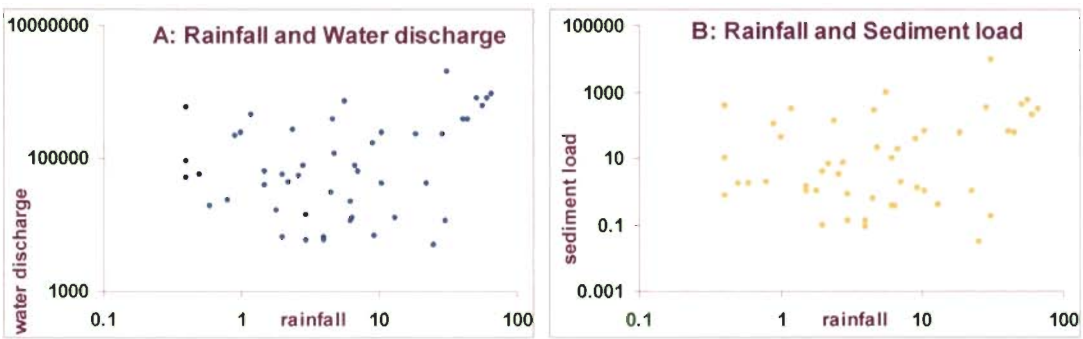


Fig. 4.13 Relationship of rainfall (mm) to water discharge (10^6 × liter day^{-1}) and sediment load (10^{-3} × tons day^{-1})

Fig. 4.13 A and 4.13 B, show relationship between rainfall and water discharge and sediment load at Hoshangabad for the year 1997-98. Both figures show large scattering, may be due to time lag in rainfall and river water flow and associated sediment transport. Immediately after the rains, water flow does not increase, because the rains initially recharge the groundwater and after it is saturated, water flow in the river show increased values with subsequent rains. Similarly availability of materials for transport does control the sediment loads, rather than just the rainfall intensity or water flow in the river. The Narmada river transports 70-99% and 90-100% of its annual water flux and sediment loads in monsoon season respectively.

4.4.2. Basin area

The volume of river water discharge and sediment load in many river basins is a function of the size of the catchment. Large catchment areas receive more rainfall and also retain surface runoff for a considerable time. Other factors being equal, the volume of water carried in drainage channels usually increases with increasing size. Sediment yield from some of the smaller rivers in the Pacific island oceans are enormous as most of the sediments eroded from these basins are directly dumped into the adjacent seas, whereas large river basins store sediments in their channels. The basin area integrates several factors, such as slope, gradient, storage capacity, etc., which influence sediment loads. For example, rivers draining only 10% of the world's drainage basins, mainly constituted by the large river basins, account for more than 60% of sediment discharge to the oceans (Milliman and Syvitski 1992).

Fig. 4.14 shows the relationship of water flux and sediment load along with with sub-basin areas in the basin, which indicate the significant role of sub-basins in accounting for high water flow and sediment loads. The forty-one tributaries of the Narmada river contribute approximately 70% of the total water flow. It is also true for sediment load. Out of the nine major sub-basins in the basin, the smaller catchments are quick to respond to rainfall and run off and show high erosive capacities, whereas over the entire river basin, the averaging effects become more significant. The relationship between sub-basin areas with water and sediment discharge is not linear for all sub-basins studied. The number of variables in sediment transport is many and hence any singular characteristic in controlling sediment loads are not observed. The amount of water flux and sediment loads generally reflects the watershed size and the prevailing patterns of the discharge as well as the land surface patterns. Catchment area of main-river and tributaries are responsible for the flux of water. Since large catchments receive more rainwater and also allow surface runoff to retain for more time, it delays high discharge conditions further downstream. According to Milliman (1991) in most large rivers, the drainage basins may be sufficiently large to modulate events, such that, a major flood in one part of the basin would have relatively little effect on the sediment discharge of the entire river. Other factors being equal, the volume of water carried in drainage channels usually increases with increasing size and development of the contributing watershed area. In the Narmada river basin, due to small catchment area of the tributaries, the lag time between rain and stream flow is shorter, allowing quick flow of surface runoff and sediments whereas the large catchment of mainstream hold surface runoff for considerable time.

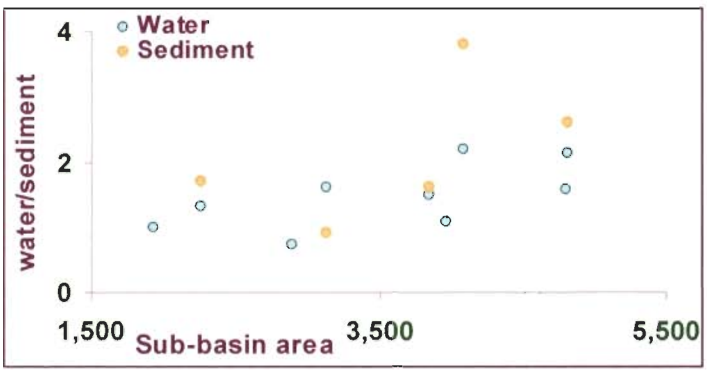


Fig. 4.14 Relationship of sub-basin area (km^2) with water flux ($km^3\ yr^{-1}$) and sediment load (10^6 tons yr^{-1})

4.4.3. Relief

The most important and obvious factor controlling the velocity of flow and flux, is the relief (both basin relief and relief ratio) gradient of a stream channel. Relief is a major factor in continental denudation as it induces greater mechanical erosion. Milliman and

Meade (1983) identified relief as one of the important natural factors which controls the suspended sediment loads of rivers. In tectonically inactive regions, mean local relief has direct consequence on erosion rate. Conversely, rivers with low relief are generally characterized by low sediment yields. According to Garrels and Mackenzie (1971) the suspended sediment loads increase exponentially with increase in mean continental elevation. Meade and Parker (1985) suggested that more than 90% of the suspended sediment in the Amazon river is derived from the Andes, although most of the water is derived from the low-lying areas of the basin. The basin relief (maximum-minimum basin elevation) is 1057 m for the Narmada basin, it is quite less in contrast to rivers derived form the extra peninsula (Himalayan rivers) such as the Indus (7833 m), Ganga (7010 m), Brahmaputra (6705 m) and the other large world rivers. The relief ratios (basin relief/basin length) of the Himalayan rivers are appreciably high 0.00449, 0.00475 and 0.00554 for the Ganga, Indus and the Brahmaputra rivers respectively (Summerfield and Hulton, 1994) than that of the Narmada river (0.00111). The mean channel gradient (elevation of channel/length of channel) for the Narmada river is (0.806 m km^{-1}), much less in comparison to the Indus (1.64 m km^{-1}) Ganga (2.39 m km^{-1}) and the Brahmaputra rivers (2.18 m km^{-1}).

Despite the low relief and channel gradient, the Narmada river shows high sediment loads and weathering rates due to significance of local relief features. Relief ratios between different study locations on Narmada mainstream vary between 0.0001 and 0.0041. Upstream location Dindori (N1) and Manot (N2) are characterized by high ratios of 0.0041 and 0.0017 respectively. The high river runoff and sediment concentration at Manot (N2) support the active role of relief (local) over water and sediment transport. The local relief feature is not very significant in the case of middle and downstream part of the basin. The channel gradients of the tributaries are significantly higher compared to the mainstream and hence play an important role in sediment transport. Due to the physical and geological heterogeneity different factors dominate the sediment yield in different regions. Geological characteristics dominate the sediment delivery in the Deccan Plateau (Biksham & Subramanian, 1988) whereas topography dominates the sediment dynamics of the Himalayan region (Carson, 1985).

4.4.4 Basin geology and soil characteristics

The role of geology on sediment loads in rivers is less understood. The influence of lithology on erosion rates is high with respect to channel erosion, but less significant with respect to hill slope erosion, as the outcrop lithologies are normally covered with soils. Thick vegetation on soils results in organic acids, which accelerate chemical erosion. Kattan et al. (1987) estimated that in the Senegal river 20% of total river transport is derived from the channel erosion. In the Taiwan orogen, despite low relief, highest erosion rates are observed where weak substrates occur (Dadson et al. 2003). Spatial variability of sediment load is evident in large river basin, primarily in response to lithological and geomorphic variations (Subramanian, 1993). Studies by Biksham and Subramanian (1988), on the Godavari river show that the Deccan Traps (Tertiary, 48% of the basin area) and sedimentary rocks (Precambrian or younger, 33%) in the basin contribute 51 and 33% sediment loads respectively, of total annual sediment loads.

A large part of the Narmada river basin is occupied by the Deccan basalts and black soils. The Narmada river at Manot and the Burhner river (upstream basin) which drain red soils, show high sediment loads whereas tributaries, such as the Banjar river which partially drain black soil, show low loads (Table 4.5) although relief also plays a major role. The Kanha national park, an extremely dense reserve forest area is located in the sub-basin of the Banjar river which prevents high sediment yields. In the middle part of the basin, a number of tributaries drain rocks of Gondwana Group and carry high sediment loads. The Quaternary soils cover a large area in the central Narmada valley which are mainly composed of highly calcareous light grey silts, sand, gravels, calcareous sandstone and conglomerate of Hirdepur Formation. Due to abundance of silt and sand size particles, in this part, the Narmada river shows drop in suspended sediment loads. Most of the major tributaries (except the Chota-Tawa and the Kundi rivers) discussed in the present study, mostly drain over rocks other than basalts and carry high sediment loads. The Chota-Tawa river drains mostly basalts and carries high sediment loads with coarse and medium particles. The basin is tectonically stable with no reports of large landslides, mainly because the major rock types, the basaltic traps are near horizontal.

4.4.5. Impact of reservoirs/ dams

Among all the categories of human influences on river basins, none show as much influence as the reservoirs on river transported materials. The natural sedimentary cycle has been greatly altered by land use changes, deforestation and soil conservation practices. Between 1951 and 1982, large dams were being constructed at a rate of 900 per year (Syvitski et al., 2003). Reservoirs are the sites of major sediment accumulation, resulting in a large reduction in sediments reaching the oceans. A decrease in sediment loads to the river through damming results in increase in coastal erosion and deterioration of coastal marine ecosystem. For example, the Aswan Dam was completed in 1964, and since then the sardine fish catch reduced by 95% and the delta shrank rapidly (Saito et al., 1994). Vorosmarty et al. (2003) estimated that 30% of global sediment flux is trapped behind large reservoirs. Several large basins such as the Colorado and the Nile river show near complete trapping of sediments due to large reservoir construction and flow diversion.

Due to favorable agro-climate, by and large the Indian economy has been traditionally based on agriculture since centuries. About 80% of the annual rainfall and runoff are concentrated in the monsoon months. During this period about 70% of river flows are discharged into the sea without utilization (World Commission on Dams, 2000). Hence, it becomes necessary to store water for multiple purposes, consequently a large number of large reservoir and storage tank construction have taken place in India. An average amount of 305×10^6 tons of sediment are trapped by the three reservoirs (Tarbela, Mangla, and Bhakra) in the Indus basin (Khan, 1985; CWC, 1991) far exceeding the estimated annual sediment flux of the Indus river towards ocean. Sediment trapped by the Indian reservoirs is estimated at 480×10^6 tons (Narayana and Ram Babu, 1983), which is almost half of the direct sediment flux from India to the Oceans. The sediment trapped by the Indian reservoirs is almost 20% of the sediment eroded in India (Singh 1990).

The Bargi dam, Indra Sagar Dam and the Sardar Sarovar Dam are three large dams on the Narmada mainstream. The Sardar Sarovar Dam is the largest dam in the basin. From its source to mouth, the Narmada river shows significant changes in water and sediment loads, influenced by contributions from tributaries and entrapment of sediments in the reservoirs. Comparative studies of average sediment loads at various locations on the Narmada river for more than two decades, show overall reduction in sediment loads in the river. Sardar Sarovar Dam, traps large proportions of sediments being carried by the river. The dam is situated between Rajghat (N10) and Garudeshwar (N110 and is 8 km upstream of Garudeshwar. Sediment load estimations during the monsoon seasons of three years (1996-99) indicate large trapping of sediments during the monsoon season, to the extent of 60-80% of its upstream loads (Fig. 4.15) whereas in the water year 1999-2000, it shows

76% trapping. The presence of dam reduces 70 - 90 % of coarse and approximately 50 % of medium sized particles on their way to downstream allowing them to settle in the reservoir.

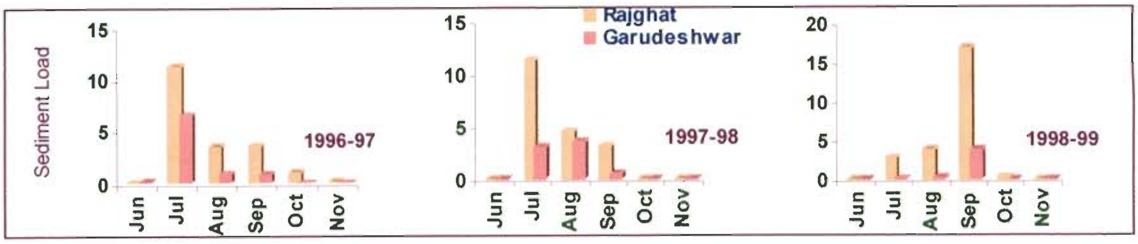


Fig. 4.15 Trapping of suspended sediments (10^6 tons) in the Sardar Sarovar Reservoir

Fig. 4.16 A, suggest a decrease in water flux downstream to dam, may be due to enhanced evaporation rates whereas Fig. 3.16 B, C and D show the impact of dam over sediment transportation. Plots of multi-annual daily sediment concentrations (mg l^{-1}) and sediment loads ($\times 10^6$ tons day^{-1}) during monsoon and annual loads ($\times 10^6$ tons) suggest an overall decrease. There is a significant reduction in annual sediment loads in the river after the river passes through the dam.

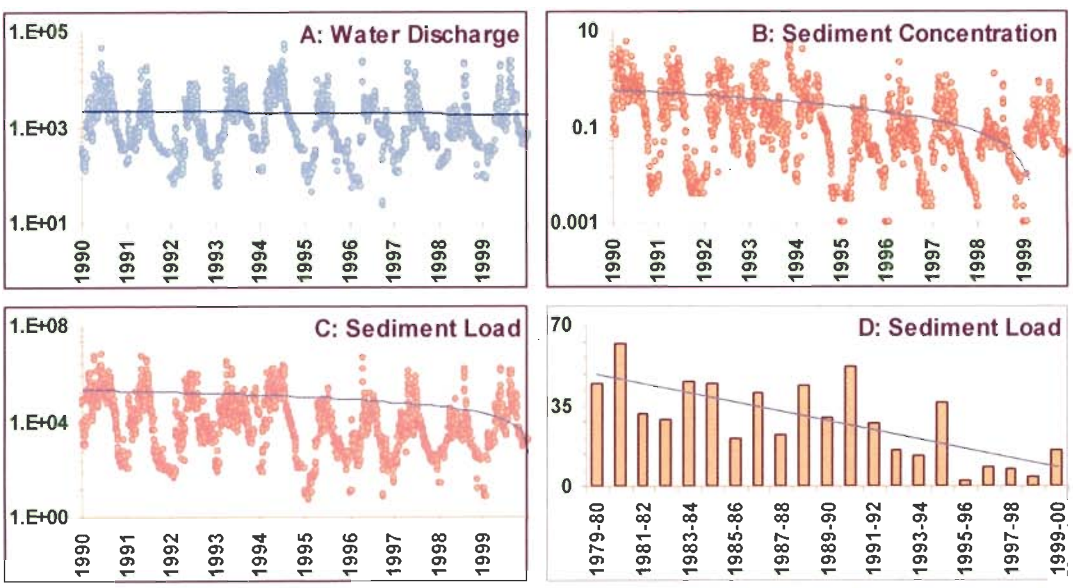


Fig. 4.16 Influence of the Sardar Sarovar Reservoir/Dam on water discharge and sediment load. A-Daily water discharge; B-Daily sediment concentration (monsoon); C-Daily sediment load and D-Annual sediment load

The previous estimations of the sediment flux of the Narmada river were 61×10^6 t yr^{-1} (Narayana and Ram Babu, 1983) and 70×10^6 t yr^{-1} (Subramanian, 1993), whereas the present estimation is 28.3×10^6 tons yr^{-1}, establishing the fact that sediment transfer from rivers to the oceans has been reduced over the years. The Dams trapped approximately 30% of sediments of Narmada river during twenty water-years (1980-2000).

4.5 PHYSICAL WEATHERING RATE (PWR)

The present estimations of erosion rates in the basin are calculated based on the multi-annual sediment load data from 1980-2000 (Table 4.6). Physical weathering rates in the basin vary between 208 and 1320 tons km^{-2} yr^{-1} (Fig.4.17).

Table 4.6 Physical weathering rates at different locations in the Narmada river basin

Location Code	Location	PWR (tons km^{-2} yr^{-1})
Narmada mainstream		
N2	Manot	1320
N3	Jamtara	208
N4	Barmanghat	452
N5	Sandia	377
N6	Hoshangabad	530
N7	Handia	602
N9	Mandleshwar	523
N10	Rajghat	548
N11	Garudeshwar	322
Tributaries		
T1	Mohgaon	923
T2	Hirdayangar	274
T5	Gadarwara	743
T7	Ginnore	546
T9	Chandwara	410

The highest erosion is observed at Manot (N2) whereas Jamtara (N3) 160 km downstream to Manot shows least erosion rates. Among the tributaries, the Burhner river at Mohgaon (T1) shows highest erosion rate (953 tons km^{-2} yr^{-1}) whereas the Banjar river at Hirdaynagar from the upstream basin show less erosion rate (229 tons km^{-2} yr^{-1}). High lands in the basin (500-1000 m) are responsible for high sediment loads and sediment yield. The final erosion rate of the basin at downstream location (Garudeshwar N11) is 322 ton km^{-2} yr^{-1}, significantly lower than the upstream location Rajghat (N10; 548 ton km^{-2} yr^{-1}).

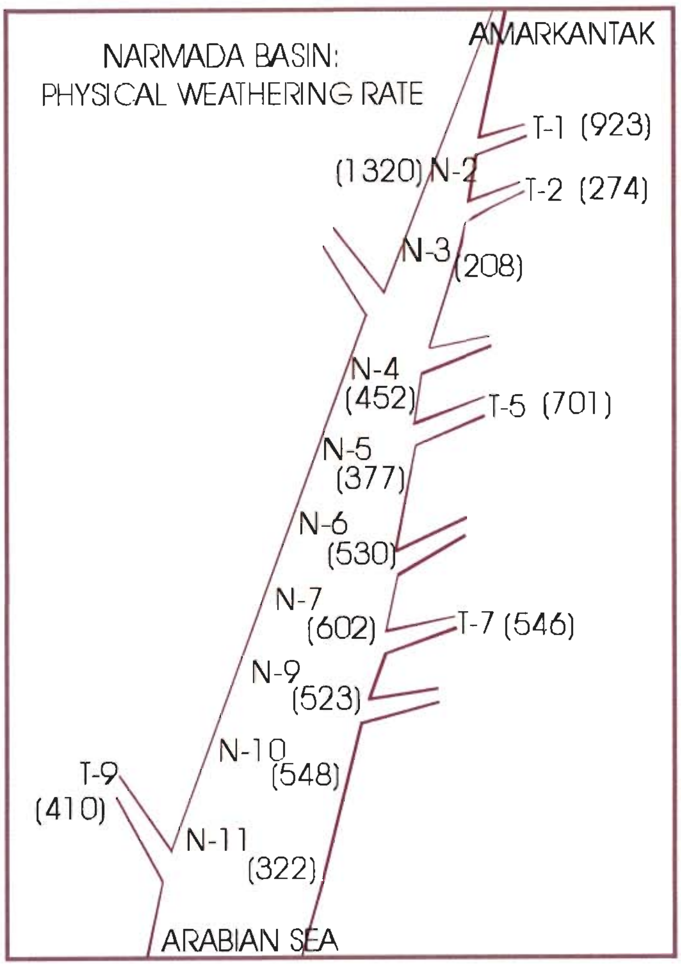


Fig. 4.17 Spatial distribution of physical weathering rates (ton km^{-2} yr^{-1}) in different sub-catchment areas in the Narmada river basin

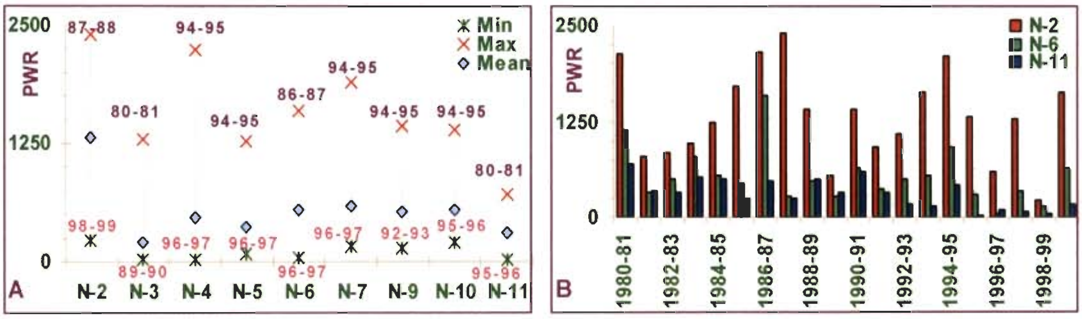


Fig. 4.18 Temporal and spatial variations in the physical weathering rates (ton km^{-2} yr^{-1}) in the Narmada river basin; A-Range and average values of weathering rates at different locations on the Narmada mainstream and B-Temporal variations at three different locations in the Narmada basin

Fig. 4.18 A shows the minimum, maximum and mean erosion rates during past twenty years at different locations on the Narmada mainstream. It is observed that the minimum and maximum erosion rates do not necessarily correspond with the amount of water flow, may de due to increased anthropogenic actives (including dams) in the basin. Fig. 4.18 B shows the temporal and spatial variations in physical weathering rates during the past twenty years at upstream location Manot (N2), midstream location Hoshangabad (N6) and downstream location Garudeshwar (N11). It is evident that physical weathering rates at different locations show large temporal variations.

4.6 MAJOR ION CHEMISTRY

The major ion concentrations along with pH, dissolved silica and total dissolved solids (TDS) are presented in Table 4.7 and the sampling locations are shown in Fig. 4.19. Major elements show large heterogeneity in concentrations in the Narmada river basin. The pH of Narmada river water varies from almost neutral to mild alkaline (6.9 to 8.5), with most of samples in the range of 7.0 - 8.0. The pH shows significant spatial and temporal variations. The maximum and minimum pH values in the Narmada mainstream vary from 6.9 to 8.5 whereas in the tributaries, it varies from 7.1 to 8.4. Samples collected during low-flow are more alkaline, than those collected during high flows.

The ionic strength of (IS= $0.5 \sum m_i z_i^2$, where m_i is the molality and z_i is the charge of the i^{th} ion in the solution, considering all major cations and anions) in the Narmada river vary between 3 - 5 x 10^{-3} (mol l^{-1}). Samples collected during non-monsoon seasons show high ionic strength compared to those collected during monsoon.

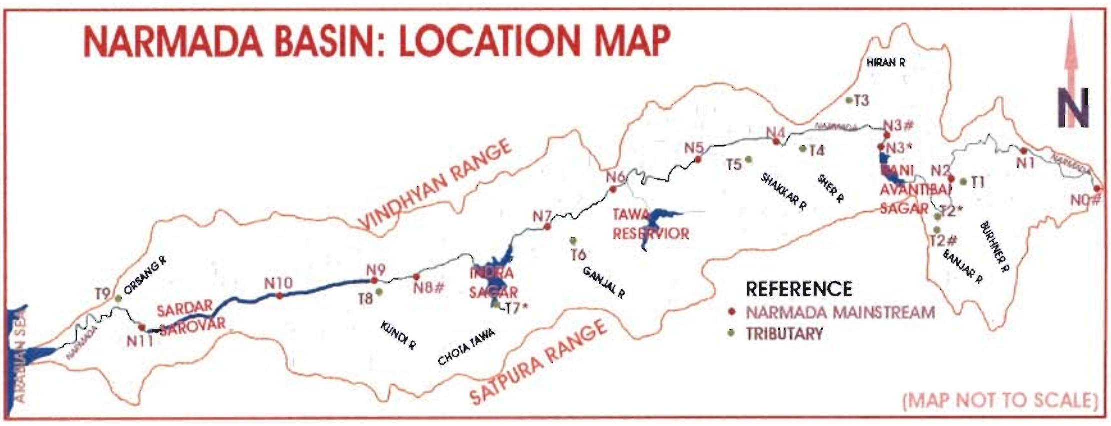


Fig. 4.19 Sampling locations in the Narmada river basin.

Table 4.7 Major ion composition of the Narmada river and the tributaries at different sampling locations

Monsoon-2003 August

Sampling Location	Sample Code - River	pH	HCO_3 μM	Cl μM	NO_3 μM	SO_4 μM	Na μM	K μM	Ca μM	Mg μM	TZ^+ μel^{-1}	TZ^- μel^{-1}	NICB %	SiO_2 μM	TDS $mg\ l^{-1}$
Amarkantak	R1-Narmada	----	----	----	----	----	----	----	----	----	----	----	----	----	----
Dindori	R2-Narmada	8.2	2224	112	19	10	588	12	595	234	2259	2374	-5.1	359	207
Mohgaon	R3-Burhner	7.4	808	51	18	9	174	9	202	131	848	894	-5.5	201	81
Manot	R4-Narmada	7.8	1920	124	34	5	445	8	416	353	1991	2087	-4.8	319	179
Bamni	R5-Banjar	7.4	1640	65	32	14	428	18	351	257	1661	1764	-6.2	188	148
Jabalpur	R6-Narmada	----	----	----	----	----	----	----	----	----	----	----	----	----	----
Patan	R7-Hiran	7.5	2120	157	45	26	407	57	848	53	2266	2373	-4.7	208	200
Belkheri	R8-Sher	8.0	2160	68	18	9	554	9	519	280	2160	2264	-4.8	348	198
Barman	R9-Narmada	7.3	1760	45	25	7	340	12	461	249	1774	1842	-3.9	211	157
Gadarwara	R10-Shakkar	7.2	2176	22	27	10	571	9	498	280	2135	2245	-5.2	379	199
Sandia	R11-Narmada	7.6	2016	47	16	7	408	14	517	268	1994	2093	-5.0	212	176
Hoshangabad	R12-Narmada	7.1	2320	45	18	9	465	13	596	333	2338	2400	-2.6	224	202
Chhidgaon	R13-Ganjal	7.5	2736	157	26	21	418	13	692	513	2843	2960	-4.1	563	260
Handia	R14-Narmada	7.5	2320	67	18	12	538	14	554	334	2328	2429	-4.4	216	203
Mortakka	R15-Narmada	7.2	2240	67	12	20	546	15	517	317	2230	2359	-5.8	213	196
Mandleshwar	R16-Narmada	7.2	2144	22	29	13	520	14	489	308	2128	2223	-4.4	214	187
Kogaon	R17-Kundi	7.4	2672	203	41	23	602	16	665	449	2848	2962	-4.0	291	245
Rajghat	R18-Narmada	7.3	2336	45	29	19	576	15	539	329	2328	2447	-5.1	213	204
Garudeshwar	R19-Narmada	7.4	2280	67	8	14	452	17	558	341	2267	2383	-5.1	222	198
Chandwara	R20-Orsang	7.2	1904	134	16	12	532	18	465	260	1999	2079	-4.0	149	170

Post monsoon- 2004 January Cont....

Sampling Location	Sample Code - River	pH	HCO_3 μM	Cl μM	NO_3 μM	SO_4 μM	Na μM	K μM	Ca μM	Mg μM	TZ^+ μel^{-1}	TZ^- μel^{-1}	NICB %	SiO_2 μM	TDS $mg\ l^{-1}$
Amarkantak	R21-Narmada	7.0	752	84	18	17	238	26	160	130	845	888	-5.1	166	79
Dindori	R22-Narmada	7.5	3024	141	19	16	727	41	709	435	3056	3215	-5.2	371	271
Mohgaon	R23-Burhner	7.4	2808	24	10	24	638	38	609	441	2776	2890	-4.1	270	243
Manot	R24-Narmada	7.5	3456	103	15	15	889	47	662	589	3439	3604	-4.8	313	300
Bamni	R25-Banjar	7.2	1800	122	45	52	650	85	364	263	1989	2071	-4.1	174	171
Jabalpur	R26-Narmada	----	----	----	----	----	----	----	----	----	----	----	----	----	----
Patan	R27-Hiran	7.7	4576	427	158	58	743	58	1426	685	5022	5277	-5.1	197	416
Belkheri	R28-Sher	7.9	4320	160	59	29	597	48	972	889	4366	4597	-5.3	461	378
Barman	R29-Narmada	7.6	2768	122	34	20	679	51	572	484	2841	2963	-4.3	269	245
Gadarwara	R30-Shakkar	----	----	----	----	----	----	----	----	----	----	----	----	----	----
Sandia	R31-Narmada	7.6	3264	141	40	15	679	55	589	700	3312	3475	-4.9	284	283
Hoshangabad	R32-Narmada	7.7	3056	141	62	32	1035	59	625	407	3156	3322	-5.2	293	276
Chhidgaon	R33-Ganjal	8.0	2544	255	39	44	854	60	463	498	2835	2927	-3.2	288	239
Handia	R34-Narmada	7.7	3296	141	43	30	1354	55	575	438	3434	3541	-3.1	305	296
Mortakka	R35-Narmada	8.0	3456	160	34	14	1253	56	640	507	3601	3678	-2.1	417	316
Mandleshwar	R36-Narmada	7.8	3360	136	39	19	1051	57	628	535	3434	3573	-4.0	290	295
Kogaon	R37-Kundi	7.6	2896	480	53	32	522	91	568	823	3395	3493	-2.9	291	273
Rajghat	R38-Narmada	7.9	3688	141	39	10	1202	74	677	555	3739	3888	-4.0	360	325
Garudeshwar	R39-Narmada	8.0	3536	155	49	16	1277	62	564	647	3761	3771	-0.3	292	312
Chandwara	R40-Orsang	----	----	----	----	----	----	----	----	----	----	----	----	----	----

Pre monsoon-2004 May Cont….

Sampling Location	Sample Code - River	pH	HCO_3 µM	Cl µM	NO_3 µM	SO_4 µM	Na µM	K µM	Ca µM	Mg µM	TZ^+ μel^{-1}	TZ^- μel^{-1}	NICB %	SiO_2 µM	TDS mg l^{-1}
Amarkantak	R41-Narmada	6.9	680	62	32	3	176	28	172	86	720	779	-8.3	171	70
Dindori	R42-Narmada	8.5	3056	113	7	18	705	47	697	470	3087	3211	-4.0	427	276
Mohgaon	R43-Burhner	8.3	2496	86	4	9	382	37	596	448	2505	2604	-4.0	577	236
Manot	R44-Narmada	8.2	3720	145	9	17	803	53	752	684	3726	3908	-4.9	592	337
Bamni	R45-Banjar	8.0	1968	66	13	13	351	37	523	270	1974	2072	-5.0	402	185
Jabalpur SG	R46-Narmada	7.9	2240	69	6	16	259	28	678	304	2252	2347	-4.2	426	208
Jabalpur BG*	R46-Narmada	7.9	2048	47	6	12	228	28	589	313	2060	2124	-3.1	387	189
Patan	R47-Hiran	8.3	4176	324	24	19	1237	128	475	1078	4472	4562	-2.0	408	373
Belkheri	R48-Sher	----	----	----	----	----	----	----	----	----	----	----	----	----	----
Barman	R49-Narmada	8.0	2736	115	1	16	388	41	746	428	2777	2883	-3.8	243	238
Gadarwara	R50-Shakkar	8.3	3720	194	5	17	870	44	569	912	3875	3952	-2.0	412	327
Sandia	R51-Narmada	8.2	3224	94	18	13	506	46	860	497	3266	3363	-3.0	368	284
Hoshangabad	R52-Narmada	7.8	3456	112	15	20	749	40	775	575	3489	3624	-3.9	450	308
Chhidgaon	R53-Ganjal	8.4	5616	66	19	15	2627	51	461	1040	5680	5731	-0.9	442	480
Handia	R54-Narmada	8.4	3984	27	20	1	971	52	719	696	3853	4034	-4.7	484	344
Mortakka	R55-Narmada	8.3	3120	103	23	19	574	48	787	493	3182	3283	-3.2	261	271
Mandleshwar	R56-Narmada	8.4	3152	168	24	22	760	35	691	541	3260	3389	-4.0	387	285
Kogaon	R57-Kundi	8.1	2880	221	11	12	742	54	623	500	3041	3135	-3.1	320	261
Rajghat	R58-Narmada	8.5	3024	131	3	22	675	36	620	549	3049	3203	-5.0	450	274
Garudeshwar	R59-Narmada	8.5	2088	75	4	18	338	25	594	291	2133	2202	-3.2	404	196
Chandwara	R60-Orsang	----	----	----	----	----	----	----	----	----	----	----	----	----	----

Monsoon-2004 September Cont....

Sampling Location	Sample Code - River	pH	HCO_3 µM	Cl µM	NO_3 µM	SO_4 µM	Na µM	K µM	Ca µM	Mg µM	TZ^+ µel^{-1}	TZ^- µel^{-1}	NICB %	SiO_2 µM	TDS mg l^{-1}
Amarkantak	R61-Narmada	----	----	----	----	----	----	----	----	----	----	----	----	----	----
Dindori	R62-Narmada	7.5	2280	74	46	12	264	27	673	167	2312	2423	-4.8	372	206
Mohgaon	R63-Burhner	8.1	1976	60	11	16	313	21	556	308	2001	2080	-3.9	442	189
Manot	R64-Narmada	7.9	2592	69	6	19	296	15	771	431	2623	2705	-3.1	511	242
Bamni	R65-Banjar	7.7	1456	73	16	19	302	22	401	216	1527	1584	-3.7	274	140
Jabalpur	R66-Narmada	8.2	3000	126	13	19	422	35	865	608	3052	3176	-4.1	353	272
Patan	R67-Hiran	7.8	2800	57	5	11	331	25	806	442	2775	2884	-3.9	512	257
Belkheri	R68-Sher	8.2	3264	95	32	29	444	14	966	675	3356	3450	-2.8	505	303
Barman	R69-Narmada	7.1	2480	76	35	21	415	43	675	337	2483	2632	-6.0	275	221
Gadarwara	R70-Shakkar	8.3	3288	75	23	23	434	24	936	637	3265	3432	-5.1	432	297
Sandia	R71-Narmada	8.1	2120	73	30	19	246	33	637	213	2190	2261	-3.2	231	187
Hoshangabad	R72-Narmada	7.0	3040	87	14	41	488	49	855	416	3102	3223	-3.9	316	270
Chhidgaon	R73-Ganjal	7.8	3616	114	9	31	576	23	1017	675	3651	3801	-4.1	250	314
Handia	R74-Narmada	7.7	3040	85	7	31	504	41	851	412	3098	3193	-3.1	378	272
Mortakka	R75-Narmada	7.7	2336	80	11	23	318	50	669	302	2376	2474	-4.1	244	206
Mandleshwar	R76-Narmada	7.0	2384	114	12	22	359	57	693	319	2494	2553	-2.4	299	216
Kogaon	R77-Kundi	8.1	3672	135	24	40	470	57	1066	468	3726	3911	-5.0	271	318
Rajghat	R78-Narmada	7.7	2480	127	12	26	415	44	693	342	2539	2670	-5.1	289	224
Garudeshwar	R79-Narmada	7.6	2080	87	4	28	301	36	593	267	2116	2227	-5.3	261	187
Chandwara	R80-Orsang	8.1	4080	640	41	16	1259	61	1112	625	4655	4794	-3.0	408	391

Water in the Narmada river have high ionic charges ($\sum^+$ 719-3853 μeql^{-1}) with an average of 2700 μeql^{-1} whereas, the tributaries show comparatively high ion charges ($\sum^+$ 848-5680 μeql^{-1}) with an average of 2987 μeql^{-1}. Water in the Narmada mainstream and the tributaries show specific charge balance, denoted as normalized inorganic charge balance (NICB = $(\sum^+ - \sum^-)/\sum^+$). NICB values are normally close to 4%, with r^2 value about 0.998 (Fig. 4.20). The NICB values in the present study are within the cumulative uncertainties in major ion chemistry and suggest that contributions of organic species are not significant.

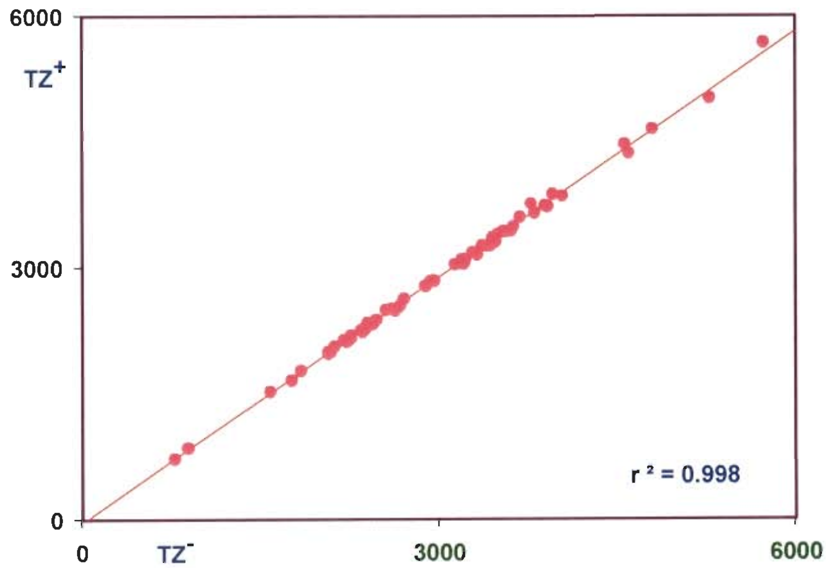


Fig. 4.20 Relationship between inorganic cations and anions in the river water

Chemical compositions of water in the river are highly variable. Fig. 4.21 shows the variations in total dissolved solids (TDS) in the Narmada river. The TDS values for the Narmada mainstream vary from 70 to 344 mg l^{-1}. Among the tributaries, the Burhner river shows lowest TDS value (81 mg l^{-1}), whereas the highest mean TDS value is observed for the Ganjal river (323 mg l^{-1}), followed by the Hiran river (311 mg l^{-1}) whereas the highest individual TDS value is observed in the Ganjal river 480 mg l^{-1} (May, 2004). High loads at Dindori and Manot are the result of high relief coupled with basaltic lithology. Downstream to Barmanghat, the Narmada river flows through quaternary soil formations and hence carries high dissolved loads. High dissolved loads also result from the degraded soils, which were formed by loss of top soils or by salinization. From upstream of Hoshangabad upto Handia in downstream, the Narmada mainstream and the Ganjal river drain the saline soils and show high dissolved loads. The water samples collected during non-monsoon (low flow) generally show higher TDS values and suggest that low runoff and high temperature result in efficient chemical weathering and result in dissolved components in water. The variable presence of basalts, Gondwana sediments, quaternary soils, saline soils, relief, runoff and temperature, are some of the major factors which control water chemical compositions in the Narmada river basin.

Total dissolved solids for the Narmada basin (70-480 mg l^{-1}) are higher than other rivers draining basalts, such as in Caribbean Island (27-255 mg l^{-1}; Rad et al., 2006), Central Siberia (30-70 mg l^{-1}; Pokrovsky et al., 2005), Iceland (39-102 mg l^{-1}; Steffanssan and Gislason, 2001) but are similar to Reunion Island (24-580 mg l^{-1}; Louvat and Allegre, 1997).

4.6.1 Major Anions

In dissolved form CO_2 occurs as H_2CO_3, HCO_3^- and CO_3^{2-} depending on pH of water. HCO_3^- is dominant in the pH range 6.4 to 10.3, hence HCO_3^- governs the other species such as H_2CO_3 and CO_3^{2-} in river waters in nature. Among the anions in the Narmada river, HCO_3^- is the most dominant anion and constitutes approximately 83 - 99% of total anion charge (TZ^-) for the Narmada river basin. Bicarbonate varies from 85 to 99% for the Narmada river and 83 - 98% for the tributaries. The HCO_3^- concentrations in the Narmada mainstream vary between tributaries are moderately higher as it varies from 808 to 5616 μM. Major source of bicarbonate in the river waters is CO_2 consumption during silicate mineral weathering dissolution of carbonate minerals and soil respiration.

Das et al. (2005), observed bicarbonate concentrations between 170 and 4624 μM for the Krishna river system and the small western flowing rivers, which is marginally lower than the alkalinity in the Narmada basin. The Narmada river shows higher alkalinity in comparison to the other rivers draining basalts - Caibbean Island (mean-578 μM; Rad et al., 2006), Central Siberia (307-1125 μM; Pokrovsky et al., 2005), Sao Miguel Island (202-4120 μM; Louvat and Allegre, 1997) and Reunion Island (250-3560 μM; Louvat and Allegre, 1997).

Among the anions Cl^- is second abundant chemical specie and constitutes approximately 1-14% of total anion charge (TZ^-) in the Narmada river. The Cl^- concentrations in the Narmada river vary between 22 and 640 μM. In Narmada mainstream (Fig 4.21) the Cl^- concentrations vary from 22 to 168 μM and in tributaries, it varies from 22 to 640 μM. Except in areas of heavy industrial pollution, atmospheric chloride concentration by evaporation may not exceed 560 μM (20 ppm), in rivers from areas with runoff more than 200 mm yr^{-1} (Holland, 1978). Among the total 73 river water samples collected for present study, only seven samples show Cl^- concentrations higher than 200 μM, which include samples from the tributaries, Kundi (3), Hiran (2) Ganjal (1) and the Orsang rivers (1). The Orsang river drains over quaternary soils (Gujarat Alluvium Plains) and these sediments are often saline (Chamyal and Maurya, 2003). Dessert et al. (2001) observed Cl^- concentrations for the rivers draining North Deccan trap between 53 μM and 1568 μM. Das et al. (2005) also observed high variations in Cl^- concentrations (75 to 2333 μM) for the Krishna river basin and the western ghat rivers. Mean

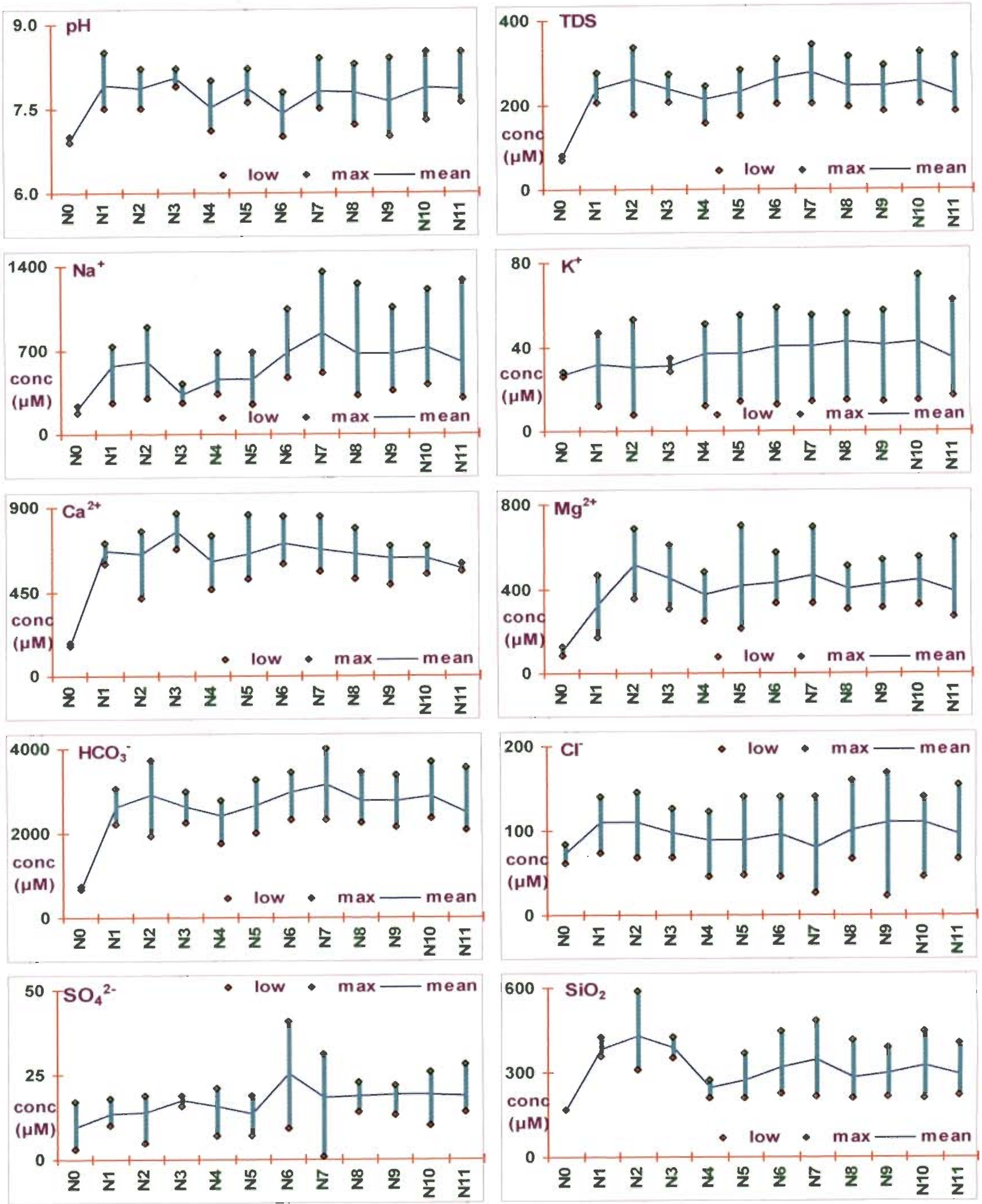


Fig. 4.21A Range and mean values of pH, TDS, major ions and dissolved silica in Narmada mainstream (Samples of September 2004)

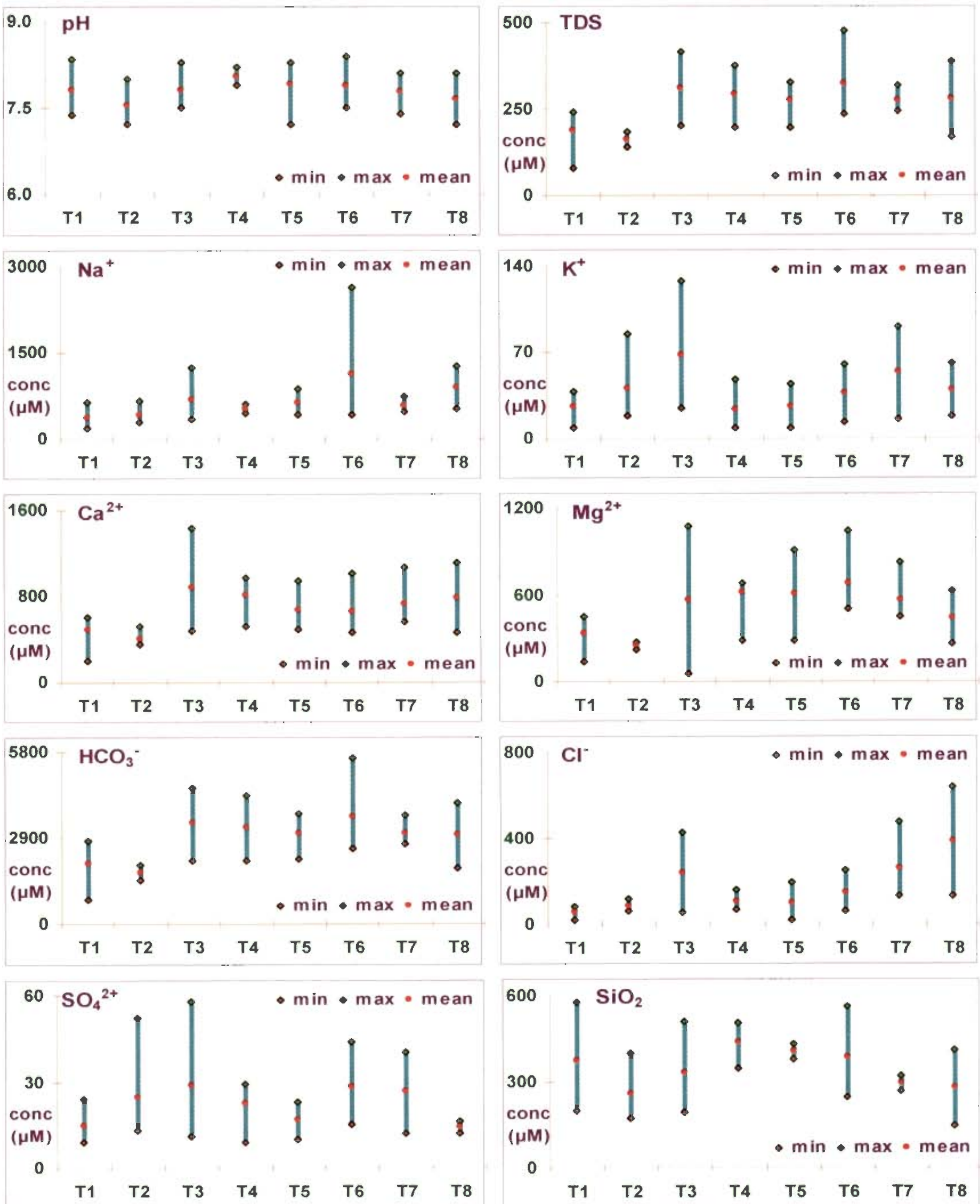


Fig. 4.21B Range and mean values of pH, TDS, major ions and dissolved silica in major tributaries

Cl^- concentrations for the Central Siberian rivers are 125 μM (Pokrovsky et al., 2005), Reunion Island (<200 μM; Louvat and Allegre, 1997), Caribbean Island 340 μM (Rad et al., 2006).

NO_3^- is the next abundant species followed by SO_4^{2-}. The tributaries show high concentrations of both NO_3^- and SO_4^{2-}. Among the tributaries, the Hiran river recorded highest values (158 μM) of NO_3 which is, probably derived from anthropogenic source. Garrels and Mackenzie (1975) suggested that about 45% of sulfate in river water may come from anthropogenic sources. The rainwater in the Narmada river basin contain abundant sulfate, which suggests that most of anthropogenic sulfate is produced during fossil fuel burning and tied up with rains. Traceable amounts of PO_4 and F^- are also present in river water.

A better assessment of the dominance of alkalinity over other anions and dissolved silica can be made by ternary plots, as shown in Fig. 4.22 A and 4.22 B, which demonstrate the relative abundance of alkalinity, $Cl^- + SO_4^{2-}$ and dissolved silica and show clustering of data points at HCO_3^- summit. Fig. 4.22 B shows comparative picture of the data of present study (2003-2004) with multi-annual data (1990-2001). To understand the cause of scattering in Fig 4.22, the multi-annual data (anions and silica) are plotted separately for upstream, midstream and downstream for the Narmada mainstream (Fig. 4.23 A, B and C) and the tributaries (Fig. 4.24 A, B, C and D). Fig. 4.23 A and B show good resemblance between relative abundance of alkalinity in the river water at different locations from the upstream and midstream, whereas Fig. 4.23 C shows a remarkable decrease in alkalinity and dissolved silica and shift of data cluster towards the $Cl^- + SO_4^{2-}$ end for water composition at Garudeshwar. This may be due to precipitation of bicarbonate as Ca-Mg carbonates. Fig. 4.24 A Although Fig. 4.24 B and C also show similar relative distributions of major anions and dissolved silica, little shift of data cluster towards $Cl^- + SO_4^{2-}$ end for the Hiran and the Chota-Tawa rivers and the Orsang river shows significant shift towards $Cl^- + SO_4^{2-}$ end (4.24 D). A closer look of multi-annual data suggest that, during high temperature and low runoff during summer or non-monsoon season, dissolved silica concentrations attain higher than 1000 μM.

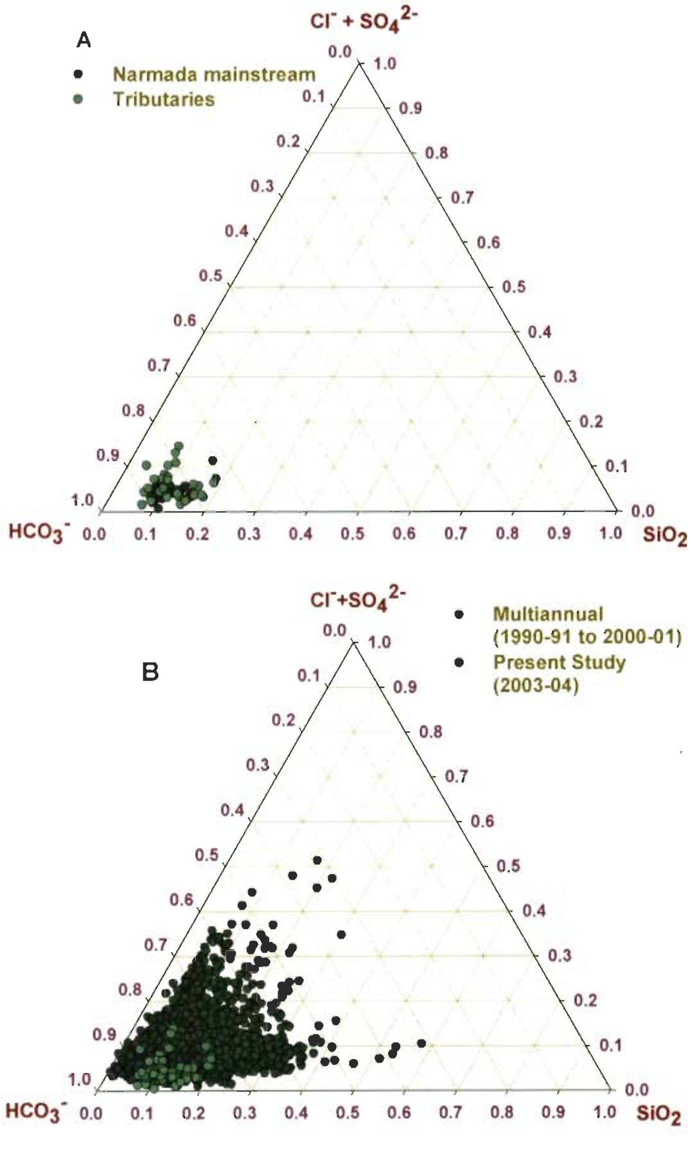


Fig. 4.22 Ternary plots for anions; A-Dominance of alkalinity in the water sample collected during field trips and B-Comparison between data of present study (collected during Aug 2003 and Sept 2004) with that of multi-years.

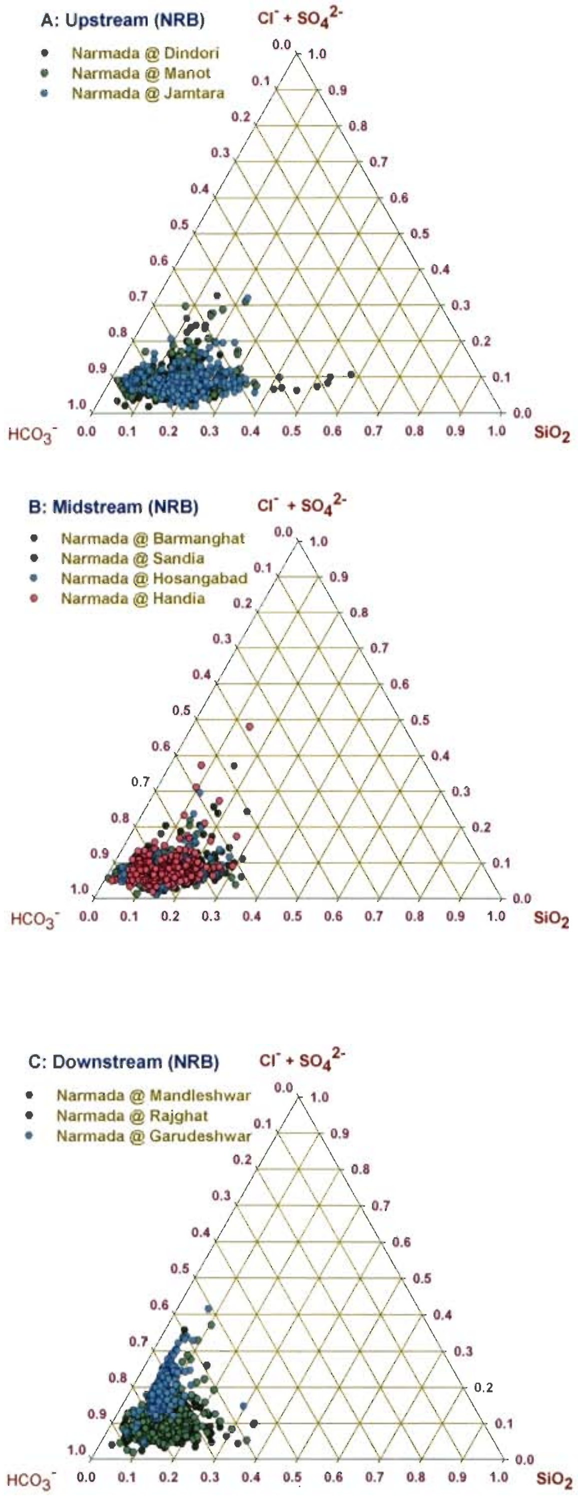


Fig. 4.23 Ternary plots for dissolved anions and silica (the Narmada mainstream); A-upstream locations; B-midstream locations and C-downstream location

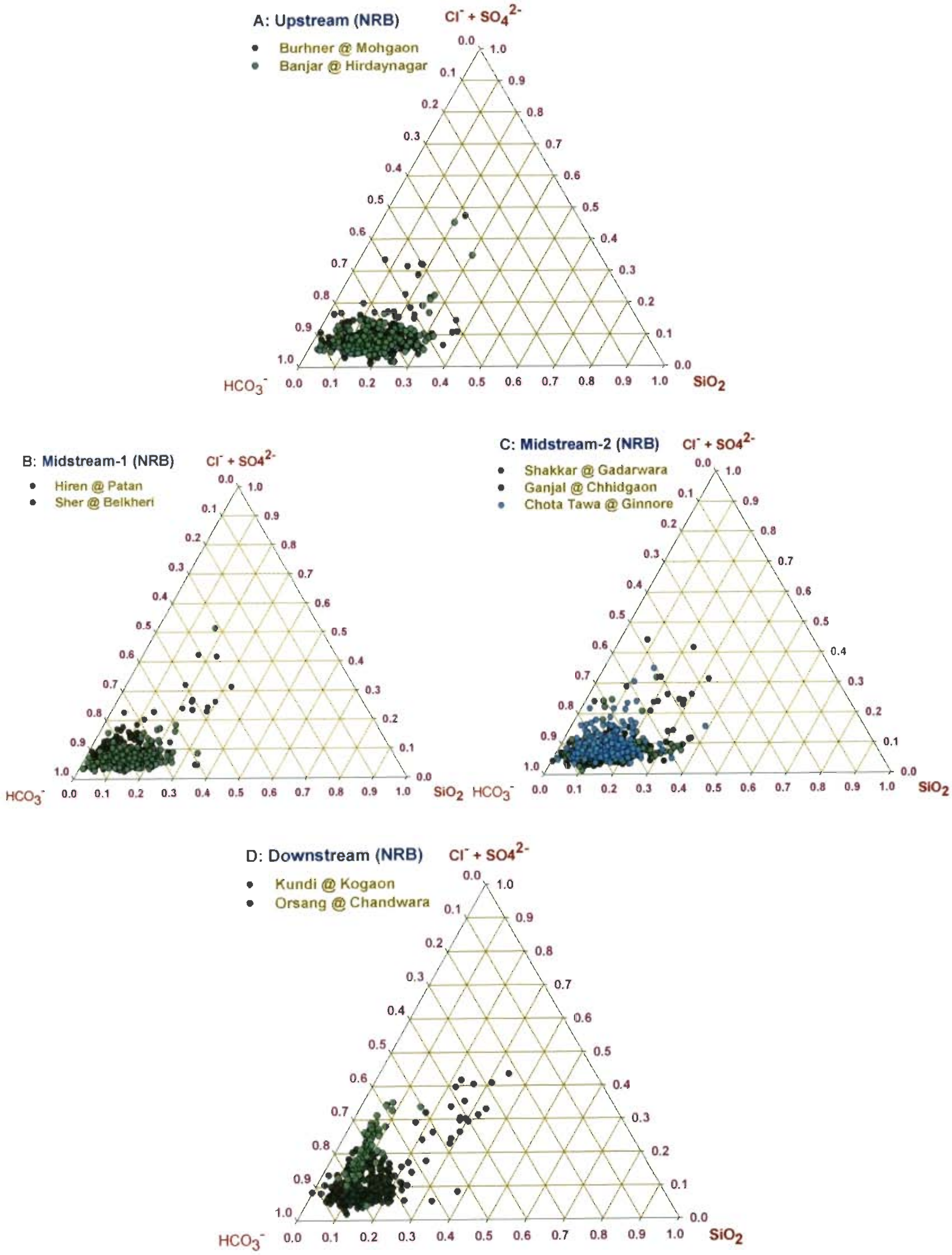


Fig. 4.24 Ternary plots for dissolved anions and silica (in major tributaries); A-upstream locations; B - midstream locations (1); C-midstream location (2) and D-downstream locations

4.6.2 Major Cations

Among the cations, Ca^{2+} is the most dominant, contributing 16 - 75%, followed by Mg^{2+} (5- 48%), Na^+ (11-46%) and K^+ (<1-5%) of cations charge (TZ^+). Ca^{2+} remains the dominant cation all along the river course. Na^+ concentrations in the Narmada river varies between 174-2627 μM, K^+ is the least abundant cation and its concentration fluctuates between 8-128 μM. Ca^{2+} is the most abundant cation in the Narmada river system and varies between 160 and 1426 μM, 160-865 μM in the tributaries. Mg^{2+} varies between 53 and 1078 μM and from 53 to 1078 μM (mean-504 μM) in major tributaries. Dessert et al. (2001) and Das et al. (2005) have observed similar concentrations for cations in rivers draining the northern Deccan Trap and the Krishna river basin with the other west flowing rivers, respectively.

Fig. 4.25 A shows clustering of water composition in the middle part of the ternary plot with a large scattering of the data. Fig. 4.25 B shows a comparison between data of present analysis with multi-annual data of the basin. Fig. 4.26 A shows the relative distribution of major cations in the Narmada mainstream, upstream locations Dindori (N1) and Manot (N2). In Fig 4.26 B, water composition at three midstream stations (Barmanghat, Sandia and Hoshangabad) show identical relative abundance of cations, whereas Handia (N7) shows shift towards $Na^+ + K^+$ end in ternary plot. In Fig. 4.26 C, the Narmada river at Mandleshwar and Rajghat, show similar patterns whereas, at Garudeshwar it depicts significant increase in $Na^+ + K^+$ and Ca^{2+} or decrease of Mg^{2+} concentrations. Water composition in ternary plots of downstream locations on the Narmada mainstream suggests an increase in $Na^+ + K^+$ ions. The tributaries show large variations in relative abundance of different cations in comparison to the Narmada mainstream.

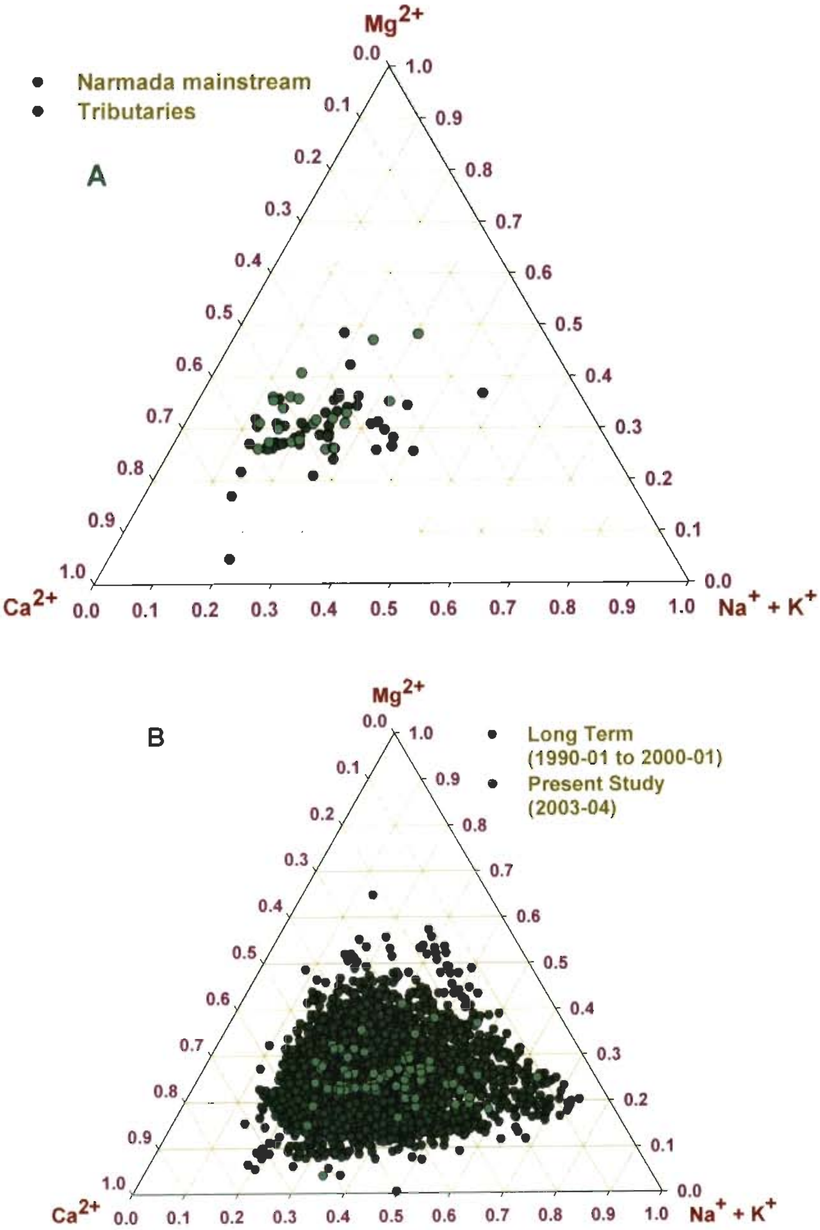


Fig. 4.25 Ternary plots illustrate the relative abundance of major cation in the Narmada mainstream and tributaries; A-Samples from present study and B-comparison with multi-annual data.

The upstream tributaries (Fig. 4.27 A), depict relative abundance of Ca^{2+}. In contrast to the upstream tributaries, midstream and the downstream tributaries, illustrate large variations among the relative abundance of major cations. The Hiran river shows high

$Na^+ + K^+$ whereas, the Sher river shifts towards Ca^{2+} and Mg^{2+} line (Fig. 4.27 B). The Shakkar river water is dominated by Ca^{2+}, the Ganjal river water is dominated by $Na^+ + K^+$ ions. (Fig. 4.27 C). Downstream tributaries show large scattering of data, the Kundi river falls towards $Na^+ + K^+$ and Mg^{2+} line whereas, the Orsang river shows shift towards Ca^{2+} and $Na^+ + K^+$ line (Fig. 4.27 D).

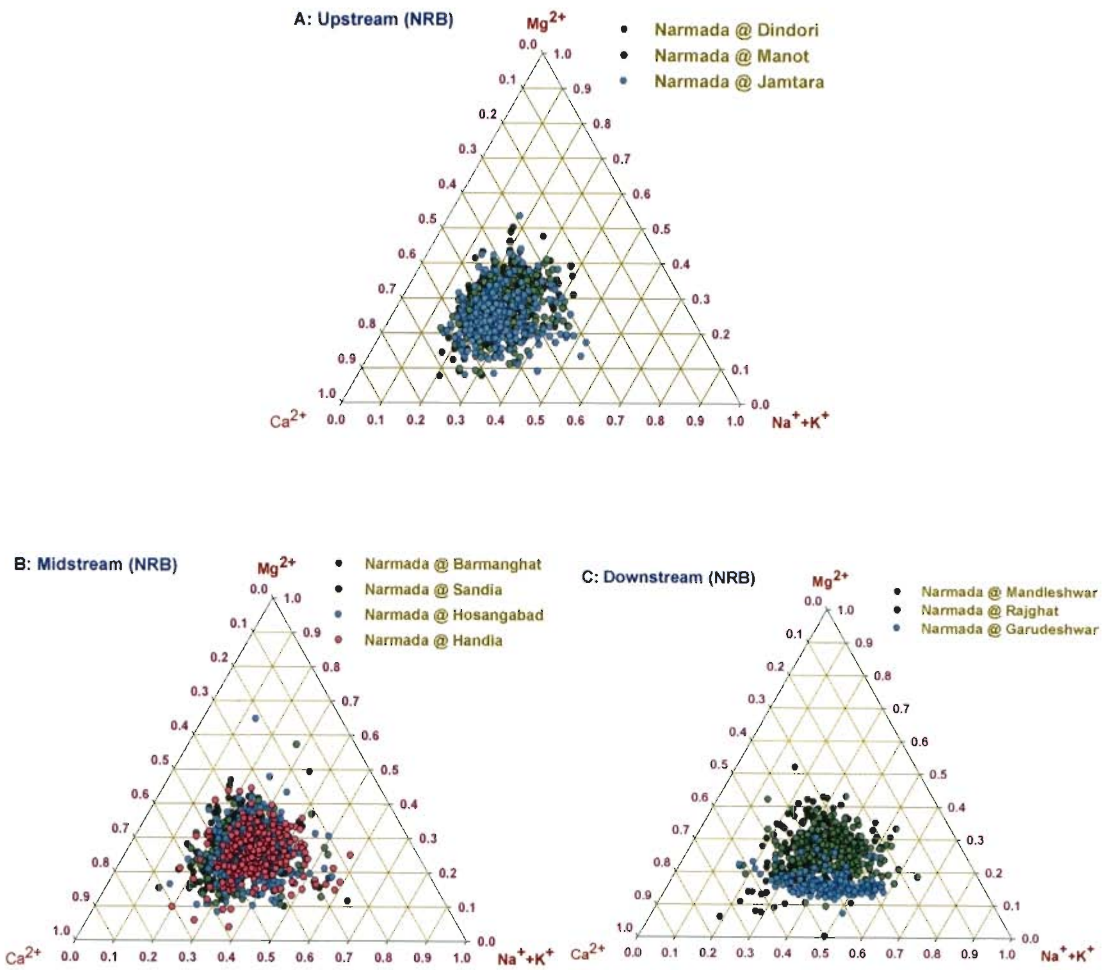


Fig. 4.26 Ternary plots (multi-annual data) of major cations for the Narmada mainstream; A- upstream locations; B-midstream locations and C-downstream locations

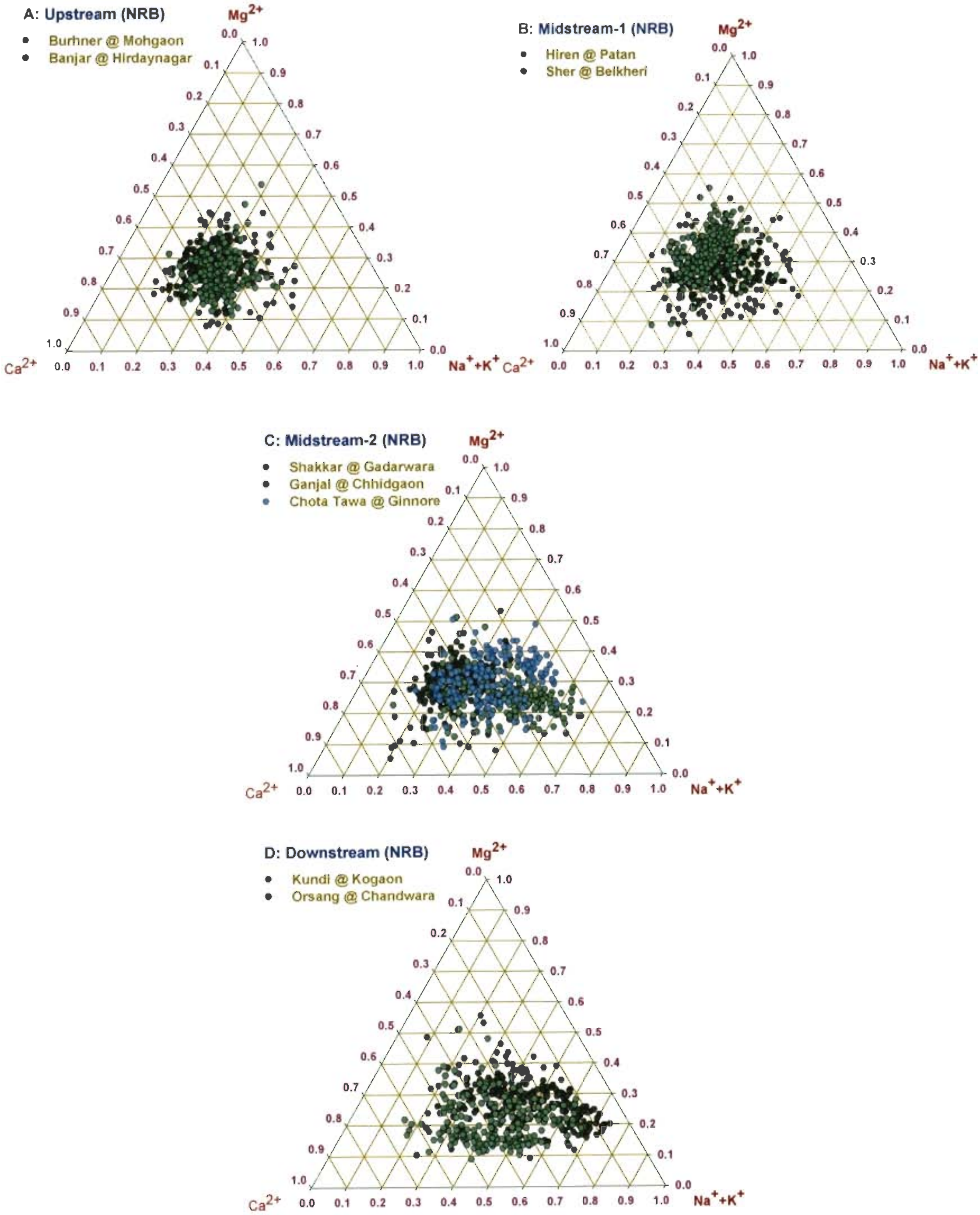


Fig. 4.27 Ternary plots (multi-annual data) of major cations for the major tributaries; A- upstream locations; B-midstream locations (1); C-midstream locations (2) and D-downstream locations

Fig. 4.28 A shows the variations in mean concentrations of major cations in the Narmada mainstream at different locations. Increase in Ca^{2+} concentrations at Jabalpur indicates the control of carbonate rocks (Bheraghat marble rocks) over water chemistry. A small carbonate outcrop occurs along the river course and exerts strong influence on water chemistry. Sample no R46 BG and R46 SG, collected from upstream (N3^) and downstream (N3#) of marble rocks respectively show the influence of marble on Ca^{2+} concentrations. All of the river water samples collected in the present study show super-saturation with respect to Ca^{2+}. Downstream of Jabalpur (N#) and Handia (N7), Mg^{2+} concentration increase due to presence of dolomites. Changes in Na^{+} concentrations show good correspondence with dissolved silica concentrations in the Narmada mainstream. The major ion concentrations in the tributaries are mainly controlled by lithology of the catchment. The upstream tributaries (the Burhner and the Banjar rivers) drain lithologies other than basalt, midstream tributaries (the Sher, Shakkar and the Hiran rivers) drain calcified quaternary soils whereas the Ganjal and Orsang rivers flow through saline soils and hence, the water composition varies accordingly (Fig. 4.28 B).

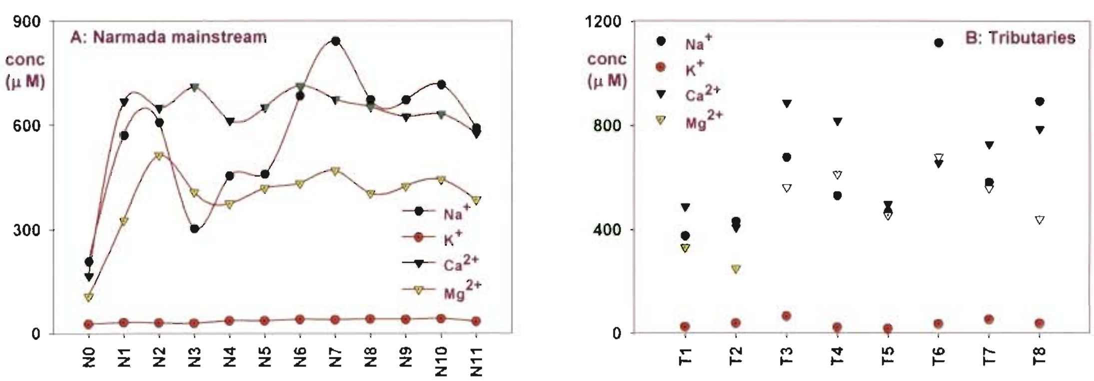


Fig. 4.28 Spatial variations in cation concentrations (mean) in the Narmada mainstream (A) and the tributaries (B)

A comparison of major cations, alkalinity, silica concentrations and TDS and their Na-normalized molar ratios draining Deccan basalts (Present study and Dessert et al. (2001)) and other basaltic terrains are presented in Table 4.8.

Table 4.8 Major ion concentrations in the rivers draining basaltic terrain

Study area	Na^+ (μM)	K^+ (μM)	Ca^{2+} (μM)	Mg^{2+} (μM)	HCO_3^- (μM)	SiO_2 (μM)	TDS Mg l^{-1}	Ca/Na	Mg/Na	K/Na
Narmada basin[1]	174-2627	8-128	160-1426	53-1078	680-5616	149-592	70-480	1.46±83	0.96±0.4	0.08±0.05
Krishna Basin[2]	100-2950	5-97	57-1162	36-1206	75-2333	91-685	27-640	N/A	N/A	N/A
North Deccan trap[3]	47-2794	7-163	31-919	17-1271	2720	187-836	17-717	N/A	N/A	N/A
Caribbean Island[4]	188-808	11-56	32-697	31-380	578 (mean)	213-1000	27-255	N/A	N/A	N/A
Central Siberia[5]	57-791	2.6-148	89-950	2.6-156	307-1125	5-336	30-70	N/A	N/A	N/A
Reunion Island[6]	90-1940	10-100	50-700	35-460	250-3560	200-800	24-580	0.6±0.3	0.6±0.4	0.1±0.08
Sao Miguel Island[7]	305-2840	33-355	29-245	41-270	202-4120	268-1250	67-447	0.72±0.02	0.5±0.1	0.28±0.02
Iceland[8]	N/A	N/A	N/A	N/A	N/A	420-2700	39-102	0.4±0.2	0.3±0.2	0.05±0.04
Parana basin[9]	231 (mean)	94	173	86	N/A	N/A	N/A	2.5±1.0	1.3±0.9	0.4±0.3
Columbia[10]	217 (mean)	28	450	206	354	N/A	N/A	2.07	0.95	0.12
Mount Cameroon[11]	397-1208	83-201	141-420	205-775	610-3677	370-1034	N/A	N/A	N/A	N/A

(1- Present Study, 2-Das eat al. (2005); 3-Dessert et al. (2001); 4-Rad et al. (2006); 5-Pokrovsky et al. (2005); 6-Louvat and Allegre, (1997); 7- Louvat and Allegre, (1998); 8- Gislason et al. (1996); 9/10-Dessert et al. (2003); 11- Benedetti et al. (2003) and N/A: Data not available)

Ca/Na molar ratios between 0.15 and 3.55 (mean-1.46) and Mg/Na molar ratios between 0.03 and 2.52 (mean-0.96) in Narmada basin show good resemblance with the molar ratios given by Gaillardet et al (1999) and Dessert et al (2003), however HCO_3/Na ratios in the basin vary between 2.17 and 13.3 (mean-6.4) are still higher (Fig. 4.29 A and 4.29 B). A few samples in the basin, also show high Na normalized ratios (HCO_3/Na>10), similar to the observations by Dessert et al. (2003) for rivers from Hawaii. In contrast to rivers draining basalts, small streams draining granitoids are characterized by low Na-normalized molar ratios (Meybeck, 1986; Edmond et al., 1995; White and Blum, 1995).

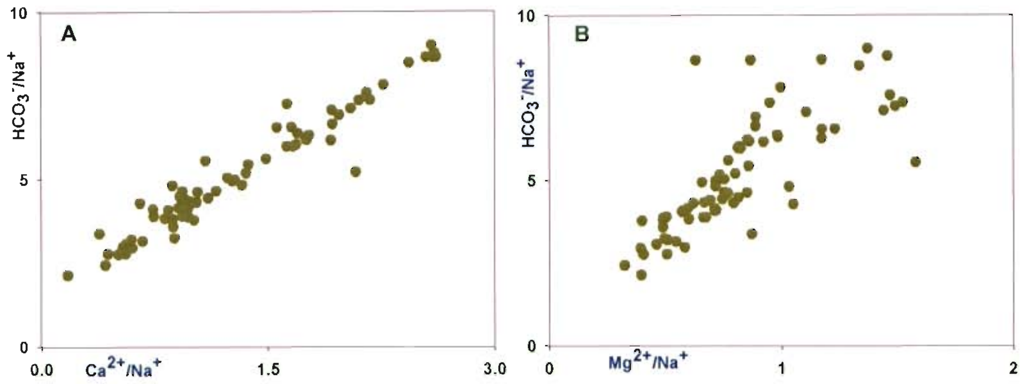


Fig. 4.29 Scatter plot of normalized HCO_3^- with normalized Ca^{2+} (A) and Mg^{2+} (B)

Plots of Na-normalized Ca^{2+}, HCO_3^- and Mg^{2+} are shown in Fig. 4.30 (A and B) to facilitate comparison with similar plots by Gaillardet et al (1999) and Dessert et al (2003) for rivers draining silicate terrains. The figure is plotted using the data collected in the field trips (2003 to 2004) and the multi-annual data. A good linear relationship is seen between molar ratios in the river water of the Narmada. The Ca^{2+}/Mg^{2+} ratios in the basin are approximately 1.5 (excluding one sample (R7; Aug 2003) from the Hiran river). According to Dessert et al. (2003) relative low Ca^{2+}/Mg^{2+} ratios of Ca^{2+} and Mg^{2+} rich rivers (0.7-1.8) are consistent with those of basaltic rocks (0.9-3). The ratios indicate that silicates particularly basalt weathering, is the major source of dissolved loads in the Narmada basin.

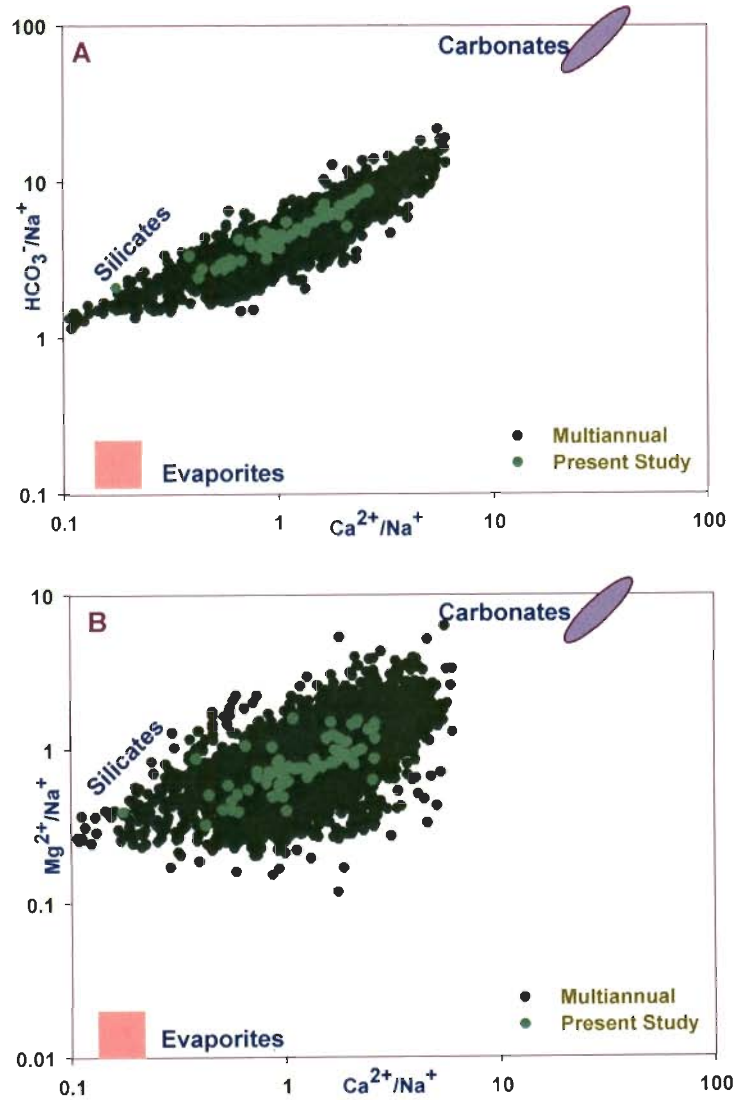


Fig. 4.30 Mixing diagrams using Na-normalized molar ratios in the dissolved phase of the Narmada basin

4.6.3 Dissolved Silica

Silica in river water is present largely as H_4SiO_4 derived from the weathering of silicate minerals. Dissolved silica at pH values less than 9 is present as monomeric silicic acid H_4SiO_4. At pH values above 9, H_4SiO_4 dissociates to $H_3SiO_3^-$ and $H_2SiO_4^{2-}$. All the water samples analyzed in present study and the long term data indicate that pH values in the Narmada basin always remains less than 9, hence H_4SiO_4 or SiO_2 is the common species in the Narmada river. The dissolved silica concentrations in river water samples collected during present study (Table 4.7) vary from 149 to 592 μM. The SiO_2 concentrations in the Narmada mainstream vary from 166 to 592 μM, whereas the tributaries contain 149 to 577 μM. Fig. 4.21(SiO_2) shows the variation in dissolved silica concentration in the Narmada mainstream at different locations and the concentrations in major the tributaries respectively. The SiO_2 abundances in river water are between those expected based on solubility of quartz (~100 μM) and amorphous silica (~2000 μM) at 25°C. SiO_2 concentrations observed in the Narmada river are relatively higher in comparison to the Yamuna river (67-378 μM; Dalai et al., 2002), Amazon river (60-160 μM; Gaillardet et al 1997), Congo river (140-210 μM; Dupre et al., 1996), Ganga-Brahmaputra river system (71-296 μM; Sarin et al., 1989), and the Indus river (40-292 μM; Ahamd et al., 1998), all of which flow over non-volcanic rocks. The SiO_2 concentrations in the Narmada river are of similar order to the rivers draining mostly volcanic rocks such as, the Krishna river (91-685 μM; Das et al 2005), Reunion Island (200-800 μM; Louvat and Allegre, 1997), Sao Miguel Island (268-1250 μM; Louvat and Allegre, 1998) Caribbean Island (213-1000 μM ; Rad et al., 2006), Iceland (420-2700 μM; Gislason et al., 1996), Mount Cameroon (276-1034 μM; Benedetti et al., 2003) and the Nyong basin (490-1086 μM; Viers et al., 2000).

Fig. 4.31 shows monthly SiO_2 concentrations at three locations, Barmanghat, Handia and Garudeshwar on the Narmada mainstream. High dissolved concentrations are observed during summer season with low flow in river. Low temperature during winter months of January shows less SiO_2 concentrations, whereas in May, dissolved silica is very high.

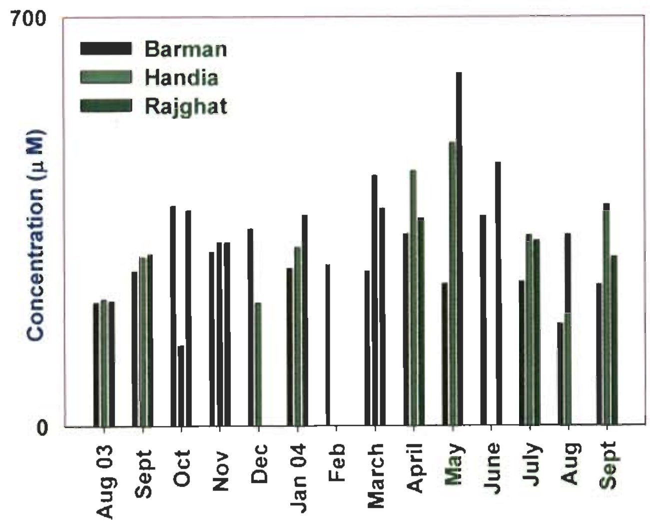


Fig. 4.31 Monthly silica concentrations in the Narmada mainstream at three locations (from the upstream, midstream and downstream basin).

4.6.4 Seasonal Variations

Fig. 4.32 A and Fig. 4.32 B show the seasonal variations in water chemical parameters (pH, TDS, Na^+, K^+, Ca^{2+}, Mg^{2+}, HCO_3^-, Cl^-, SO_4^{2-} and SiO_2) in the Narmada river mainstream and tributaries respectively. It is evident from the figures that the most of the major species, pH and TDS show high concentrations during non-monsoon season. The samples collected in August 2003 and September 2004 show significant variations, due to differences in river runoff at the time of sampling.

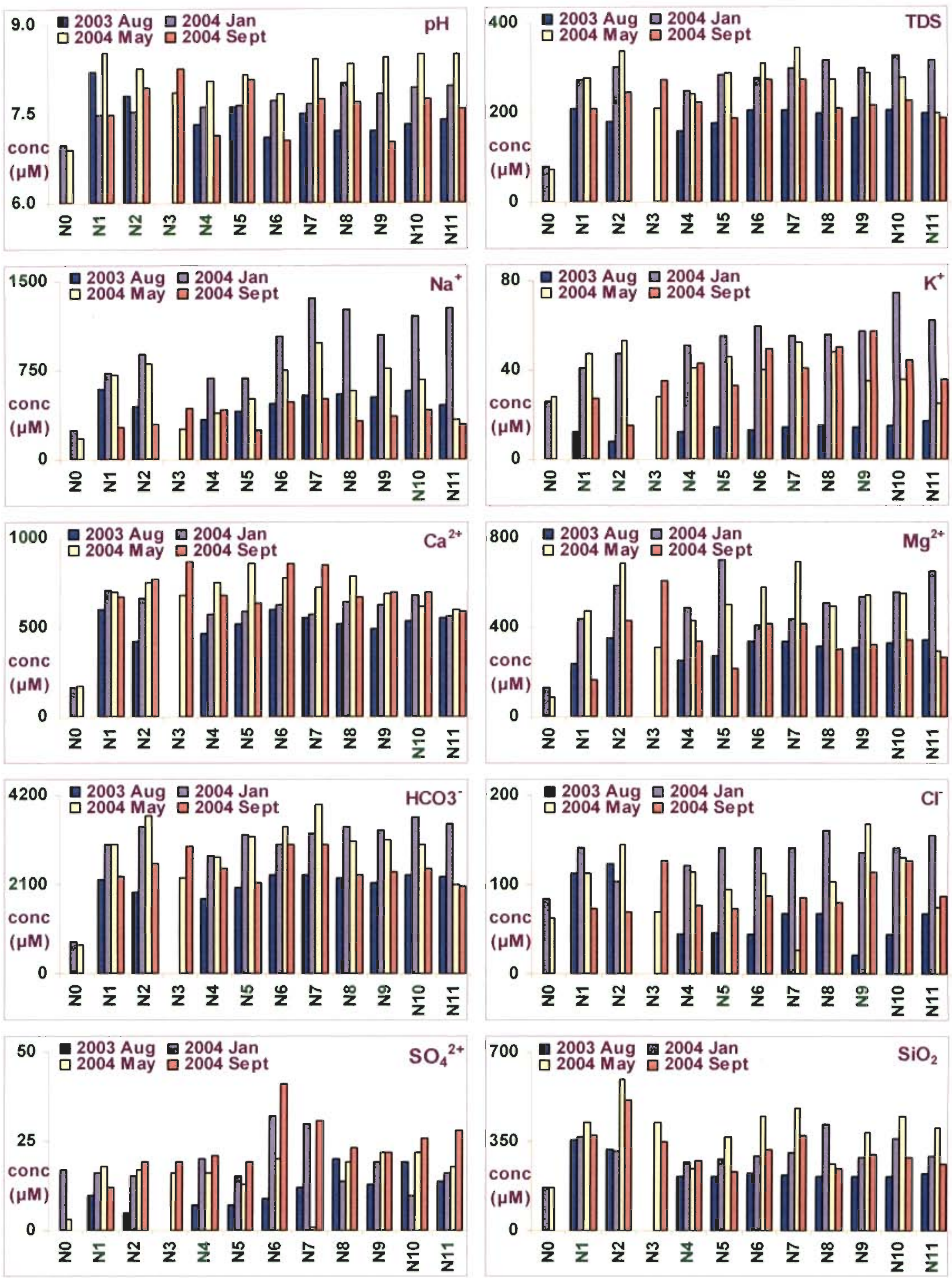


Fig. 4.32 A Seasonal variations in pH, TDS, major ions and dissolved silica in the Narmada river

Fig. 4.32 B Seasonal variations in pH, TDS, major ions and dissolved silica in the major tributaries

Temporal and spatial variations in major dissolved species in any river water may be a result of cumulative effect of a number of factors, which can be categorized as, (i) physical, and (ii) climatic. Lithology, basin area, relief are the physical factors which control the spatial variations in the Narmada river, since these factors remain identical for the particular sampling location throughout the period. Consequently climatic components such as rainfall, river runoff or water discharge and temperature are among the important natural factors that control the daily, seasonal, annual (temporal) variations of water compositions. Moreover, in recent past, alterations in river water compositions due to human interference have been very significant. Climate, characterized by alternating wet and dry seasons may favor weathering reactions, that produces considerably large amounts of soluble inorganic matter at some times of year than at other season. Streams in regions having this kind of weather may fluctuate greatly in volume of flow, and the water may have a wide range of chemical composition. The influence of climate on water composition may thus be displayed not only in amount and kinds of solute ions, but also in the annual regime of water composition fluctuations. River runoff or water discharge in the Narmada river is directly dependent upon rainfall whereas, seasonal variations are primarily related to substantial variation in discharge during different seasons. Variation in the average rainfall of the world's different climatic zones is an important factor in extent and type of weathering reactions. Most rainfall in the Narmada river, occurs during the five months of monsoon, which result in peak flows in the river. A major part of total dissolved loads is transported during this period, but with low ionic concentrations. During the monsoon period, increased input of CO_2 from atmosphere in the form of dissolved CO_2 in rainwater plays an active role in chemical weathering. Dissolved constituents are more concentrated in waters during non-monsoon and show significant variations during different seasons. Low river runoff and subsequently increased residence time, support more chance for rock-water interaction. According to Drever (1997), time in the sense of time of contact between rock and water, is probably the most important variable in determining the chemistry of runoff from igneous rocks, but contact time is itself a function of other environmental parameters.

4.6.5 Average Chemical Composition

To calculate average concentrations, first discharge weighted fortnight concentrations (total 24 days in a year) are calculated and are added and then divided by total water discharge of these 24 days to obtain mean concentrations (Equations 1 to 5). These mean concentrations are taken as annual mean for the particular year at that particular location. Similarly concentrations during high flow and low flow are calculated form the discharge weighted concentrations during monsoon (June to Oct.; 10 samples) and non-monsoon (Nov to May; total 14 samples) (Table 4.9). The data is analyzed carefully for any missing sample (which is very rare) and wherever a gap existed, the missing values were replaced by average values for same duration of the rest of the years.

The following equations present the procedure opted to calculate the flux,

$$F_{fn} = Q_{fn} \times C_{fn} \quad (1)$$

$$F_{fn(t)} = F_{fn1} + F_{fn2} + \ldots\ldots\ldots\ldots + F_{fn24} \quad (2)$$

$$C_{fn\,(A)} = F_{fn(T)}/Q_{fn(T)} \quad (3)$$

$$C_{fn\,(HF)} = F_{fn(HF)}/Q_{fn(HF)} \quad (4)$$

$$C_{fn\,(LF)} = F_{fn(LF)}/Q_{fn(LF)} \quad (5)$$

Where F = flux, Q = discharge ($m^3\ s^{-1}$), C = concentration ($mg\ l^{-1}$)

HF = High flow (monsoon), LF = Low flow (non-monsoon) and AM = Annual mean

Table 4.9 Average Chemical Composition of the Narmada river (TDS in mg l^{-1}, others in μ M) (HF- high flow; LF- low flow and AM- annual mean)

	Concentration														
	HF	LF	AM	HF	LF	AM	HF	LF	AM	HF	LF	AM	HF	LF	AM
	Dindori (N1)			Manot (N2)			Jamtara (N3)			Barman (N4)			Sandia (N5)		
K	48	34	46	46	34	45	45	38	42	46	39	43	50	43	49
Na	246	380	276	253	404	264	279	276	278	293	356	312	432	513	448
Ca	530	750	584	533	738	547	488	513	497	572	605	575	729	791	739
Mg	297	459	336	279	443	290	252	295	268	275	408	306	378	470	395
HCO_3	1655	2556	1860	1642	2459	1701	1538	1737	1616	1752	2149	1838	2401	2812	2481
Cl	188	181	190	169	181	170	172	156	171	177	181	177	191	197	191
SO_4	56	58	58	53	81	54	43	31	39	48	41	46	51	45	48
SiO_2	406	511	431	467	529	473	434	449	444	397	475	422	341	484	379
TDS	175	251	193	177	248	182	166	178	172	181	215	189	231	270	239
	Hoshangabad (N6)			Handia (N7)			Mandleshwar (N9)			Rajghat (N10)			Garudeshwar (N11)		
K	52	45	50	44	45	44	51	47	51	55	51	54	28	29	29
Na	368	606	427	379	602	438	434	659	472	519	911	589	505	805	582
Ca	596	775	637	568	765	625	645	741	660	664	780	682	715	744	738
Mg	301	496	341	338	496	378	348	536	375	375	629	415	239	296	256
HCO_3	1922	2893	2142	1962	2795	2191	2165	2873	2274	2268	3214	2422	1925	2198	2028
Cl	176	202	181	183	234	197	194	238	201	227	385	253	346	511	385
SO_4	48	47	47	43	52	45	61	53	60	66	80	68	101	111	107
SiO_2	377	465	400	377	474	411	413	478	424	472	481	471	211	210	210
TDS	194	276	213	196	272	217	218	279	227	234	319	247	199	232	211

Table 4.10 Average Chemical Composition of major tributaries (TDS in mg l^{-1}, others in μ M) (HF- high flow; LF- low flow and AM- annual mean)

	Concentration			Concentration			Concentration			Concentration			Concentration		
	HF	LF	AM	HF	LF	AM	HF	LF	AM	HF	LF	AM	HF	LF	AM
	Burhner @ Mohgaon			Banjar @ Hirdeyanagar			Hiran @ Patan			Sher @ Belkheri			Shakkar @ Gadarwara		
K	46	36	45	49	53	50	55	60	56	45	42	44	44	45	44
Na	241	368	250	309	510	319	454	916	507	329	672	380	285	735	321
Ca	424	703	445	409	767	428	709	1156	757	632	1033	662	575	1160	624
Mg	225	384	234	236	412	245	324	794	371	397	875	458	305	885	348
HCO_3	1330	2269	1395	1411	2672	1477	2239	4423	2467	2131	4180	2352	1807	4463	2017
Cl	155	189	157	159	190	161	210	309	219	195	239	200	165	302	175
SO_4	51	50	51	49	47	50	61	69	62	59	62	56	50	57	51
SiO_2	423	460	430	420	480	426	380	415	384	504	641	519	469	571	479
TDS	148	225	154	154	258	160	224	403	243	219	389	237	190	412	208
	Ganjal @ Chhidgaon			Chota-Tawa @ Ginnore			Kundi @ Kogaon			Orsang @ Chandwara					
K	49	50	49	38	40	56	49	50	49	29	29	30			
Na	421	1330	464	353	718	508	673	1264	743	536	884	545			
Ca	609	953	628	527	716	759	717	753	757	725	650	726			
Mg	388	802	410	336	731	493	587	897	631	265	251	266			
HCO_3	2086	4425	2209	1849	3089	2675	2852	3786	3055	1981	1838	1985			
Cl	227	299	229	182	367	268	261	413	289	342	603	349			
SO_4	71	87	71	41	66	60	58	86	64	102	114	103			
SiO_2	556	647	558	377	609	541	594	674	635	227	192	227			
TDS	223	419	233	188	315	272	290	386	311	206	210	206			

Table 4.9 and 4.10 suggest that water compositions in two different seasons, show significant variations, most of the major ions show high concentrations during low flow (non-monsoon), whereas K^+ is generally high during monsoon. Although concentrations of major ions except K^+ are appreciably higher during non-monsoon, still the mean annual concentrations are quite close to high flow concentration. Since nearly 90% runoff in the basin occurs during monsoon season, high rainfall leads to rapid fluxing of water and involves less contact time.

Fig. 4.33 (A to J) shows the relationship between multi-annual fortnight data (major ion concentrations and TDS) water discharge at Hoshangabad (mid-stream location). All the dissolved species show a strong dependence on water discharge and indicate the effect of dilution during peak flow. Similar patterns are also observed for other locations in the Narmada mainstream and the tributaries. Dissolved nitrate and phosphate show positive trends with increased runoff. Rest of the major ions, silica and TDS shows significant decrease in the concentrations.

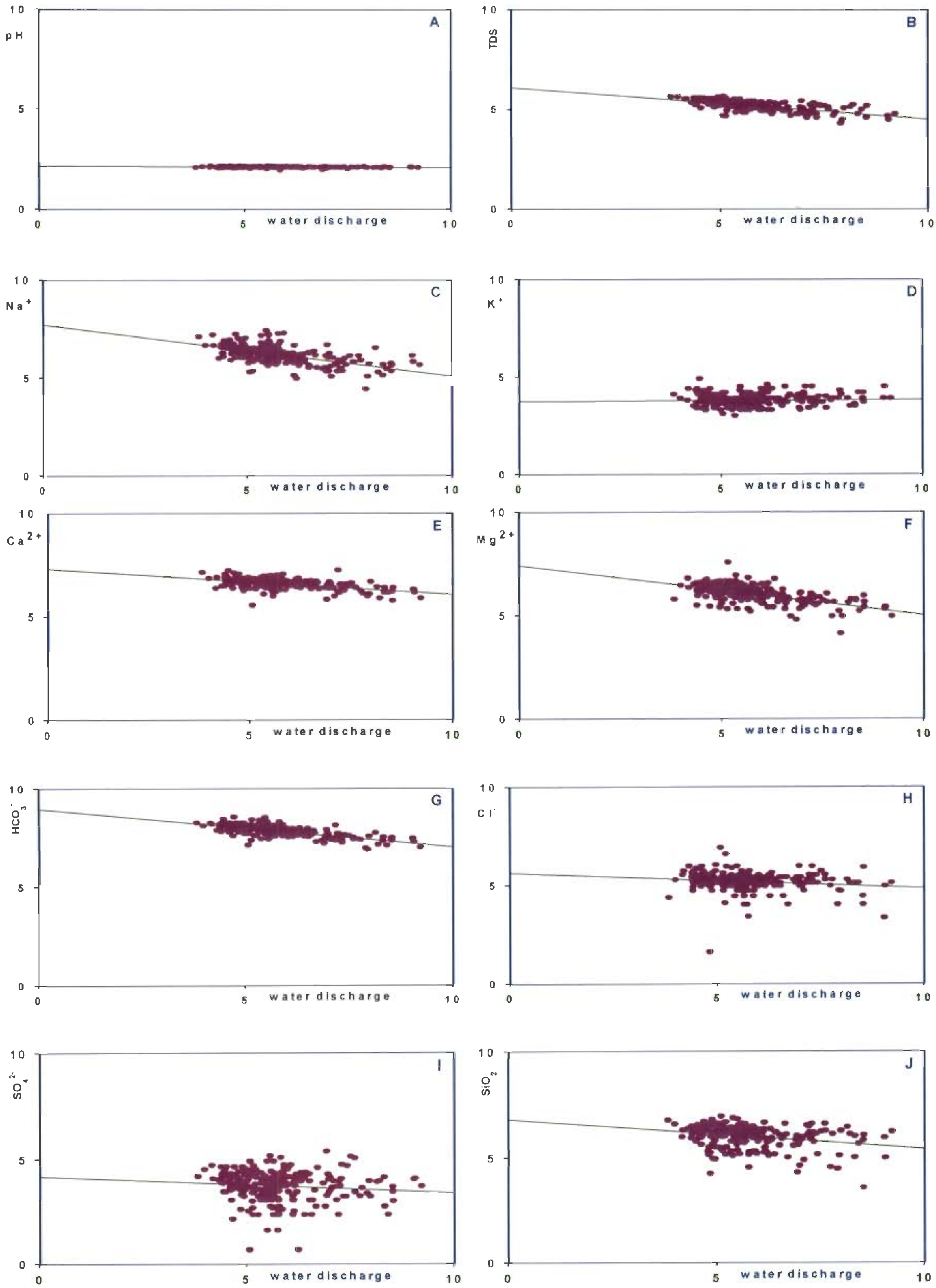


Fig 4.33 Influence of water discharge over chemical composition of the Narmada river at Hoshangabad

4.7 DISSOLVED FLUX

One of the key tasks of any river water chemical study is to assign flux of various dissolved species and their relative contributions to dissolved loads of rivers. On one hand, rivers play an important role in the evolution of ocean water composition, and on the other, water chemistry and dissolved and suspended loads reflect the various natural and anthropogenic processes, which are in operation in the river basin. Estimation of dissolved flux is also important to assign chemical weathering rates in the respective catchments. The solute transport of the Narmada mainstream and the major tributaries, are estimated in the present work from the discharge weighted mean annual loads of eleven water years (1990-2001) of dissolved constitutes. The average annual loads for individual water year are calculated from discharge weighted mean fortnight concentrations and subsequently mean of eleven years is calculated. Dissolved loads of major dissolved constituents (Na^+, K^+, Ca^{2+}, Mg^{2+}, HCO_3^-, Cl^-, SO_4^{2-} and SiO_2) at ten locations on the Narmada mainstream and nine locations on the nine major tributaries are presented in Table 4.11 and 4.12 respectively. Total dissolved solid (TDS) loads are calculated from major dissolved constitutes (including NO_3^-) for the Narmada mainstream and the major tributaries as well. Tables 4.11 and 4.12 also present percentage contribution during monsoon (high flow) and the percentage contribution of each element to the total load. The present work estimates, the most precise annual loads for the Narmada river. The final dissolved loads of the Narmada river to Arabian sea are approximately 7.40 $\times 10^6$ tons yr^{-1}. To calculate final loads, dissolved loads of Orsang river are added to the loads at Garudeshwar. Along the main course, the highest dissolved loads are observed at Mandleshwar (N9), which is about 7.55 x 10^6 tons yr^{-1}; thereafter it shows decrease in dissolved loads.

Table 4.11 Contribution of monsoon loads (HF%) to total load of the species, percentage contribution to total dissolved solid loads and flux of dissolved major species in the Narmada mainstream at different locations

	Load HF (%)	Load % of Total	Load (10^6 t yr^{-1})	Load HF (%)	Load % of Total	Load (10^6 t yr^{-1})	Load HF (%)	Load % of Total	Load (10^6 t yr^{-1})	Load HF (%)	Load % of Total	Load (10^6 t yr^{-1})	Load HF (%)	Load % of Total	Load (10^6 t yr^{-1})
	Dindori (N1)			Manot (N2)			Jamtara (N3)			Barmanghat (N4)			Sandia (N5)		
K	88	1.0	0.002	95	1.0	0.006	66	1.0	0.017	75	0.9	0.021	71	0.8	0.031
Na	81	3.3	0.007	89	3.4	0.018	63	3.9	0.065	68	3.9	0.090	67	4.3	0.157
Ca	83	12.2	0.027	91	12.1	0.065	62	11.4	0.187	72	12.3	0.286	69	12.4	0.454
Mg	81	4.1	0.009	89	3.9	0.021	60	3.8	0.062	65	3.9	0.090	66	4.0	0.148
HCO_3	81	58.4	0.130	90	57.3	0.308	60	57.4	0.941	69	59.2	1.379	67	63.3	2.313
Cl	87	3.6	0.008	93	3.5	0.019	64	3.6	0.060	72	3.4	0.080	70	2.9	0.105
SO_4	84	2.9	0.006	90	2.8	0.015	68	2.2	0.036	75	2.3	0.054	71	2.1	0.076
SiO_2	84	13.6	0.030	92	15.0	0.080	61	15.8	0.258	68	13.3	0.310	63	9.3	0.341
TDS	82	***99.1***	0.223	91	***99.0***	0.537	61	***99.1***	1.638	70	***99.1***	2.330	67	***99.1***	3.657
	Hoshangabad (N6)			Handia (N7)			Mandleshwar (N9)			Rajghat (N10)			Garudeshwar (N11)		
K	77	1.0	0.039	76	0.8	0.043	84	0.8	0.064	82	0.9	0.065	76	0.6	0.039
Na	66	4.6	0.184	69	4.5	0.243	77	4.7	0.353	72	5.4	0.402	69	6.3	0.438
Ca	71	12.0	0.487	72	11.5	0.613	82	11.7	0.881	80	11.1	0.822	77	14.0	0.978
Mg	66	3.8	0.156	70	4.2	0.227	78	4.0	0.303	74	4.1	0.302	74	2.9	0.204
HCO_3	68	61.1	2.473	71	61.5	3.291	80	61.3	4.626	77	59.9	4.441	75	58.2	4.073
Cl	73	3.0	0.123	72	3.2	0.171	81	3.1	0.233	74	3.6	0.266	71	6.6	0.460
SO_4	76	2.3	0.091	73	2.0	0.108	84	2.5	0.190	79	2.7	0.200	75	5.1	0.357
SiO_2	70	11.4	0.461	73	11.5	0.617	81	11.1	0.840	81	11.3	0.837	77	6.3	0.440
TDS	69	***99.2***	4.048	72	***99.3***	5.353	81	***99.2***	7.552	78	***98.9***	7.419	75	***99.9***	6.996

Table 4.12 Contribution of monsoon loads (HF%) to total load of the species, percentage contribution to total dissolved solid loads and flux of dissolved major species in tributaries at different locations

	Load HF (%)	Load % of Total	Load (10^6 t yr^{-1})	Load HF (%)	Load % of Total	Load (10^6 t yr^{-1})	Load HF (%)	Load % of Total	Load (10^6 t yr^{-1})	Load HF (%)	Load % of Total	Load (10^6 t yr^{-1})	Load HF (%)	Load % of Total	Load (10^6 t yr^{-1})
	Burhner @ Mohgaon (T1)			Banjar @ Hirdeynagar T2)			Hiran @ Patan (T3)			Sher @ Belkheri (T4)			Shakkar @ Gadarwara (T5)		
K	94	1.1	0.004	95	1.3	0.005	89	1.0	0.004	89	0.7	0.001	95	1.1	0.003
Na	89	3.7	0.012	93	5.1	0.018	81	4.7	0.019	81	3.7	0.005	85	3.7	0.010
Ca	89	11.6	0.036	93	10.4	0.037	85	12.4	0.051	85	11.1	0.015	89	12.0	0.034
Mg	89	3.8	0.012	93	3.7	0.013	80	3.8	0.015	82	4.7	0.006	83	3.6	0.010
HCO_3	89	55.5	0.172	93	56.3	0.203	83	61.1	0.249	83	60.2	0.083	86	56.6	0.162
Cl	91	3.7	0.011	96	3.8	0.014	87	3.5	0.014	87	2.9	0.004	90	3.3	0.009
SO_4	92	3.3	0.010	97	3.0	0.011	88	2.8	0.011	89	2.5	0.003	95	2.7	0.008
SiO_2	91	16.4	0.051	96	15.8	0.057	89	9.6	0.039	87	13.6	0.019	93	15.9	0.045
TDS	90	***99.1***	0.309	94	***99.3***	0.360	84	***98.9***	0.407	84	***99.3***	0.137	88	***98.9***	0.285
	Ganjal @ Chhidgaon (T6)			ChotaTawa @ Ginnore (T7)			Kundi @ Kogaon (T8)			Orsang @ Chandwara (T9)					
K	93	0.8	0.003	97	0.7	0.006	93	0.5	0.003	97	0.6	0.002			
Na	85	3.8	0.014	94	5.2	0.045	88	5.2	0.026	94	5.5	0.022			
Ca	91	10.7	0.039	96	10.2	0.088	93	9.6	0.048	97	14.1	0.057			
Mg	88	4.5	0.017	94	4.5	0.039	90	5.1	0.026	97	3.3	0.014			
HCO_3	88	58.3	0.215	95	60.5	0.521	91	58.3	0.293	97	59.3	0.241			
Cl	92	3.2	0.012	95	3.4	0.029	90	3.3	0.017	94	5.8	0.023			
SO_4	91	2.8	0.010	96	1.9	0.016	89	1.7	0.009	95	4.4	0.018			
SiO_2	93	15.2	0.056	95	11.6	0.100	93	13.3	0.067	98	7.0	0.028			
TDS	91	***99.3***	0.369	95	***97.9***	0.863	91	***97.1***	0.503	97	***99.9***	0.406			

Present estimation shows a significant departure from earlier estimations 13.11 x 10^6 tons yr^{-1} by Subramanian (1983) for the Narmada river. The reason may the difference in approach of calculation and the long term data we have used and may be the result of trapping of dissolved loads behind large dams in the basin. Dissolved loads at downstream Garudeshwar (N11) location are 7.4% less than upstream Mandleshwar (N9). Location Rajghat (N10) also falls in the reservoir area and shows about 2% decrease in dissolved loads than Mandleshwar. A number of small tributaries such as Hatni, Uri, Man, Udai and Goi also drain their water along with dissolved and suspended loads in between Mandleshwar and Garudeshwar, suggesting the overall trap of dissolved loads may be higher than 10% of dissolved loads at Garudeshwar. Major ions (Na^+, K^+, Ca^{2+}, Mg^{2+}, HCO_3^-, Cl^- and SO_4^{2-}) along with dissolved silica constitute about 99% of total dissolved loads in the river. Among the major ions, alkalinity alone, constitutes between 57- 63% of total loads, whereas, Ca varies between 11-14% and silica 6 - 16% of total dissolved loads. The relative abundance of different ions (percentage) in the Narmada mainstream at different sampling locations may be denoted as,

$$HCO_3^- >> Ca^{2+} > Na^+ \geq Mg^{2+} > Cl^- > SO_4^{2-} > K^+$$

To understand long term variations, three locations one each from upstream, midstream, and downstream of the basin, namely Dindori (N1), Hoshangabad (N6) and Garudeshwar (N11) have been selected and multi-annual fortnight data are used (Fig. 4.34 A,B,C). Any missing data (very rarely) was replaced by the average value of the same time period for rest of the years. A strong seasonal variation is noticed, which indicates the important role of rainfall and temperature over water chemistry. Geology, relief and other physical factors have no direct link with temporal variations. Construction of large reservoirs in the river course also act as important controlling factor in the Narmada river. Reservoir induced changes in water composition is observed from Fig. 4.34 C (Garudeshwar; N11), which show an increase in Ca, Na, HCO_3, SO_4 and Cl concentrations whereas decrease in K and SiO_2 concentrations, over a time period of eleven water years (1990-2001).

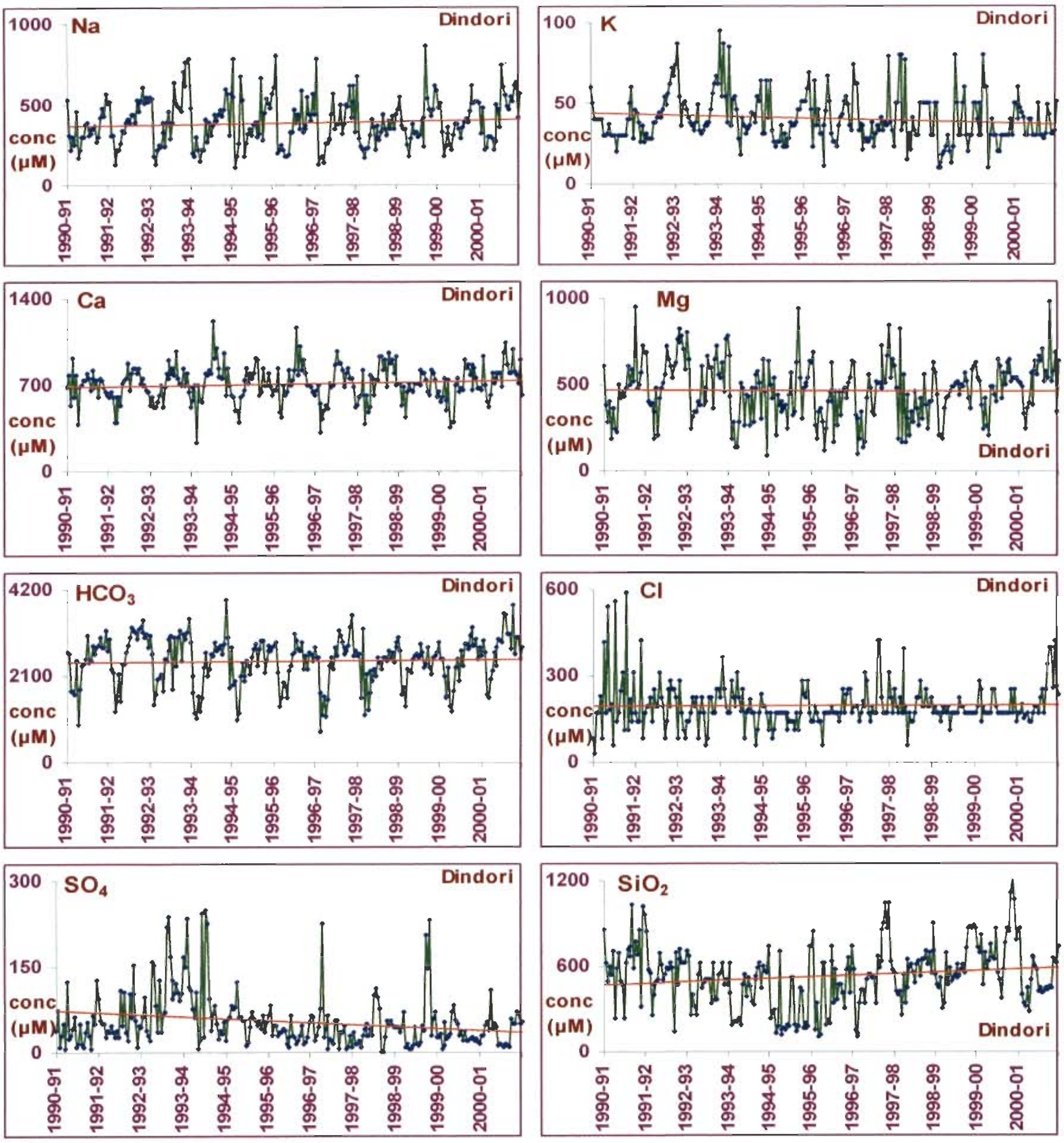


Fig. 4.34 A. Long term data of major constituents in river water at Dindori (N1)

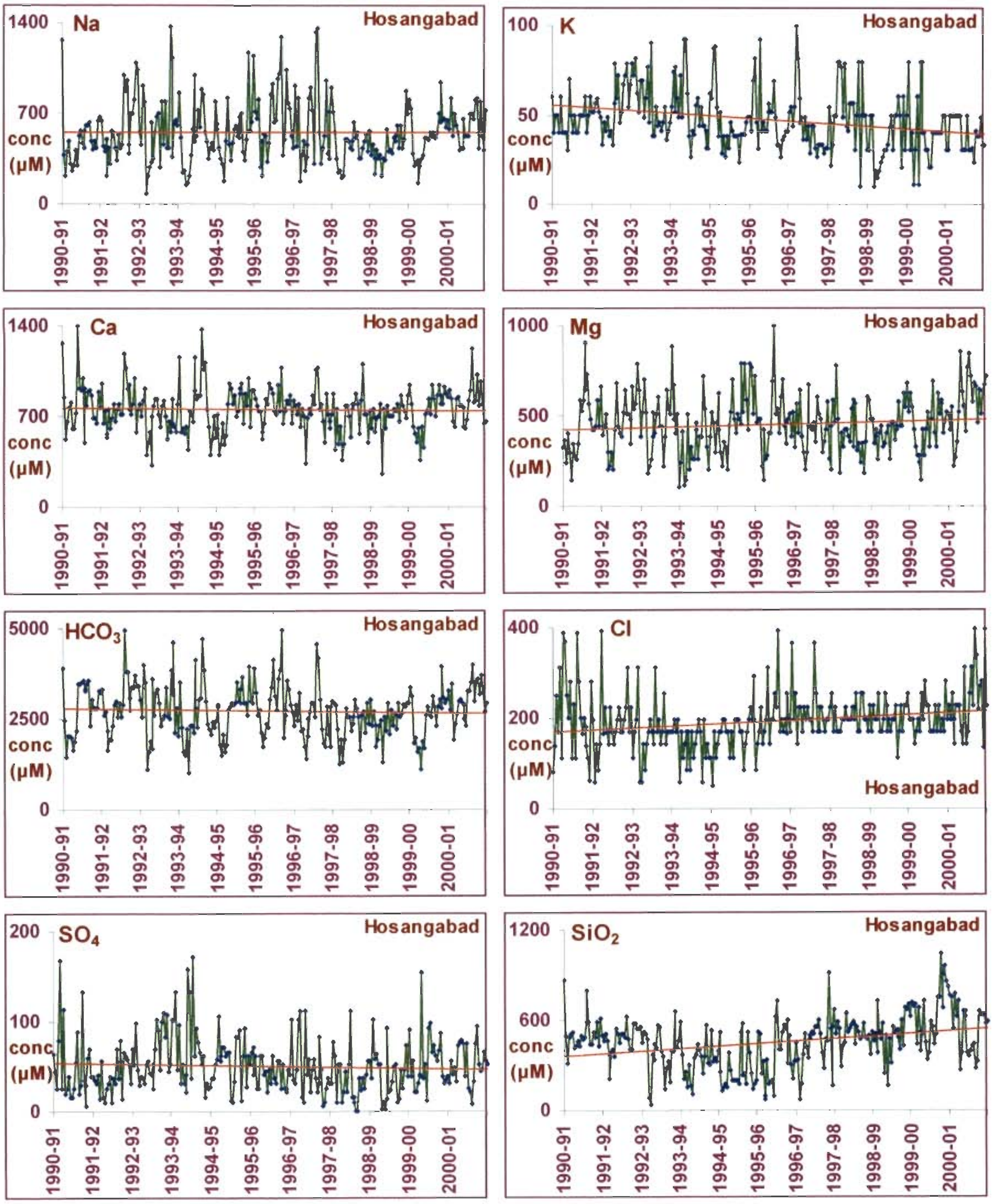


Fig. 4.34 B Long term data of major constituents in river water at Hoshangabad (N6)

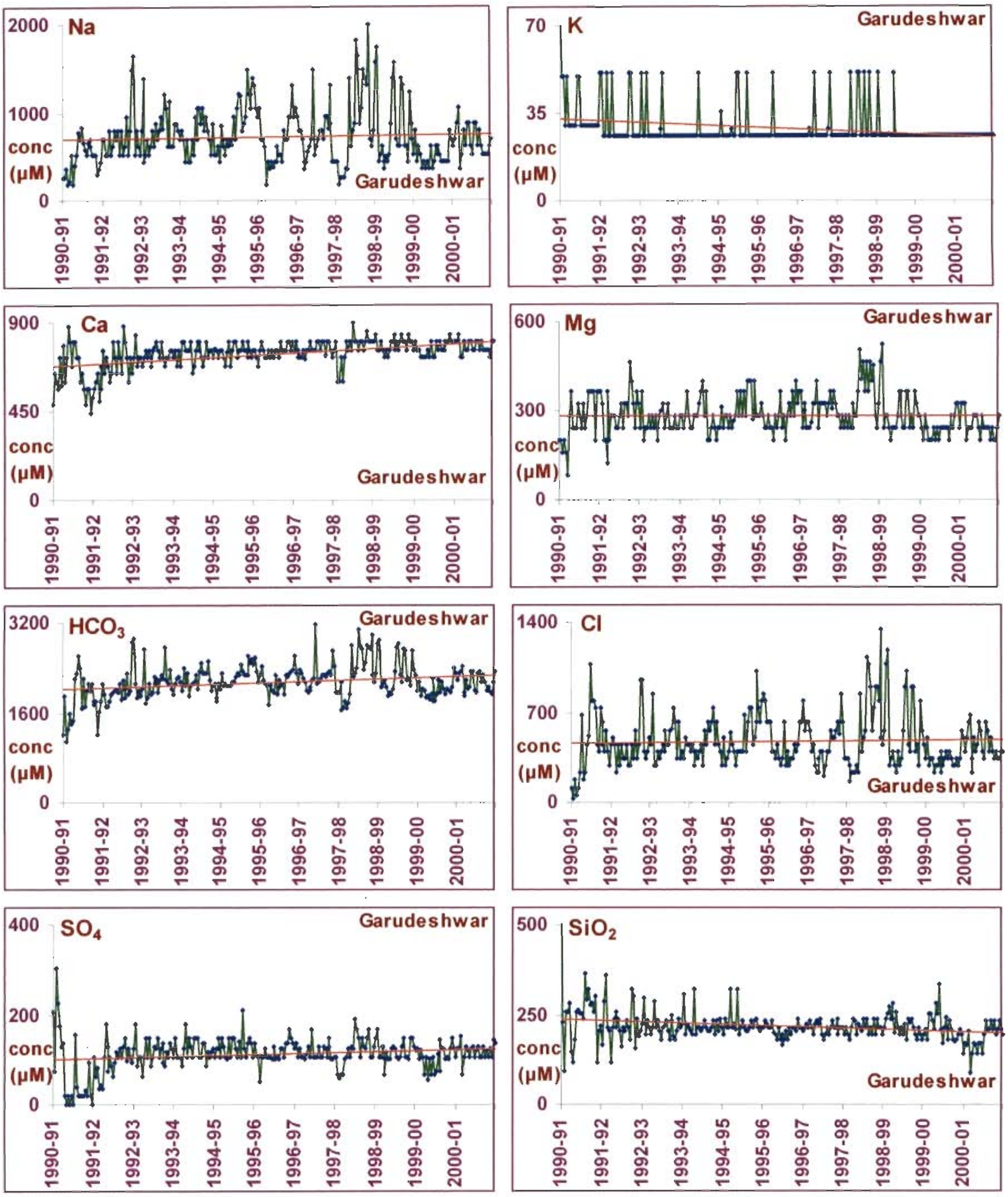


Fig. 4.34 C Long term data of major constituents in river water at Garudeshwar (N11)

4.8 SOURCE OF DISSOLVED CONSTITUENTS

Physical weathering processes are generally recognized as six times more effective than chemical weathering, while eroding the surface rocks (Lasaga et al., 1994). However, rock fragments or mineral particles, disintegrated by physical weathering processes escape simultaneously or subsequently undergo chemical reactions. The supply of naturally occurring solid reactants are ultimately controlled by geological processes. Decomposing agents may be water, air and biota. Mineral decomposition essentially consists of a number of chemical reactions (oxidation, hydration, carbonation, hydrolysis, base exchange and chelation), all of these reactions alter the primary mineral (unstable under prevailed environment) to secondary (more stable one) minerals and soluble constituents. Rivers transport these soluble species to the world oceans and act as link between land and coastal waters. Through the history of the Earth, chemical weathering has been a major buffer in the biogeochemical system, and maintains atmospheric O_2 and CO_2 content and global temperature within sustainable limits (Bloom, 2003). Basalts are primarily composed of silicate minerals (Plagioclase, Augite and Olivine). The weathering of silicates is primarily a process of hydrolysis, a type of mineral-water reaction that produces an excess of H^+ or OH^- ions in solution. The resulting hydrogen ions act upon the silicate minerals and form a very weak silicic acid. More commonly in the natural environments, the proton is supplied by carbonic acid. In most unpolluted catchments, lithology is the dominant source of solutes.

The Narmada river water derives its dissolved constituents, mainly from decomposition of various silicate minerals, and part of Ca^{2+} is derived from carbonate rocks exposed in the basin whereas, bicarbonate is derived from CO_2 consumption during the silicate mineral decomposition, soil CO_2 and bacterial respiration .

The chemical balanced equations for chemical weathering of the minerals that commonly occur in basalts can be written as:

$(NaAlSi_3O_8)_2 + 2CO_2 + 3H_2O \rightarrow Na^+ + 2HCO_3^- + 4H_4SiO_4\ (aq) + Al_2Si_2O_5(OH)_4$
Albite — ions in solution — silicic acid — kaolinite

$CaAl_2Si_2O_8 + 2CO_2 + 3H_2O \rightarrow Ca^{2+} + 2HCO_3^- + Al_2Si_2O_5(OH)_4$
Anorthite — ions in solution — kaolinite

$CaSiO_3 + 2CO_2 + 3H_2O \rightarrow Ca^{2+} + 2HCO_3^- + H_4SiO_4\ (aq)$
Wollastonite — ions in solution — silicic acid

$MgSiO_3 + 2CO_2 + 3H_2O \rightarrow Mg^{2+} + 2HCO_3^- + H_4SiO_4(aq)$
Enstatite — ions in solution — silicic acid

$FeSiO_3 + 2CO_2 + 3H_2O \rightarrow Fe^{2+} + 2HCO_3^- + H_4SiO_4(aq)$
Ferrosilite — ions in solution — silicic acid

$MgSiO_3 + 2CO_2 + 3H_2O \rightarrow Mg^{2+} + 2HCO_3^- + H4SiO_4(aq)$
Hypersthene — ions in solution — silicic acid

$FeSiO_3 + 2CO_2 + 3H_2O \rightarrow Fe^{2+} + 2HCO_3^- + H_4SiO_4(aq)$
Hypersthene — ions in solution — silicic acid

$Mg_2SiO_4 + 4CO_2 + 8H_2O \rightarrow 2Mg^{2+} + 4HCO_3^- + H_4SiO_4(aq)$
Olivine — ions in solution — silicic acid

$Fe_2SiO_4 + 4CO_2 + 8H_2O \rightarrow 2Fe^{2+} + 4HCO_3^- + H_4SiO_4(aq)$
Olivine — ions in solution — silicic acid

$Ca_3(PO_4)_2 + 6CO_2 + 6H_2O \rightarrow 3Ca^{2+} + 6HCO_3^- + 2H_3PO_4$
Apatite — ions in solution — phosphoric acid

In a simplification of the net global weathering process, atmospheric CO_2 is converted to bicarbonate, and balanced by a dissolved cation from the weathered bedrock, transported to the ocean by the rivers. Over million year timescales, the process of chemical weathering of the continents may shift considerable amount of CO_2 from the atmosphere to seafloor carbonate sediments via river runoff (Bluth and Kump, 1994).

Generally the solutes in river water analyzed are derived from more than one source, lithology acts as prime source for solutes, however inputs from atmosphere in the form of rainwater contents, groundwater and a number of anthropogenic sources may be equally important. Thus soluble elements in rivers are a mixture of atmospheric and ground water, spring water input and weathering of rocks (evaporite, sulfide, silicates and carbonates). The budget equation for any element X is given as,

$$[X]_{river} = X_{cyclic} + X_{groundwater} + X_{rock} + X_{anthropogenic}$$

The mixing relationships of the elemental or isotopic ratios can help to identify and quantify the end members and their relative proportions. Chemical weathering can be estimated from our budget of silicate/carbonate weathering and surface and hydrological data available for the basin. This type of approach allows comparison of rates of weathering between different basins, where sufficient data is available to estimate yearly discharge. Hence, chemical weathering based on a multi-annual data as is considered here, makes for a better justification. No considerable outcrops of sulfides have been reported from the Narmada basin, although saline soils are present in the middle and lower parts of the basin. Estimation of chemical weathering involves input of the fraction of various elements supplied to the river water in dissolved phase from the weathering of catchment rocks. No other anthropogenic source is identified as a major source for supply of major ions in dissolved water. Since rainwater composition is a major source for river water composition, to estimate chemical weathering rates, rainwater composition has been taken into account and subtracted from the measured river water composition. To determine silicate weathering rates it is also necessary to correct data for contributions from carbonate rocks exposed in the catchment area. Hence, it is crucial to know the share of these sources to the dissolved loads of river water to estimate chemical erosion rates in the basin.

Compared to surface and sub-surface, rainwater has lower concentrations of most of the dissolved solids, although the amount of dissolved solids in rainwater shows large temporal and spatial variations. Overall, rains carry a small amount of dissolved load, but contribute significantly to circulation of water by active participation in the hydrologic cycle. To determine the contribution of rain, it is essential to know the regional rainwater composition. During the study period a large number of rainwater samples have been collected from fourteen locations covering the entire basin (Fig. 4.35). Table 4.13 shows the locations of sampling of rainwater, and their mean composition. Considerable temporal and spatial variations are observed in the rainwater compositions; however mean values for individual locations only have been used here. For locations where rainwater compositions are not available, the data of nearby location data has been used.

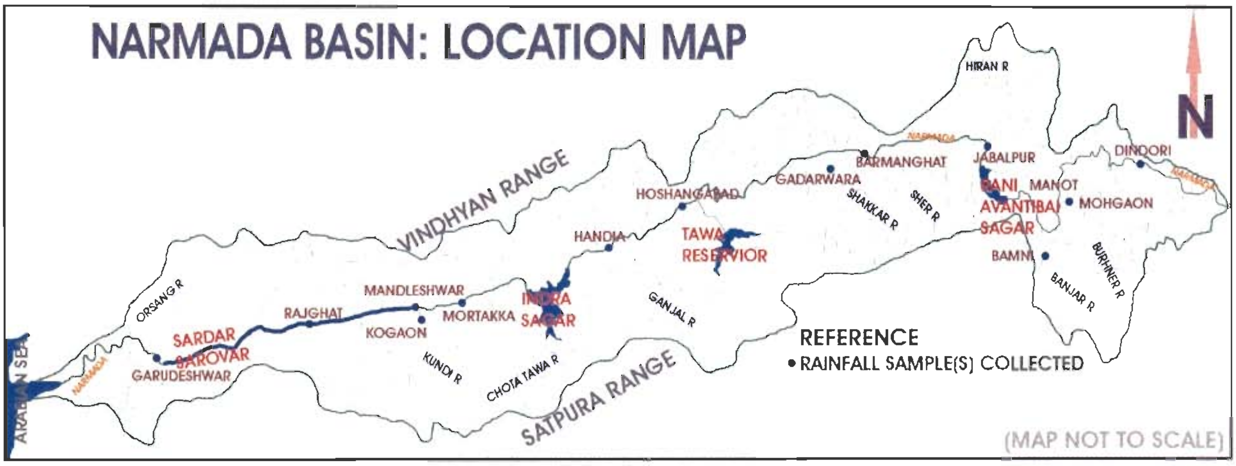


Fig. 4.35 Sampling locations of rainwater samples

Table 4.13 Sampling locations and average composition of rainwater in the Narmada basin

Location	n (36)	pH	Cl µM	NO_3 µM	SO_4 µM	Na µM	K µM	Ca µM	Mg µM	NH_4 µM
Dindori	3	6.5	33	23	3	31	3	28	3	0
Mohgaon	4	6.5	32	19	5	32	3	26	4	0
Manot	1	6.2	31	29	3	28	3	21	9	0
Bamni	2	6.8	32	10	5	29	1	24	2	5
Jabalpur	1	6.9	33	24	4	28	2	38	11	0
Barman	3	6.6	39	24	6	36	2	27	3	29
Gadarwara	2	6.6	35	24	4	34	3	28	4	22
Hoshangabad	1	6.5	30	28	2	27	3	17	5	0
Handia	3	6.7	18	21	6	19	2	27	3	0
Mortakka	4	6.8	47	36	6	45	3	22	10	30
Mandleshwar	1	7.4	39	26	4	40	2	21	12	0
Kogaon	3	6.9	36	22	5	35	2	27	5	7
Rajghat	4	6.5	27	38	4	26	4	26	5	4
Garudeshwar	4	6.8	39	19	6	38	3	26	1	0

The concentrations of Cl^- in rain water in the Narmada river basin varies between 18 and 47 µM. Cl/Na molar ratios vary between 0.96 and 119 µM, these ratios are close to typical marine end members (1.17). Presence of Ca^{2+} and Mg^{2+} in moderate amounts suggests contribution from atmospheric aerosols, whereas presence of $NO_3^-$and SO_4^{2-} and slight acidic pH values point to the contribution from vehicular fossil fuels burning. Silica is present in only traceable amounts, and may have been derived from wind blown dust.

Cl^- concentration in the Narmada river basin in the present study varied between 22 and 640 μM depending on location and season, whereas the Cl in rainwater varies between 18 and 47 μM. Large scale evapo-transpiration rates enhance the overall rain contributions. Hence, values of rainwater concentrations presented in Table 4.14 are also corrected for evapo-transpiration factor. Evapo-transpiration factor (ratio of runoff over precipitation) for each individual station is determined using average annual runoff values (Gupta and Chakrapani, 2005) and average annual rainfall at each location. The calculated evapo-transpiration factor for individual locations amplify 29 -80% of rainwater concentration. Hence, rainwater contributions to river water are corrected following the relation,

$$X_{rain} = (X/Cl)_{rain} \times Cl_{rain}/f_{et}$$

Where X_{rain} is the contribution of rain (μM) to river water; (X/Cl) is the molar abundance ratios in rains; f_{et} is the correction factor for evapo-transpiration. Evapo-transpiration factor f_{et} and the average composition of major ions in rainwater, X_{rain} (Na, K, Ca, Mg and SO4) at different locations in the basin are presented in Table 4.14.

Table 4.14 Evapo-transpiration factor and atmospheric contribution of major ions

Station	f_{et}	Na_{rain}	K_{rain}	Ca_{rain}	Mg_{rain}	$SO_{4\ rain}$
Amarkantak	0.36	47	5	44	5	5
Dindori	0.36	47	5	44	5	5
Mohgaon	0.61	80	8	66	10	13
Manot	0.51	56	6	42	17	6
Bamni	0.57	68	2	57	4	12
Jabalpur	0.61	71	5	99	28	10
Patan	0.74	107	4	150	42	19
Belkheri	0.80	181	5	136	13	10
Barmanghat	0.62	94	5	71	7	16
Gadarwara	0.46	63	6	52	8	7
Sandia	0.61	86	5	72	11	13
Hoshangabad	0.62	70	8	45	14	4
Chhidgaon	0.55	42	7	60	7	9
Handia	0.57	44	5	62	8	14
Mortakka	0.54	97	7	47	21	13
Mandleshwar	0.44	71	4	37	22	7
Kogaon	0.67	105	6	82	16	15
Rajghat	0.29	37	6	36	7	6
Garudeshwar	0.64	105	8	73	3	17
Chandwara	0.36	59	5	41	2	9

The dissolved major ion concentrations in rivers resulting from chemical weathering of the basin (X*) are calculated as:

$X^* = X_{river} - X_{rain}$

Where X = Na, K, Ca, Mg and SO_4. Table 4.15 presents the major ions in river waters of the Narmada basin after correction for atmospheric contributions. Total dissolved solids corrected for atmospheric inputs, TDS_w ($=\sum X^* + SiO_2$) is the amount of geo-chemically derived dissolved ions in river water. TDS_w in the Narmada river basin vary from 21 to 129 mg l^{-1} during different seasons. The average TDS_w monsoon (Aug 2003 and Sept 2004) and non-monsoon (Jan 2004 and May 2004) are calculated and presented in Table 4.16.

Table 4.15 Major ions in river waters of the Narmada basin after correction for atmospheric contributions (TDS- mg l^{-1}, others μM)

Sampling	Na^+	K^+	Mg^{2+}	Ca^{2+}	SO_4^{2-}	TDS_w
R1-Narmada	N/A	N/A	N/A	N/A	N/A	N/A
R2-Narmada	541	7	551	229	5	73
R3-Burhner	94	1	136	121	0	25
R4-Narmada	389	2	373	336	0	59
R5-Banjar	360	16	294	252	2	45
R6-Narmada	N/A	N/A	N/A	N/A	N/A	N/A
R7-Hiran	300	53	698	10	7	56
R8-Sher	373	4	383	266	0	59
R9-Narmada	246	7	391	242	0	45
R10-Shakkar	508	4	446	271	3	70
R11-Narmada	322	9	446	257	0	51
R12-Narmada	396	6	551	319	0	61
R13-Ganjal	375	7	633	506	12	89
R14-Narmada	494	9	491	326	0	62
R15-Narmada	449	9	470	296	7	59
R16-Narmada	449	11	452	286	6	58
R17-Kundi	497	10	584	433	8	74
R18-Narmada	539	10	503	322	13	66
R19-Narmada	347	9	484	337	0	56
R20-Orsang	473	13	424	258	3	53

Sampling	Na^+	K^+	Mg^{2+}	Ca^{2+}	SO_4^{2-}	TDS_w
R21-Narmada	191	22	116	125	12	24
R22-Narmada	680	36	665	429	11	77
R23-Burhner	557	31	543	431	11	64
R24-Narmada	833	41	620	572	9	79
R25-Banjar	582	82	307	259	40	49
R26-Narmada	N/A	N/A	N/A	N/A	N/A	N/A
R27-Hiran	636	54	1276	642	39	99
R28-Sher	416	43	836	876	19	95
R29-Narmada	584	46	501	477	4	63
R30-Shakkar	N/A	N/A	N/A	N/A	N/A	N/A
R31-Narmada	592	50	517	688	0	70
R32-Narmada	965	51	579	393	27	77
R33-Ganjal	812	53	403	490	36	69
R34-Narmada	1309	50	513	430	17	83
R35-Narmada	1155	49	592	486	1	89
R36-Narmada	980	54	591	513	12	79
R37-Kundi	417	85	486	807	17	71
R38-Narmada	1166	69	640	547	5	90
R39-Narmada	1172	53	491	644	0	82
R40-Orsang	N/A	N/A	N/A	N/A	N/A	N/A

(Table 4.15 Cont....)

Sampling	Na^+	K^+	Mg^{2+}	Ca^{2+}	SO_4^{2-}	TDS_w	Sampling	Na^+	K^+	Mg^{2+}	Ca^{2+}	SO_4^{2-}	TDS_w
May 2004							September 2004						
R41-Narmada	128	24	128	81	0	21	R61-Narmada	N/A	N/A	N/A	N/A	N/A	N/A
R42-Narmada	658	43	653	465	13	81	R62-Narmada	217	22	630	161	7	58
R43-Burhner	301	30	530	437	0	75	R63-Burhner	233	13	490	298	3	60
R44-Narmada	747	47	709	666	11	100	R64-Narmada	240	9	728	414	13	77
R45-Banjar	283	34	466	266	1	57	R65-Banjar	234	19	344	211	8	42
R46-Narmada	188	23	579	276	6	61	R66-Narmada	351	29	766	579	8	76
R46-Narmada#	157	23	490	285	1	54	R67-Hiran	224	21	657	400	0	72
R47-Hiran	1129	125	326	1036	0	93	R68-Sher	263	9	830	662	19	88
R48-Sher	N/A	N/A	N/A	N/A	N/A	N/A	R69-Narmada	321	38	605	330	5	58
R49-Narmada	293	36	675	422	0	60	R70-Shakkar	372	19	883	629	16	87
R50-Shakkar	807	39	517	904	9	88	R71-Narmada	159	28	565	202	6	47
R51-Narmada	420	41	788	485	1	77	R72-Narmada	418	42	810	402	37	76
R52-Narmada	679	32	730	561	16	88	R73-Ganjal	534	16	958	668	22	85
R53-Ganjal	2584	44	402	1032	6	129	R74-Narmada	460	37	788	404	17	78
R54-Narmada	927	47	656	689	0	95	R75-Narmada	221	44	622	281	10	54
R55-Narmada	477	41	740	472	5	70	R76-Narmada	288	53	656	297	15	62
R56-Narmada	689	32	654	519	15	81	R77-Kundi	366	51	984	453	25	79
R57-Kundi	637	48	541	484	0	69	R78-Narmada	379	38	657	335	20	64
R58-Narmada	638	31	584	541	16	81	R79-Narmada	195	28	520	264	11	49
R59-Narmada	232	17	521	287	1	58	R80-Orsang	1200	56	1071	624	7	113

4.9 CHEMICAL WEATHERING RATES (CWR)

The chemical weathering rates at each location (except Amarkantak) on the Narmada mainstream and major tributaries vary between 20 - 49 tons km^{-2} yr^{-1} (Table 4.16), with an average of ~30 tons km^{-2} yr^{-1}. Chemical weathering rates during monsoon are significantly higher than non-monsoon. Along the Narmada mainstream, at Manot highest weathering rates (49 tons km^{-2} yr^{-1}) are observed, followed by Hoshangabad with 38 tons km^{-2} yr^{-1}. A few tributaries show significantly higher weathering rates, such as the Shakkar river followed by the Ganjal river with 48 and 46 tons km^{-2} yr^{-1} respectively. Although chemical erosion is more effective during non-monsoon, approximately 84% of chemical load is derived during the monsoon season. The chemical weathering rates (monsoon) is little higher for tributaries, as compared to the in the sub-basin areas of the Narmada mainstream.

The chemical weathering rates calculated from the multi-annual data at different locations on the Narmada mainstream vary between 20 and 40 tons km^{-2} yr^{-1}, whereas for the major tributaries it varies from 21 to 64 tons km^{-2} yr^{-1}. The chemical weathering rates calculated from the multi-annual data and those calculated in present study show good correspondence for a number of locations. Dessert et al (2001) have estimated chemical weathering rates of 21-63 tons km^{-2} yr^{-1}. However, because of the strong data used in the present study, the present weathering rates may be considered to be more appropriate. The specific chemical weathering rates for the Narmada basin is higher than those of most of the world's large rivers (Table 4.17).

Table 4.16 Total dissolved solids (after rain input correction) and runoff during monsoon (high flow) and non-monsoon (low flow) and the chemical weathering rates at different locations in the Narmada river basin.

	TDS_w (mg l^{-1})		Runoff (%)		CWR (tons km^{-2} yr^{-1})			
	high flow	Low flow	high flow	Low flow	high flow	Low flow	total	Multi-annual
Amarkantak	----	23	----	----	----	----	----	----
Dindori	66	79	90	10	33.0	4.4	37.4	38.6
Mohgaon	42	69	93	7	21.4	2.6	24.1	24.9
Manot	68	90	92	8	43.6	5.0	48.5	40.2
Bamni	44	53	95	5	21.9	1.4	23.3	38.8
Jabalpur	76	58	70	30	19.1	8.7	27.8	31.4
Patan	64	96	87	13	19.1	4.1	23.2	23.0
Belkheri	73	95	92	8	17.4	2.0	19.4	21.4
Barman	51	62	76	24	18.4	7.0	25.4	27.7
Gadarwara	78	88	93	7	44.6	3.8	48.4	43.0
Sandia	49	73	77	23	16.8	7.5	24.3	30.4
Hoshangabad	68	83	79	21	28.8	9.3	38.1	28.3
Chhidgaon	87	99	93	7	42.6	3.6	46.3	64.2
Handia	70	89	81	19	26.6	7.9	34.6	30.5
Mortakka	57	79	82	18	20.4	6.3	26.7	20.6
Mandleshwar	60	80	83	17	22.9	6.3	29.2	31.3
Kogaon	77	70	97	3	19.8	0.5	20.4	39.8
Rajghat	65	86	83	17	24.0	6.5	30.6	30.1
Garudeshwar	53	70	85	15	17.5	4.1	21.6	21.0
Chandwara	83	0	99	1	28.8	0.0	28.8	29.4
Ginnore	----	----	97	3	----	----	----	55.1

Table 4.17 Chemical weathering rates in large world river basins and rivers draining basalts

River	CWR	Source
Large World rivers		
Amazon	25	Gaillardet et al. (2001) and reference therein
Congo/Zaire	6	
Orinoco	15	
Changjiang	65	
Brahmaputra	46	
Mississippi	24	
Yenissei	16	
Lena	14	
Mackenzie	19	
Parana	9	
Ganges	42	
Indus	18	
Rivers draining basalts		
Godavari	53	Ramesh and Subramanian (1993)
Narmada	30	Present work
Iceland	58	Gislason et al. (1996)
Columbia	24	Dessert et al. (2003)
Krishna	14	Das et al. (2005)
West Flowing rivers (India)	54	Das et al. (2005)
Sao Miguel	35	Dessert et al. (2003)
Reunion	102	Louvat and Allegre (1997)
Central Siberia	13	Pokrovsky (2005)
Jawa	326	Dessert et al. (2003)
Hawaii	34	Dessert et al. (2003)
M. Central	13	Negrel and Deschamps (1996)
Parana Traps	60	Dessert et al. (2003)
World average	24	

- **Comparison of Chemical and Physical Weathering Rates**

Fig. 4.36 shows a good correlation between physical and chemical weathering rates in the Narmada river basin, except at Manot and Mohgaon. Narmada at Manot and Burhner at Mohgaon demonstrate diverse trend due to the high river gradient. The Narmada at Manot and the Burhner at Mohgaon also represent locations with high physical and chemical weathering rates in the basin. Fig. 4.37 shows the spatial distribution of physical and chemical weathering rates in relative proportions at different locations.

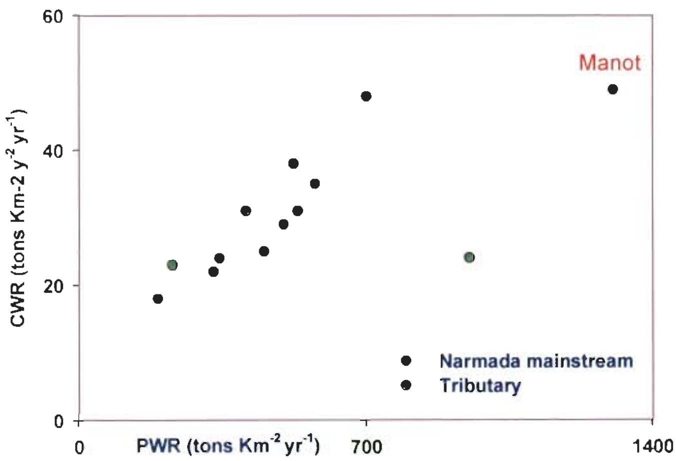


Fig. 4.36 Relationship between chemical and physical weathering rates in Narmada river

Sediment load dominates over chemical load in the Narmada river by a factor of 17.5. The dissolved/suspended load ratio in the basin is about 0.06 which is significantly lower than world average 0.232 (Milliman and Meade, 1983). The chemical weathering rates seldom exceed one-tenth of physical weathering rates in the Narmada river basin. With suspended/dissolved ratios of approximately 17.5, the Narmada river shows significant increase in physical weathering over chemical weathering process. According to Gibbs (1981), physical weathering is more dominant in Asian rivers.

Table 4.18 Total weathering rates and the relations between chemical and physical rates

Station	PWR	CWR	CWR/PWR	CWR % of TWR	TWR
Manot	1320	49	0.04	3.71	1369
Jabalpur	208	18	0.09	8.65	226
Barman	452	25	0.06	5.53	477
Sandia	377	24	0.06	6.37	401
Hoshangabad	530	38	0.07	7.17	568
Handia	602	35	0.06	5.81	637
Mandleshwar	523	29	0.06	5.54	552
Rajghat	548	31	0.06	5.66	579
Garudeshwar	322	22	0.07	6.83	344
Mohgaon	923	24	0.03	2.60	947
Bamni	274	23	0.08	8.39	297
Gadarwara	743	48	0.06	6.46	791
Chandwara	410	29	0.07	7.07	439

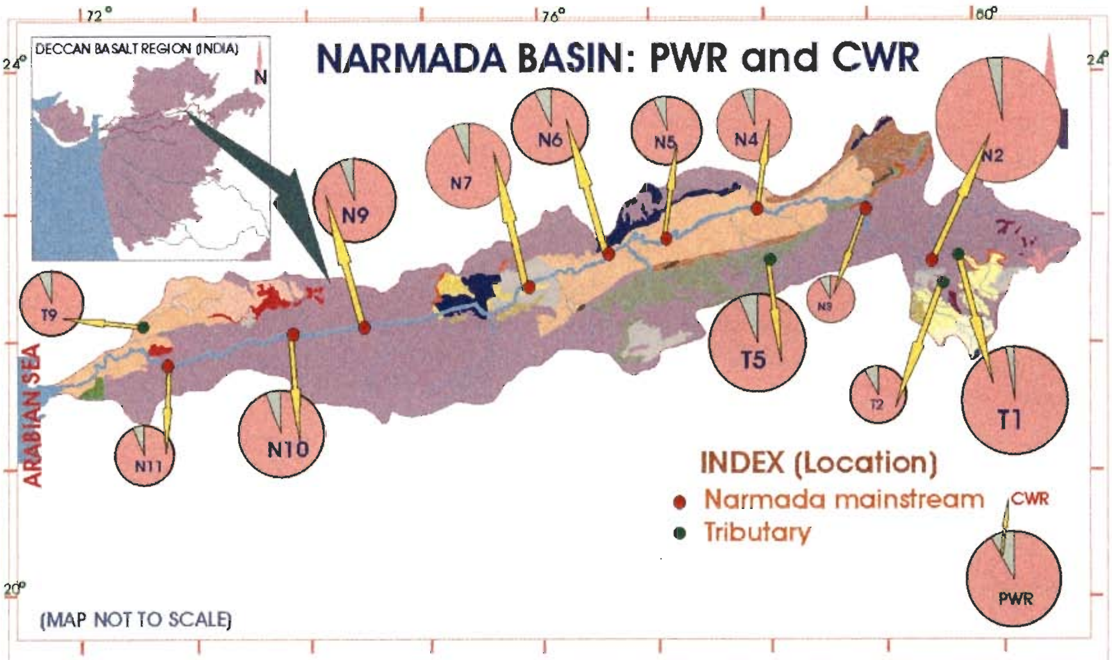


Fig. 4.37 Spatial Distribution of PWR and CWR in the Narmada river basin

Total weathering rates in the Narmada river basin are calculated by addition of physical and chemical weathering rates. Out of a total of thirteen locations, nine on the Narmada mainstream and four on the major tributaries (the Burhner, Banjar, Shakkar and the Orsang river) have been considered to calculate the total weathering rates (4.18). Since physical weathering rates at Jabalpur and Bamni are not available, data available at nearest locations (Jamtara for Jabalpur and Hirdaynagar for Bamni) are used for both locations. The total weathering rates in the Narmada river basin vary between 212 and 1353 tons km^{-2} yr^{-1}. The total weathering (physical and chemical) rate in the basin show good correspondence with the other rivers draining basaltic terrains, e.g. Sao Miguel (184-525 tons km^{-2} yr^{-1}) and other major world rivers (data from Milliman et al., 1987) such as the Amazon (192), Mississippi (104), Congo/Ob (25) Nile/Yenisei/Niger/Murray (35), Parana/St. Lawrence (50), Yangtse (362), Huang He (1432) Mekong (274), Indus (540), Ganges (549), Brahmaputra (953) and Irrawady (837). Tight coupling between physical and chemical weathering rates in the Narmada river basin suggest that more or less similar factors, such as climatic factor (rainfall and temperature), runoff, basin geology and soil characteristics, relief, catchment area and presence of dams control weathering rates in the basin.

4.10 DISSOLVED STRONTIUM ISOTOPIC COMPOSITIONS

Being a powerful solvent, water contains all 92 naturally occurring chemical elements at widely varying concentrations (3–6 orders of magnitude), without any influence from human pollution. Among the various chemical elements and isotopes that are transported to the oceans by rivers, dissolved strontium isotopes are being used to delineate the relative proportion of silicates and carbonate weathering (Raymo et al.; 1988, Krishnaswami et al. 1992; Singh et al., 1998; Oliver et al., 2003). Strontium in river water is derived from dissolution of Ca-containing minerals, either carbonates or silicates. Strontium from both sources exhibit peculiar characteristics. Carbonate rocks are characterized by high strontium content but low $^{87}Sr/^{86}Sr$ ratios (less radiogenic), whereas silicate rocks illustrate low strontium content but high $^{87}Sr/^{86}Sr$ isotopic ratios (more radiogenic). According to Palmer and Edmond (1989) $^{87}Sr/^{86}Sr$ isotopic ratios offer a proxy for silicate weathering. Relative profusion of various lithologic end members, such as carbonates and silicates signify the relative abundance of strontium and $^{87}Sr/^{86}Sr$ isotopic ratios in river waters. In presence of both end members, the strontium isotopic ratios and content will be the cumulative result of two component mixing. The $^{87}Sr/^{86}Sr$ isotopic ratios of carbonate end member typically multitude about ~0.708, while silicate end member varies widely (Pande et al, 1994). According to Goldstein and Jacobsen (1987) Sr isotopic composition is also controlled by the degree of chemical weathering of source rocks and strongly affected by the weathering of authigenic precipitates such as carbonates and phosphates in the drainage basin.

Considered to be among the largest basaltic province on the Earth's surface and due to relatively faster weatherability, the Deccan Traps have contributed significantly to strontium isotope budget of oceans since their emplacement. Trivedi et al (1995) and

Dessert et al (2001) have studied the rivers draining the Deccan basalts for strontium isotopic compositions. According to Dessert et al. (2003) the rivers draining the northern Deccan Traps show high $^{87}Sr/^{86}Sr$ isotopic ratios (~0.707 to 0.714), with a total flux of 3.75 X 10^8 mol yr^{-1} , which accounts for 3.7% of strontium derived from silicate weathering and account for ~1.15% of global contribution of strontium to oceans by means of rivers. These fluxes are disproportionately higher than the exposed area of the Deccan Traps (~0.4% of the continental area). Despite the significance, strontium concentrations, mass balance and flux of individual rivers draining the Deccan basalt are yet not established and understood. In the present study, a key set of data of strontium concentrations and $^{87}Sr/^{86}Sr$ isotopic ratio is generated to obtain flux of strontium and $^{87}Sr/^{86}Sr$ isotopic ratios at different sampling locations.

A total of nineteen river water samples (11 from the Narmada mainstream and the remaining from the major tributaries), one spring-water, two ground water and one rainwater samples were analyzed (Fig. 4.38). Since approximately, 90% of water discharge in the Narmada river takes place during the monsoon period, hence water samples collected during 2004-September (monsoon) were selected for the present study. Strontium concentrations and $^{87}Sr/^{86}Sr$ isotopic ratios in the samples are presented in Table 4.19. Dissolved strontium concentrations in the Narmada river vary between 0.77 and 2.62 μM. Strontium concentration in the Narmada mainstream ranges between 0.88 and 1.59, whereas in the tributaries, it varies from 0.77 to 2.62 μM, (basin mean-1.37 μM).

The $^{87}Sr/^{86}Sr$ isotopic ratios measured in the Narmada river vary between 0.70823 and 0.71964, similar to those observed by Dessert et al (2001). The $^{87}Sr/^{86}Sr$ isotopic ratios in the Narmada mainstream vary between 0.70850 (at Manot) and 0.71666 (at Sandia), whereas it ranges between, 0.70479 (the Sher river at Belkheri) and 0.71625 (the Orsang river at Chandwara) for the major tributaries. Among the twenty samples (nineteen present study and one from Dessert et al.; 2001) discussed in present study, twelve samples (Eight-Narmada mainstream and four-tributaries) show >0.710 $^{87}Sr/^{86}Sr$ isotopic ratios. All the values specify the chemical erosion of basaltic rocks, with unusually high $^{87}Sr/^{86}Sr$ isotopic ratios ranging between 0.705 and 0.715 (Cox and Hawkesworth, 1985; Lightfoot and Hawkesworth, 1988). $^{87}Sr/^{86}Sr$ isotopic ratios in the Narmada river are significantly higher than those reported by Das et al (2005), which vary between 0.706 and 0.709 for the Krishna river system and the west flowing rivers. The Narmada system also shows considerably higher $^{87}Sr/^{86}Sr$ isotopic ratios as compared to those of the volcanic islands studied by Louvat and Allegre (0.7035-0.7053; 1997). Hence, with a high $^{87}Sr/^{86}Sr$ isotopic ratio (mean-0.7110), the Narmada river can be placed amongst the other large and most radiogenic rivers (mean-0.7120). Mahoney (1988) suggested that high radiogenic strontium isotopic composition in the Narmada river can arise from the basalts with crustal contamination. The other source may be the contributions coming from other lithological sources other than basalts.

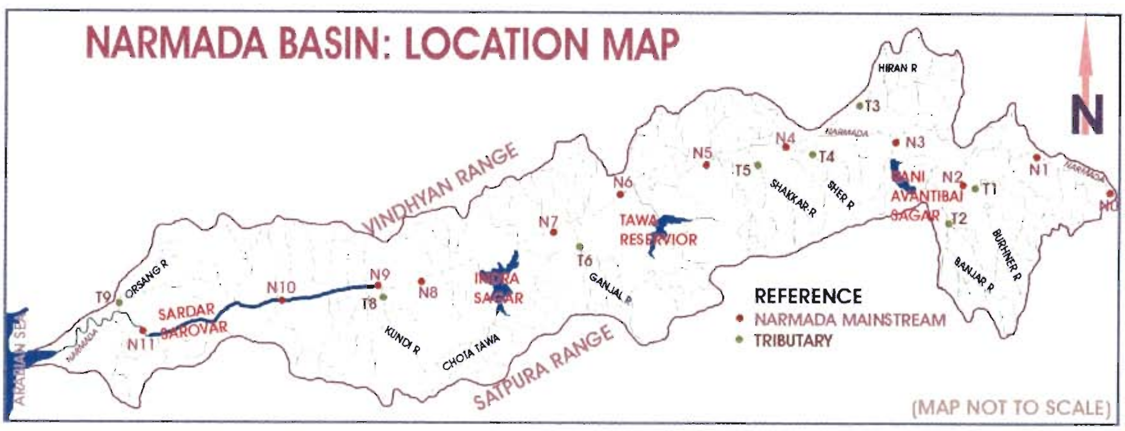


Fig. 4.38 Location map of samples for Sr analysis

Table 4.19 Strontium isotopic ratios ($^{87}Sr/^{86}Sr$), Sr concentration and specific flux by the Narmada river

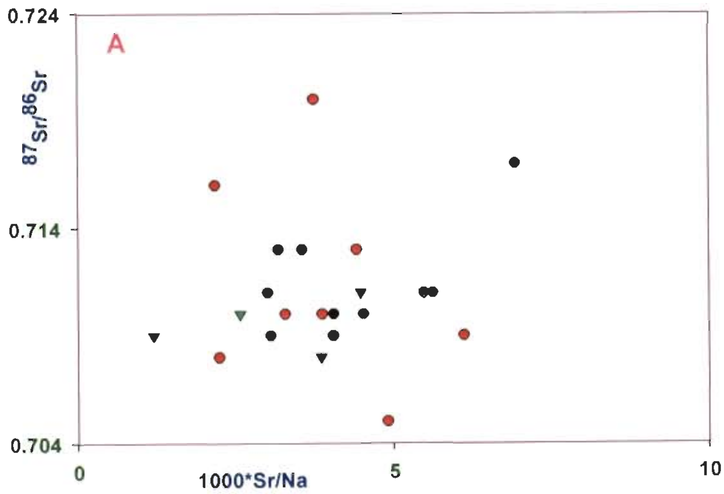
Location	Code	$^{87}Sr/^{86}Sr$	Sr Conc (μM)	Specific Flux (mol km^{-2} yr^{-1})
River water				
N1-Dindori	N62-Narmada	0.70850	0.88	490
T1-Mohgaon	N63-Burhner	0.70979	0.77	420
N3-Manot	N64-Narmada	0.70850	0.97	676
T2-Bamni	N65-Banjar	0.71964	0.88	462
N3-Jabalpur	N66-Narmada	0.71044	1.59	850
T3-Patan	N67-Hiren	0.71263	0.99	340
T4-Belkheri	N68-Sher	0.70479	1.29	333
N4-Barman	N69-Narmada	0.71322	1.02	480
T5-Gadarwara	N70-Shakkar	0.71012	1.44	881
N5-Sandia	N71-Narmada	0.71666	1.10	493
N6-Hoshangabad	N72-Narmada	0.71340	1.49	795
T6-Chhidgaon	N73-Ganjal	0.70823	1.20	635
N7-Handia	N74-Narmada	0.71118	1.38	651
N8-Mortakka	N75-Narmada	0.71053	1.24	544
N9-Mandleshwar	N76-Narmada	0.71046	1.17	539
T7-Kogaon	N77-Kundi	0.70868	2.24	596
N10-Rajghat	N78-Narmada	0.70936	1.16	519
N11-Garudeshwar	N79-Narmada	0.71059	1.07	418
T9-Chandwara	N80-Orsang	0.71625	2.62	973
T8-Chota-Tawa*	D7-Chotatawa	0.70819	2.13	924
Spring				
Jabalpur	SW3	0.71050	4.14	----
Groundwater				
Barmanghat	GW4	0.70976	11.4	----
Mortakka	GW5	0.70913	6.25	----
Rainwater				
Mortakka	RN1	0.71042	0.23	----

(* Data from Dessert et al., 2001)

The specific flux of strontium derived from the weathering of Deccan traps in the Narmada river (Table 4.19), ranges between 333 and 973 mol km^{-2} yr^{-1}, (basin mean-601 mol km^{-2} yr^{-1}). The concentrations and specific flux of strontium in the Narmada river basin is similar to the results, reported by Dessert et al (2001) for rivers draining to north Deccan traps. The total flux of strontium delivered by the Narmada river to the Arabian sea is approximately 4.05x 10^7 mol yr^{-1} (basin flux at Garudeshwar including the flux of downstream tributary Orsang). The final flux of Strontium is approximately one-tenth of the strontium flux (3.75 x 10^8 mol yr^{-1}) calculated by Dessert et al (2001) for entire Deccan basalts.

Strontium content in the Narmada river water and tributaries is mainly a result of rock-water interaction. Although the Deccan basalts and Quaternary soils are the most abundant and exposed lithology, still other rocks are also prevalent and may contribute significantly to dissolved loads. Quaternary soils prevailing in the middle part of the basin are characterized by moderate to high calcinations and may contribute significantly to Sr content of river.

The relationships of $^{87}Sr/^{86}Sr$ with Sr/Na* and Ca*/Na* with Sr/Na* can be observed in Fig. 4.39 A and 4.39 B. Sr/Na* shows good correlations with $^{87}Sr/^{86}Sr$ and Ca*/Na*, similar to the observations of Gaillardet et al. (1999) for the large world rivers. According to Gaillardet et al (1999), this sort of correlation indicates the mixing process between carbonates (high Sr/Na and Ca/Na ratios) and silicates (low Sr/Na and Ca/Na ratios), which also seems true for the Narmada river basin. Fig.4.40 A presents the relative Sr concentrations at different sampling locations in the Narmada mainstream and contributions from the major tributaries along downstream direction. The upper reaches of the Narmada river (before Jabalpur) is characterized by moderate Sr concentrations (<1.0), it is highest at Jabalpur (Fig. 4.40 B), thereafter it reduces significantly at Barmanghat and again reaches high value at Hoshangabad. After passing through Hoshangabad, Sr concentrations in the river water inexorably decrease before reaching the Arabian sea. The Narmada mainstream shows significant increase in Sr concentrations at different sampling locations, which is essentially dependent on lithological inputs. Fig. 4.40 B shows the alterations in $^{87}Sr/^{86}Sr$ isotopic ratios and strontium contents in the Narmada mainstream.



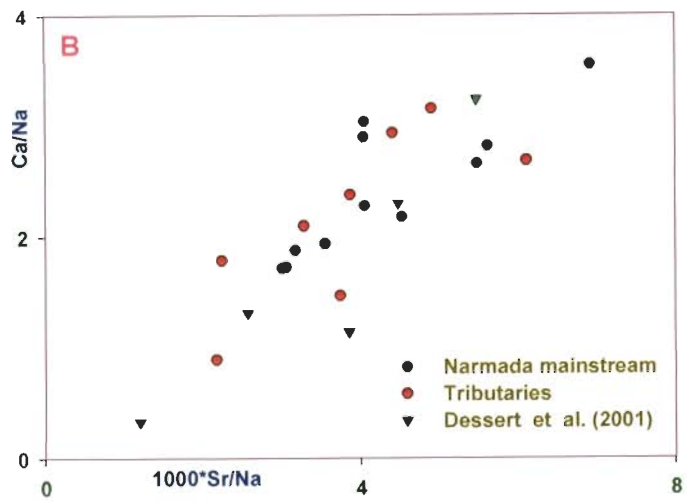


Fig. 4.39 The relationships of $^{87}Sr/^{86}Sr$ with Sr/Na* and Ca*/Na* with Sr/Na*

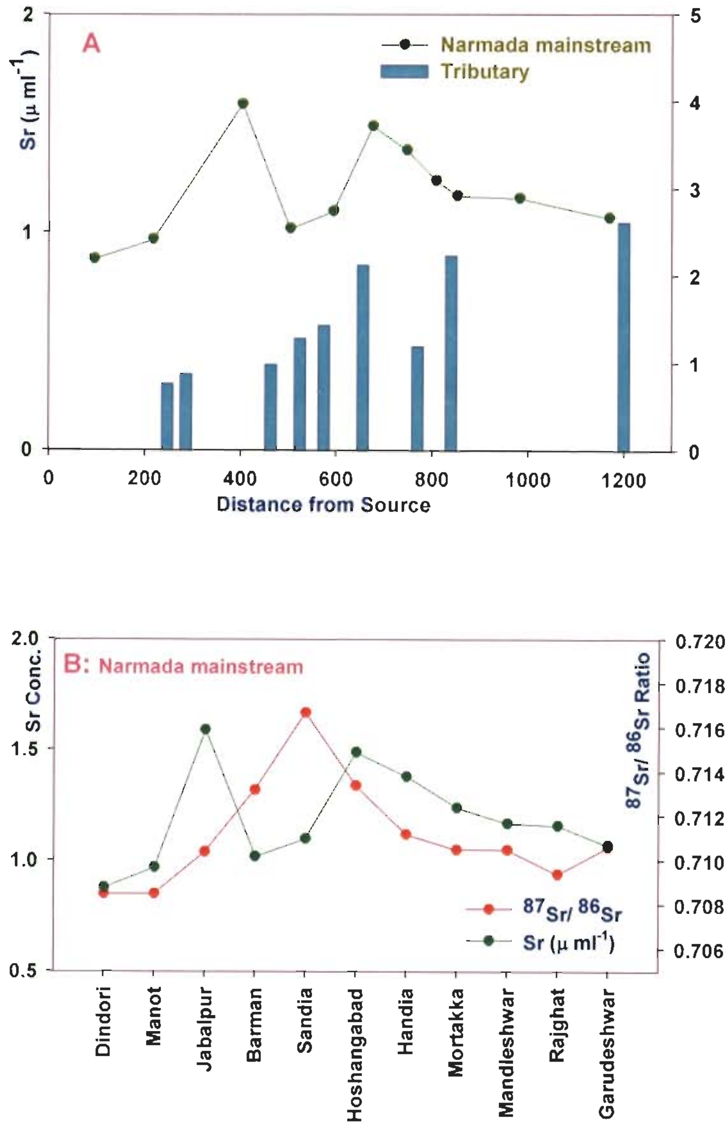


Fig. 4.40 Strontium in river water; A- concentrations in the Narmada mainstream and contribution of the tributaries and B-Strontium concentrations and isotopic ratios at different locations on the Narmada mainstream

In Fig. 4.41, the Sr content in river water is plotted against Na*, Ca*, Mg*, HCO_3 and SiO_2. In all of the figures Sr shows good correlation with major ions, indicating the release of Sr from rock weathering. Fig. 4.41 F shows negative correlation and indicates two end members mixing, between high Sr content with low SiO_2/HCO_3 ratios, and low Sr content with high SiO_2/HCO_3 ratios. The two end members identified are the basalts and carbonate rocks/soils present in the basin.

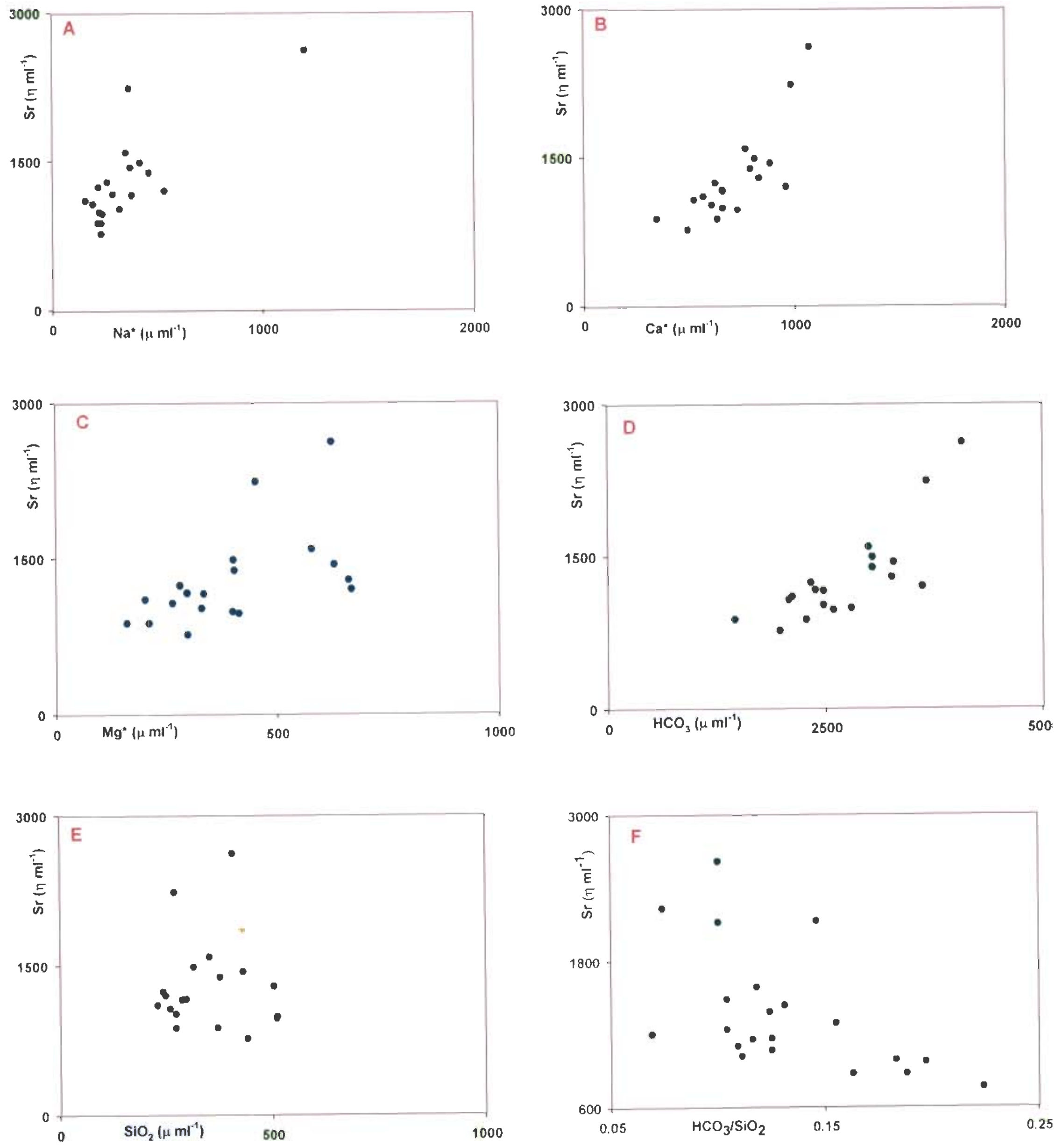


Fig. 4.41 Variations of Sr with Na*, Ca*, Mg*, HCO_3, SiO_2 and HCO_3/SiO_2

4.11 NUTRIENT DISTRIBUTION

Dissolved inorganic nutrients in the Narmada river basin discussed in the succeeding sections are based on multi-annual data between 1990 and 2001 at nineteen locations (Fig. 4.42). Dissolved inorganic nitrate, phosphate and silica are denoted henceforth, as DIN, DIP and DSi respectively.

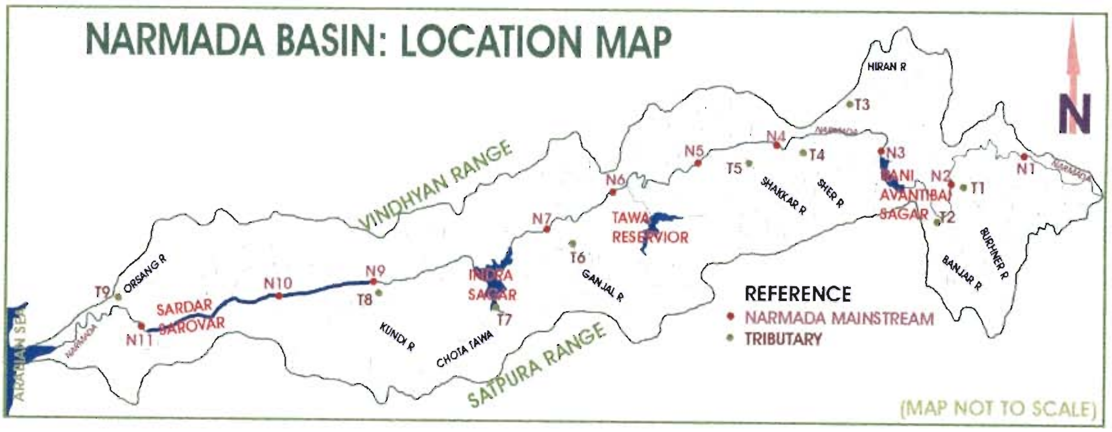


Fig. 4.42 Sampling locations for nutrients studies in the Narmada river basin

Average concentrations of nitrate in the basin calculated for 11 years show wide variations, ranging from 1.90 to 216 μM. In the Narmada mainstream (Fig. 4.43 A), the concentrations vary from 3.2 to 88.2 μM whereas, among the major tributaries concentrations vary from 1.9 to 216 μM. Nitrate concentrations follow no regular variation in the Narmada river and its tributaries. Rajghat (N10) records highest concentrations (88 μM) of nitrate followed by Sandia (N5; 69 μM). According to Alexander et al. (2000) and Peterson et al. (2001), the entry point for high nitrogen loading in mainstream rivers is from small streams, whose ability to process, to retain and to denitrify the increased N load eventually becomes overwhelmed and inorganic nitrogen is transported further and further downstream and in higher amounts as nitrogen loading increases. This holds also true for the Narmada river basin as well, among the nine major tributaries, the Kundi river at

Kogaon (T8) shows highest concentration (216 μM), followed by the Chota-Tawa river at Ginnore (T7; 154 μM). Phosphate concentration ranges from 0.32 to 1.94 μM and show limited spatial variations. For the Narmada mainstream DIP concentrations vary from 0.97 to 1.45 μM (Fig 4.43 B). Phosphate concentrations in tributaries are slightly higher than the mainstream of the Narmada river. Dissolved silica is the most abundant of the three nutrients (Si, PO_4 and NO_3). The concentrations of silica in the basin vary from 214 to 686 μM. Dissolved silica is higher in tributaries compared to the mainstream. Dissolved silica concentrations in the Narmada river (Fig. 4.43 C) vary from 214 to 472 μM. Highest concentrations in the Narmada mainstream are observed in upstream location at Manot (472 μM), followed by Rajghat (470 μM) in downstream region. Lowest concentrations in the Narmada river are observed at Garudeshwar (214 μM). Among the nine major tributaries in the basin, the Kundi river at Kogoan shows maximum concentration of silica (686 μM), followed by the Ganjal river at Chhidgaon (679 μM), the Sher river at Belkheri (653 μM), the Shakkar river at Gadarwara (652 μM) and the Chota-Tawa river at Ginnore (650 μM). Along downstream, the concentrations of phosphate and silica show a decreasing trend however, nitrate increases along downstream. Garudeshwar (N11) represents the location of least concentrations of all the three nutrients. Predominant agricultural activities in the mid-stream region on relatively flat terrain and associated utilization of fertilizers have its effect on the increase in nitrate concentrations. Phosphate source can also be linked to fertilizers. Dissolved silica is a biogenic element and may lead to decreasing concentration along downstream, due to increased organic activities downstream.

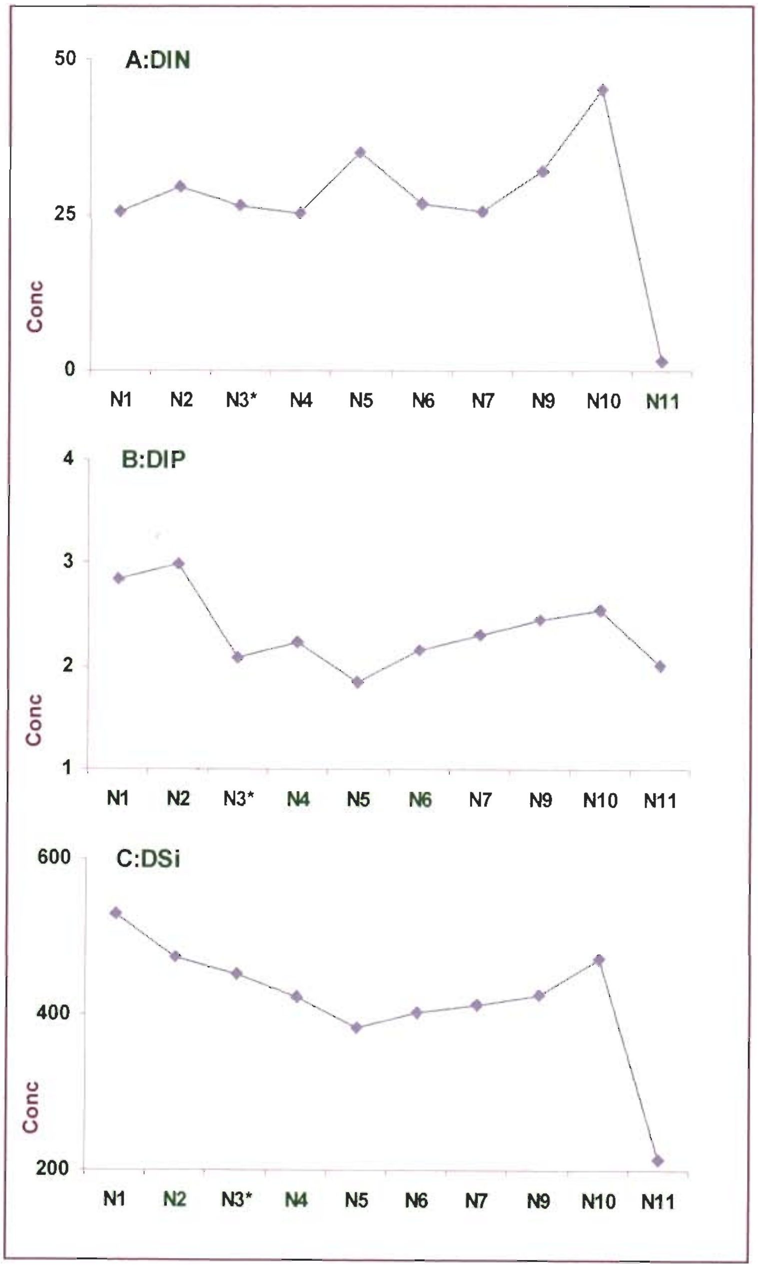


Fig. 4.43 Spatial variations (A-DIN, B-DIP and C-DSi) in nutrient concentrations (μM; average of eleven years 1990-2001)

Dissolved silica, nitrate and phosphate show significant temporal variations in the Narmada river basin. Daily, monthly and seasonal variations based on monthly average of 11 years at Hoshangabad (N6) are shown in Fig. 4.44. Nitrate shows low concentrations during the summer months, followed by a rise in concentrations during monsoon and post-monsoon. The crop season coincides with the monsoon season and hence nitrate application to agricultural fields during this time is increased. Nitrate could also be derived from atmosphere, added due to vehicular pollution. Phosphate (Fig. 4.44 B) follows the same trend, whereas silica (Fig. 4.44 C) behaves in a different manner. Higher silica concentrations are observed during non-monsoon period. Chemical dissolution of silicate rocks is very slow ($K_{eq} = 10^{-9.9}$) and get increased at higher pH and temperature conditions. Hence, we assume that dissolved silica derived from rock dissolution is present uniformly in the river water irrespective of the season, but gets substantially diluted during the monsoon season, thus showing low concentrations. In addition, dissolved silica is also used by organisms for skeletal growth. Dissolved silica present in running or flowing water is not easily accessible for the organisms, however, wherever an impediment in the form of a dam/reservoir exists, water flow is significantly reduced and hence residence time of dissolved silica is increased. This enables organisms to flourish and consumption of dissolved silica is increased. Death/decay of the organisms again might temporarily increase dissolved silica concentration in river water. Dissolved silica concentrations in the river show higher concentrations in the upland region, where higher relief causes greater break down of rocks and hence silicate minerals are better exposed for chemical weathering processes. In the mid-stream region silica concentrations reduce, to increase again in downstream region because of low flow of water. Between N10 and N11 there is significant reduction in silica concentration because of the presence of the large reservoir, where most of the silica is retained.

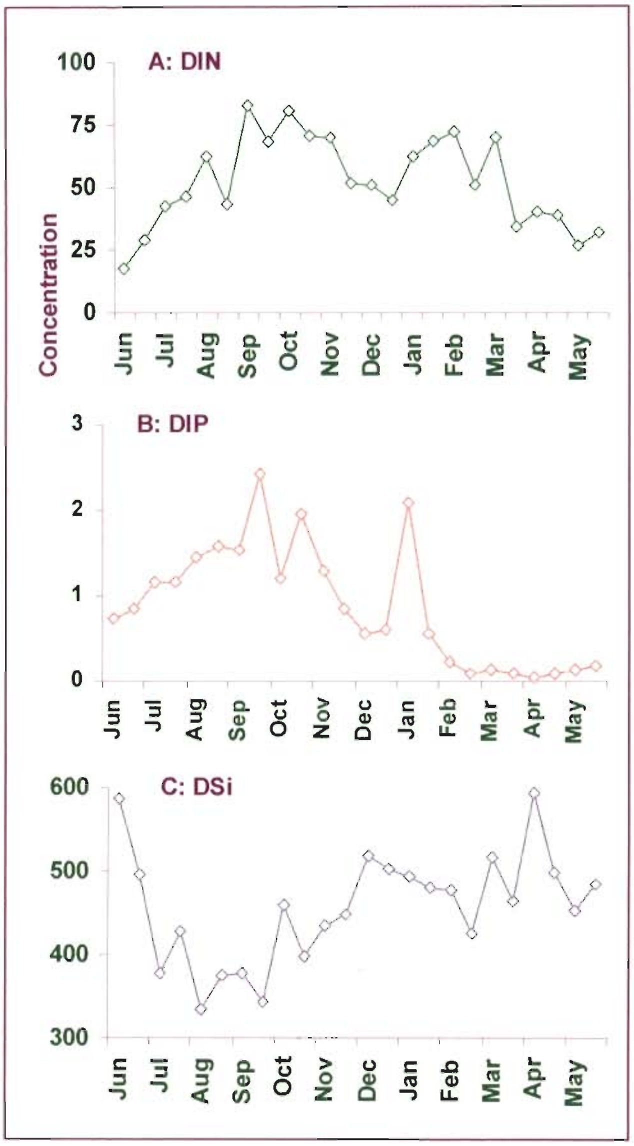


Fig. 4.44 Temporal variations in nutrient concentrations (Y axis, in µM) at Hoshangabad (A-DIN, B-DIP and C-DSi)

Table 4.20 presents the fortnight variations in DIN, DIP and DSi at three locations, upstream (Manot, N2), mid-stream (Hoshangabad, N6) and downstream (Garudeshwar, N11). Fortnight concentration of DIN, DIP and DSi for a period of eleven year is studied to understand the relative movement of nutrients in water, their controlling factors and short (monthly and seasonal) long term (annual) temporal changes. Observations of the presented data set, reveal that in most cases DIN and DIP show high concentrations during the monsoon months whereas, DSi record highest concentrations during dry seasons or peak summers. The highest concentrations among the three locations were recorded on Sept 4th 2000 (405 μM) at Hoshangabad, followed by (315 μM) at Manot on July 2nd 1990 for nitrate. Similarly, for phosphate, highest concentrations of 14.4 μM were observed on Sept 15th 1993 at Manot and on Sept 15th 1998 at Hoshangabad. All the high concentrations were recorded during monsoon periods. In most of the years, phosphate concentrations are not measurable during dry months. Highest concentrations of DSi are essentially confined to dry seasons or during peak summers and show the control of temperature on chemical weathering. Highest DSi concentration among the three locations was recorded on April 5th and 15th (1125 μM) at upstream location Manot whereas highest concentration at Hoshangabad was 1018 μM on March 1st 2000. The least DSi concentration was on Aug 17th 1992 at Hoshangabad. In some of the years DSi concentrations are relatively higher compared to other years, may be due to comparatively high average annual temperature at some of these tropical locations. Table 4.20 reveals the spatial and temporal distribution of nutrients e.g., the highest concentrations at Manot and Hoshangabad were 247 $\mu M\ l^{-1}$ and 405 μM for DIN and 3.06 μM and 4.03 μM for DIP respectively in the year 2000 on Sept 4th. But the same day observed lowest concentration of DSi at Manot (300 μM) and Hoshangabad (265 μM). This reveals that agricultural diffused runoff is responsible for increase in nitrate and phosphate concentrations in river runoff whereas, DSi does not have any anthropogenic source. The variations at Garudeshwar are very minimal, because most of the nutrient load is trapped by the Sardar Sarovar Dam, constructed before Garudeshwar and the regulated water flow contains similar concentrations.

Table 4.20 Fortnight nutrient concentrations (µM) for eleven water-years (1990-2001) at three locations on the Narmada river (N/A- Data not available).

S.	Date/	Manot			Hoshangabad			Garudeshwar		
No	Year	DIN	DIP	DISi	DIN	DIP	DISi	DIN	DIP	DISi
	1990-91									
1	1-Jun	5	3	777	10	9	863	16	29	638
2	21-Jun	3	7	513	16	1	500	4	2	230
3	2-Jul	161	3	488	68	3	310	23	72	92
4	21-Jul	79	5	632	74	3	488	11	33	257
5	1-Aug	75	3	823	55	12	507	6	7	257
6	21-Aug	48	2	745	40	3	520	1	2	283
7	1-Sep	11	0	500	16	1	415	1	1	145
8	21-Sep	27	1	620	19	2	428	3	0	119
9	1-Oct	27	6	725	35	3	462	6	2	178
10	22-Oct	39	7	725	42	6	428	4	0	257
11	1-Nov	158	14	553	56	6	500	3	0	263
12	21-Nov	21	1	810	27	0	475	4	0	250
13	1-Dec	5	1	692	34	3	482	4	0	250
14	21-Dec	5	2	765	18	2	587	4	0	237
15	1-Jan	2	1	915	11	26	797	4	1	362
16	21-Jan	58	0	658	23	1	587	2	2	290
17	1-Feb	3	2	607	11	0	442	2	0	323
18	21-Feb	8	2	573	23	0	435	1	0	277
19	2-Mar	5	2	765	19	0	520	5	0	283
20	21-Mar	5	3	672	5	0	488	1	0	257
21	1-Apr	2	1	803	2	0	587	2	0	303
22	22-Apr	6	1	765	21	0	422	2	0	119
23	1-May	5	0	863	8	0	607	2	0	205
24	21-May	13	1	850	13	0	500	1	0	217
	1991-92									
1	3-Jun	5	1	793	6	1	457	1	1	163
2	17-Jun	52	2	450	31	4	510	1	10	285
3	1-Jul	2	0	488	2	0	460	0	0	360
4	15-Jul	6	0	416	18	0	375	3	0	212
5	1-Aug	18	1	485	10	2	205	2	0	205
6	16-Aug	15	4	433	13	3	380	3	0	116
7	3-Sep	10	1	755	8	1	407	2	11	212
8	16-Sep	0	0	727	13	1	360	1	3	237
9	3-Oct	0	1	762	11	1	547	4	0	255
10	15-Oct	0	1	617	11	16	513	2	0	212
11	1-Nov	0	1	557	5	7	450	2	0	237
12	15-Nov	0	4	589	6	3	513	2	0	205
13	2-Dec	0	1	586	3	1	502	1	0	162
14	16-Dec	0	1	565	21	2	482	1	1	213
15	1-Jan	0	3	572	10	3	623	2	0	205
16	16-Jan	0	3	561	11	2	478	3	0	232
17	3-Feb	3	3	273	1	3	405	3	0	212
18	17-Feb	2	0	727	6	0	398	1	0	180
19	2-Mar	2	1	465	6	1	402	2	0	320
20	16-Mar	3	1	658	2	1	572	2	0	302

21	1-Apr	5	2	797	6	0	582	1	0	158
22	20-Apr	5	1	617	6	1	540	2	0	237
23	1-May	2	2	589	3	0	540	3	0	188
24	18-May	2	2	589	1	3	557	2	0	205
	1992-93									
1	1-Jun	2	4	745	6	1	447	2	1	222
2	15-Jun	2	7	686	3	3	517	4	6	297
3	1-Jul	3	1	596	10	1	502	1	1	195
4	15-Jul	24	0	440	24	0	468	2	1	232
5	3-Aug	61	1	381	45	5	87	1	1	212
6	17-Aug	39	1	138	15	1	35	1	1	195
7	1-Sep	53	1	631	37	1	363	2	3	212
8	15-Sep	50	1	762	34	1	333	2	3	285
9	7-Oct	16	1	544	52	1	433	2	1	213
10	15-Oct	24	2	530	52	2	415	2	1	232
11	2-Nov	2	1	568	39	1	562	2	1	205
12	16-Nov	11	1	568	50	1	557	2	2	180
13	1-Dec	2	1	488	16	3	392	3	2	213
14	15-Dec	2	1	530	26	1	353	2	1	216
15	1-Jan	26	1	520	35	4	138	4	1	232
16	15-Jan	10	0	459	39	0	280	3	1	205
17	1-Feb	8	1	416	27	1	325	3	0	180
18	15-Feb	3	1	374	13	1	187	3	0	247
19	1-Mar	3	1	520	21	1	388	2	0	232
20	15-Mar	6	1	426	8	0	395	2	0	188
21	1-Apr	13	2	492	26	1	658	1	0	180
22	15-Apr	3	1	353	15	1	415	2	0	205
23	3-May	0	1	381	6	1	415	2	0	237
24	17-May	2	2	381	6	1	457	2	0	212
	1993-94									
1	3-Jun	5	1	554	11	1	587	2	1	222
2	15-Jun	3	1	505	26	2	372	2	3	303
3	3-Jul	14	1	388	24	1	210	1	1	195
4	15-Jul	79	2	273	26	0	260	10	1	222
5	2-Aug	3	1	215	15	2	148	1	0	212
6	16-Aug	29	1	239	13	1	305	1	1	205
7	1-Sep	30	1	388	13	1	163	1	3	195
8	15-Sep	45	28	360	36	4	100	2	3	318
9	4-Oct	42	4	526	58	3	350	2	1	195
10	15-Oct	24	2	606	31	1	370	2	1	213
11	1-Nov	3	1	391	23	1	433	1	2	213
12	15-Nov	6	3	455	29	5	400	2	2	205
13	1-Dec	8	1	391	29	1	405	2	1	213
14	15-Dec	13	1	464	27	1	353	3	0	232
15	1-Jan	23	0	357	87	1	245	3	1	213
16	17-Jan	19	0	412	74	3	353	2	1	205
17	1-Feb	10	0	620	19	0	568	3	0	205
18	15-Feb	11	1	721	37	0	308	2	0	213
19	1-Mar	10	1	727	37	0	298	1	0	232
20	15-Mar	2	1	457	3	0	527	1	0	195
21	4-Apr	34	1	565	32	0	328	2	0	232
22	15-Apr	37	1	537	39	0	343	1	0	205
23	2-May	2	2	565	2	0	325	1	0	237

24	16-May	2	1	640	3	0	393	1	0	212
	1994-95									
1	1-Jun	2	0	686	2	2	520	1	1	195
2	15-Jun	13	2	329	24	2	248	2	1	217
3	1-Jul	47	3	225	21	4	132	1	2	213
4	15-Jul	37	2	225	24	2	145	2	1	222
5	1-Aug	15	0	135	27	1	173	1	1	212
6	16-Aug	23	1	160	29	1	148	2	2	318
7	1-Sep	16	1	606	3	2	380	2	3	213
8	15-Sep	19	0	125	58	1	270	1	2	222
9	3-Oct	39	1	170	48	1	190	2	1	217
10	17-Oct	32	1	144	40	1	190	2	3	318
11	1-Nov	34	0	170	42	1	202	1	1	195
12	15-Nov	31	0	190	31	2	202	2	1	213
13	1-Dec	5	1	170	28	1	170	2	2	232
14	15-Dec	5	2	225	18	0	520	2	3	213
15	2-Jan	2	2	210	29	1	582	2	3	205
16	16-Jan	34	1	180	52	0	228	1	1	205
17	1-Feb	54	1	156	48	0	242	2	0	213
18	15-Feb	24	1	125	27	0	173	3	0	232
19	1-Mar	8	1	433	11	0	520	2	0	213
20	15-Mar	2	1	457	16	0	380	2	0	232
21	3-Apr	34	1	565	50	0	245	3	0	237
22	17-Apr	37	1	538	29	0	142	3	0	213
23	1-May	2	1	565	37	0	170	3	0	205
24	15-May	2	1	641	55	0	202	3	0	212
	1995-96									
1	1-Jun	48	0	745	1	0	520	2	1	212
2	15-Jun	19	0	745	11	0	502	2	1	232
3	3-Jul	65	1	142	53	2	238	1	1	222
4	17-Jul	45	7	308	0	6	318	1	1	212
5	1-Aug	16	4	83	29	1	93	2	1	213
6	16-Aug	73	9	86	19	5	72	2	2	232
7	4-Sep	40	1	623	87	2	330	1	1	198
8	15-Sep	16	1	160	44	1	173	0	0	195
9	4-Oct	21	2	190	76	3	180	1	0	180
10	16-Oct	2	3	201	58	3	193	2	1	213
11	1-Nov	0	1	173	39	1	93	0	1	177
12	15-Nov	3	0	727	39	0	620	2	1	195
13	1-Dec	40	1	762	44	0	727	2	2	167
14	15-Dec	20	1	173	15	2	405	1	3	177
15	1-Jan	55	1	866	34	2	398	2	4	205
16	15-Jan	120	1	451	31	1	520	0	3	177
17	1-Feb	2	1	485	194	0	565	2	0	213
18	15-Feb	11	1	485	73	0	545	1	0	195
19	1-Mar	7	1	336	8	0	603	2	0	213
20	15-Mar	10	1	391	10	0	315	2	0	213
21	2-Apr	2	1	546	13	0	492	2	0	205
22	15-Apr	3	1	627	6	0	302	3	0	237
23	1-May	27	1	312	19	0	205	2	0	213
24	15-May	61	1	173	40	0	318	2	0	213
	1996-97									
1	1-Jun	11	1	537	29	1	450	1	3	205

2	15-Jun	11	1	286	24	2	337	0	3	213
3	1-Jul	18	1	936	21	3	70	0	1	222
4	15-Jul	15	1	52	24	3	177	0	1	212
5	1-Aug	56	1	600	45	3	372	0	1	232
6	16-Aug	56	0	537	47	7	507	0	1	213
7	2-Sep	26	0	589	29	4	415	0	0	195
8	17-Sep	16	0	523	23	4	343	2	1	217
9	1-Oct	3	0	745	40	4	495	1	1	232
10	15-Oct	23	0	672	19	3	472	1	0	222
11	1-Nov	2	0	606	37	1	520	1	1	237
12	15-Nov	2	0	544	34	0	510	1	0	195
13	2-Dec	3	1	606	32	1	553	2	1	177
14	16-Dec	5	1	502	24	2	550	1	3	195
15	1-Jan	3	2	97	61	1	600	2	0	213
16	15-Jan	2	2	49	13	1	513	2	0	195
17	1-Feb	2	1	600	5	0	380	2	0	213
18	15-Feb	5	0	468	5	0	277	2	0	232
19	1-Mar	3	0	693	8	0	475	2	0	213
20	15-Mar	5	0	772	8	0	457	0	0	0
21	1-Apr	8	1	752	10	0	912	3	0	237
22	15-Apr	8	1	772	11	0	537	2	0	195
23	1-May	10	3	347	10	0	163	1	0	213
24	15-May	0	2	554	1	0	553	0	0	213
	1997-98									
1	2-Jun	0	2	572	8	0	665	2	3	213
2	16-Jun	1	2	523	1	2	513	1	2	195
3	1-Jul	51	3	586	5	3	592	0	0	212
4	15-Jul	8	2	548	8	1	537	0	0	195
5	1-Aug	20	3	345	30	2	285	0	0	177
6	18-Aug	10	2	450	22	0	425	0	0	213
7	1-Sep	8	1	364	8	1	450	0	0	237
8	15-Sep	19	1	644	29	0	643	1	0	232
9	3-Oct	16	2	488	34	2	520	3	1	195
10	15-Oct	13	1	64	29	0	537	2	1	222
11	3-Nov	24	3	686	34	3	568	2	0	213
12	17-Nov	35	3	603	24	3	588	2	0	205
13	1-Dec	19	1	623	34	0	562	5	3	237
14	15-Dec	32	1	589	23	1	443	4	3	213
15	1-Jan	16	0	610	24	4	548	3	1	237
16	15-Jan	6	0	518	58	1	515	2	0	195
17	2-Feb	23	0	607	37	0	473	2	0	213
18	16-Feb	2	0	736	16	0	483	3	0	195
19	2-Mar	0	1	675	27	0	572	3	0	237
20	16-Mar	5	1	603	19	0	485	3	0	195
21	1-Apr	8	1	634	15	0	478	5	0	237
22	15-Apr	3	1	443	6	0	495	2	0	213
23	1-May	5	2	866	5	0	363	1	0	213
24	15-May	3	2	936	3	0	520	2	0	195
	1998-99									
1	1-Jun	5	1	537	5	1	460	3	0	213
2	15-Jun	3	2	544	3	2	510	4	1	237
3	1-Jul	26	6	301	11	6	385	1	1	253
4	15-Jul	24	3	378	29	3	727	2	2	273

5	3-Aug	18	2	1060	42	1	520	2	2	237
6	17-Aug	8	2	727	26	3	478	1	1	283
7	1-Sep	15	7	727	30	9	572	1	0	237
8	15-Sep	17	2	451	25	28	238	2	1	217
9	5-Oct	8	1	608	5	0	497	1	1	258
10	15-Oct	8	0	419	21	0	163	1	1	213
11	2-Nov	3	0	606	25	1	475	2	1	195
12	16-Nov	0	0	538	14	1	317	3	2	213
13	1-Dec	3	6	699	12	1	553	3	3	195
14	15-Dec	6	0	634	17	0	518	2	1	222
15	1-Jan	11	0	602	6	1	532	2	1	177
16	15-Jan	0	0	600	20	2	535	1	1	237
17	1-Feb	5	0	624	16	1	487	3	0	227
18	15-Feb	5	0	537	34	1	398	3	0	237
19	3-Mar	N/A	N/A	N/A	26	1	602	1	0	213
20	15-Mar	3	0	554	16	1	427	1	0	195
21	5-Apr	0	2	1126	10	0	682	1	0	177
22	15-Apr	0	1	1126	8	0	668	2	0	213
23	3-May	2	1	926	15	2	700	2	0	195
24	17-May	6	2	804	9	0	622	1	0	177
	1999-00									
1	1-Jun	3	0	905	16	0	715	1	1	195
2	15-Jun	11	2	826	13	0	690	2	2	210
3	1-Jul	59	3	721	10	2	705	0	1	177
4	15-Jul	27	6	513	12	7	435	1	2	253
5	2-Aug	31	2	520	28	2	675	1	1	253
6	16-Aug	2	3	703	1	9	523	0	0	232
7	1-Sep	11	14	416	25	3	392	1	1	210
8	15-Sep	20	12	378	13	3	502	0	1	283
9	4-Oct	25	5	743	34	6	725	1	1	253
10	15-Oct	26	6	339	37	8	450	0	0	337
11	1-Nov	15	3	548	71	4	340	1	1	210
12	15-Nov	25	1	572	24	2	377	0	1	170
13	1-Dec	11	1	738	52	1	588	1	1	213
14	15-Dec	15	1	606	48	0	557	1	1	245
15	3-Jan	0	1	236	40	0	433	1	2	177
16	17-Jan	5	1	579	38	0	502	1	2	210
17	1-Feb	5	1	686	27	0	745	1	0	232
18	15-Feb	2	0	727	35	0	748	1	0	210
19	1-Mar	3	0	1060	20	0	1035	0	0	177
20	15-Mar	3	0	901	17	0	675	1	0	173
21	3-Apr	5	0	1025	3	0	895	1	0	177
22	17-Apr	4	0	795	22	0	958	2	0	195
23	1-May	4	1	969	27	0	857	2	0	210
24	15-May	4	2	740	35	0	815	2	0	195
	2000-01									
1	1-Jun	5	0	866	3	0	762	1	0	140
2	16-Jun	15	0	866	15	0	744	2	1	168
3	3-Jul	35	5	449	14	0	538	2	2	167
4	17-Jul	20	3	866	22	0	771	2	3	203
5	1-Aug	40	1	824	21	0	623	0	0	88
6	16-Aug	27	1	727	17	1	727	1	1	142
7	4-Sep	126	6	300	207	8	264	1	1	172

8	16-Sep	26	4	841	88	7	381	1	1	163
9	3-Oct	2	1	887	58	2	656	1	1	142
10	16-Oct	14	1	887	54	2	656	1	2	168
11	1-Nov	2	1	677	19	2	627	2	1	172
12	15-Nov	23	0	588	12	1	376	1	0	142
13	1-Dec	11	1	438	29	2	357	2	0	195
14	15-Dec	14	1	374	33	1	388	2	1	232
15	1-Jan	8	0	529	41	1	424	2	0	210
16	15-Jan	0	4	527	14	1	433	1	3	210
17	1-Feb	0	0	391	36	0	277	1	0	232
18	15-Feb	3	0	422	22	0	321	1	0	210
19	1-Mar	6	0	602	12	0	653	0	0	232
20	15-Mar	5	1	577	15	0	632	1	0	195
21	3-Apr	5	1	497	8	0	636	1	0	210
22	16-Apr	7	0	533	18	0	638	1	0	232
23	1-May	37	1	486	14	0	582	1	0	210
24	15-May	32	4	528	17	0	589	2	0	195

4.11.1 Spatial Variations

All the nutrients show variations in their average annual concentrations. Table 4.21 presents the data of nutrient concentration for ten locations on the Narmada river. The data presented is the arithmetic mean of fortnight nutrient concentration for a period of eleven years (1990-2001). Locations N1 to N10 (except Garudeshwar) on the Narmada mainstream do not show large variations in average annual nutrient concentrations, however within the locations itself large inter annual variations are observed. Highest average annual nitrate concentration was observed during the year 1990-91 at Rajghat (N10), and the following year (1991-92), it was lower. Similarly for the location Jamtara (N3) lowest and highest nitrate concentrations were recorded in the years 1991-92 and 1993-94 respectively. For phosphate, Manot (N2) recorded lowest and highest concentrations during water year 1996-97 and 1999-2000 respectively. Manot also recorded lowest and highest silica concentrations in the years 1994-95 and 2000-01 respectively. Inter annual variations for all the locations do follow a regular pattern. This may be due to more than one factor, which controls each of the nutrient concentration in the entire basin. Some key factors may be average annual rainfall, rainfall period, agriculture runoff, rates of fertilizer used, swift change in land use, crop patterns, contribution from tributaries, point source pollutants and presence of reservoir/dams. Other than the reservoir/dams all other factors are of fragile nature.

Table 4.21 Average annual nutrient concentration (μM) for eleven years of study duration at ten locations on the Narmada river

Year	Dindori N1	Manot N2	Jamtara N3	Barman N4	Sandia N5	Hoshangabad N6	Handia N7	Mandleshwar N9	Rajghat N10	Garudeshwar N11
Nitrate										
1990-91	1.63	3.50	2.45	2.17	2.61	2.09	1.86	2.35	4.47	0.30
1991-92	1.11	0.77	0.30	0.64	0.82	0.61	0.56	0.76	0.91	0.13
1992-93	1.94	2.68	2.75	2.20	2.37	1.82	1.68	2.56	2.34	0.11
1993-94	1.69	2.09	3.88	1.72	2.97	1.70	1.94	2.74	3.43	0.12
1994-95	1.55	1.36	0.81	1.23	2.00	1.32	1.35	0.94	1.65	0.11
1995-96	1.94	2.32	1.38	1.86	1.62	2.52	2.31	1.91	2.11	0.10
1996-97	1.50	2.25	1.44	1.50	2.94	1.58	2.25	2.28	3.63	0.04
1997-98	1.25	1.05	1.09	1.55	2.30	1.35	1.18	1.93	3.58	0.06
1998-99	1.13	0.86	1.17	1.26	1.72	1.27	1.02	2.12	2.41	0.10
1999-00	0.89	0.99	0.80	1.03	1.37	1.33	1.46	1.69	2.60	0.03
2000-01	2.90	2.25	1.94	2.07	3.28	2.66	1.84	2.62	3.59	0.04
Mean	**1.59**	**1.83**	**1.64**	**1.57**	**2.18**	**1.66**	**1.59**	**1.99**	**2.79**	**0.10**
Phosphate										
1990-91	0.11	0.11	0.17	0.11	0.08	0.11	0.08	0.08	0.08	0.28
1991-92	0.05	0.09	0.07	0.05	0.05	0.07	0.05	0.07	0.09	0.11
1992-93	0.04	0.03	0.06	0.03	0.07	0.05	0.03	0.04	0.04	0.06
1993-94	0.04	0.12	0.03	0.07	0.04	0.05	0.06	0.09	0.11	0.03
1994-95	0.05	0.02	0.06	0.06	0.05	0.05	0.07	0.06	0.05	0.07
1995-96	0.06	0.13	0.03	0.09	0.05	0.05	0.08	0.10	0.13	0.04
1996-97	0.17	0.01	0.06	0.07	0.07	0.07	0.09	0.10	0.11	0.02
1997-98	0.06	0.07	0.06	0.04	0.02	0.03	0.04	0.05	0.06	0.01
1998-99	0.08	0.08	0.07	0.10	0.07	0.08	0.09	0.08	0.03	0.04
1999-00	0.19	0.33	0.07	0.12	0.09	0.13	0.11	0.11	0.13	0.02
2000-01	0.12	0.06	0.05	0.04	0.05	0.05	0.10	0.05	0.07	0.02
Mean	**0.09**	**0.09**	**0.07**	**0.07**	**0.06**	**0.07**	**0.07**	**0.08**	**0.08**	**0.06**
Silica										
1990-91	26.8	39.0	29.1	25.8	24.6	27.6	25.7	26.6	31.8	11.9
1991-92	26.6	31.5	25.3	26.3	25.9	25.9	24.1	21.6	21.3	12.1
1992-93	28.0	33.5	22.6	23.4	12.3	13.4	15.4	17.7	19.4	14.4
1993-94	14.6	19.4	22.7	21.7	18.4	16.0	21.8	17.3	25.9	13.4
1994-95	13.9	11.3	16.6	14.5	15.3	14.3	16.2	19.1	16.1	13.8
1995-96	29.5	17.0	20.5	14.0	15.7	16.1	16.6	15.3	14.7	12.5
1996-97	20.6	30.1	26.1	25.6	26.0	26.4	29.6	30.5	33.9	12.8
1997-98	25.6	24.1	27.0	29.5	29.2	26.9	33.2	31.7	36.9	12.8
1998-99	28.8	34.7	31.5	29.0	26.2	30.8	20.9	25.4	38.1	14.6
1999-00	37.0	28.2	40.2	30.9	26.3	32.2	37.1	37.5	38.4	15.4
2000-01	29.4	43.0	35.9	37.5	32.2	35.5	31.1	36.7	33.9	7.92
Mean	**25.5**	**28.3**	**27.1**	**25.3**	**22.9**	**24.1**	**24.7**	**25.4**	**28.2**	**12.9**

Fig. 4.45 show the average annual nutrient concentrations at three locations, from upstream, midstream and downstream. In Fig. 4.45 A, nitrate concentrations only at Manot and Hoshangabad show a regular pattern whereas, in case of phosphate (Fig. 4.45 B), there is no fixed order. Silica at Manot and Hoshangabad again show an organized pattern (Fig. 4.45 C).

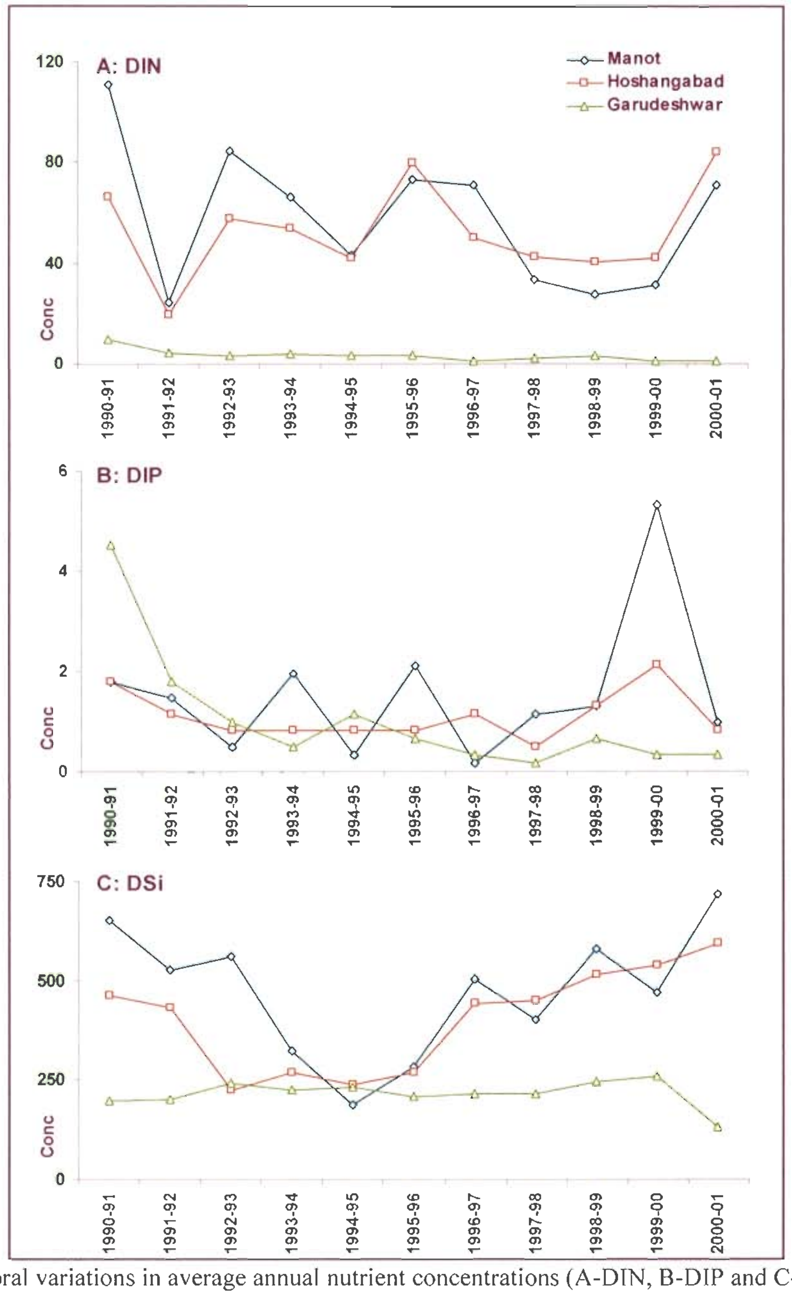


Fig. 4.45. Temporal variations in average annual nutrient concentrations (A-DIN, B-DIP and C-DSi)

4.11.2 Nutrient flux

Based on the water flow and concentration of nutrients, dissolved nutrient fluxes at different locations on the Narmada and its nine major tributaries, the average annual concentrations and flux of nutrients are calculated and presented in Table 4.22. Fig. 4.45 shows spatial variations in the nutrient flux at various locations on the Narmada mainstream and inputs from the tributaries. The nutrient flux shows regular increase along downstream. Loads of nitrate, phosphate and silica in the Narmada river vary from 1.76-98.2, 0.11-2.87 and 32.7-999 k tons yr^{-1} respectively. The sharp decrease at Garudeshwar (N11) compared to its upstream Rajghat (N10) is very noticeable; the most probable reason could be the presence of Sardar Sarovar Dam, which stores huge amounts of water and sediments in the reservoir. All the three nutrients show highest loads at Rajghat (N10), just before the location of the Dam. Loads at Rajghat are 98.2, 2.87 and 999 k tons yr^{-1} for nitrate, phosphate and silica respectively. The loads at Garudeshwar (location closest to the Arabian Sea) are 3.87, 2.59 and 450 k tons yr^{-1}, whereas the final flux at Garudeshwar to the Arabian sea are little higher than 3.95, 2.62 and 470 k tons yr^{-1} for nitrate, phosphate and dissolved silica respectively.

The Chota-Tawa contributes nearly 33.8, 0.62 and 181 k tons of nitrate, phosphate and silica respectively to the Narmada river down stream to Hoshangabad. Large loads of nitrate (8.87 k tons) come from a relatively small tributary Kundi (1.06 km^3 water discharge) whereas, for other two nutrients phosphate (0.18 k tons) and silica (58 k tons), Burhner follow the Chota-Tawa. High nutrient loads of nitrate and phosphate in relatively small tributaries, such as the Chota-Tawa and the Kundi indicate anthropogenic sources, since most of the agricultural activities are confined to the middle and down stream part of the basin. The application of fertilizers also has rendered the soils to be rich in NPK fertilizers in this region. The nutrient concentration (Fig. 4.43) and the nutrient load (Fig. 4.46) diagrams show disparate patterns, indicating that increase in water discharge is not the only factor controlling nutrient concentrations in the Narmada river.

Table 4.22 Nutrient concentration (μM) and nutrient flux (k ton yr^{-1}) at different locations in the Narmada river

Location No.	DIN		DIP		DSi	
	Conc	Load	Conc	Load	Conc	Load
N 1	50	1.76	1.45	0.11	425	32.66
N 2	58	6.20	1.45	0.36	471	99.66
N 3	52	15.6	1.13	0.73	451	281.7
N 4	50	20.8	1.13	1.05	421	335.5
N 5	69	37.1	0.97	1.10	382	402.7
N 6	52	38.5	1.13	1.80	402	574.6
N 7	50	42.3	1.13	2.04	412	683.9
N 8	63	64.0	1.29	2.74	423	876.8
N 9	88	98.2	1.29	2.87	470	998.8
N 10	3	3.87	0.97	2.59	215	450.2
T 1	43	2.98	1.13	0.18	373	58.08
T 2	22	1.21	1.45	0.16	518	55.24
T 3	82	2.74	2.26	0.16	510	37.43
T 4	38	0.59	1.13	0.03	653	17.34
T 5	78	2.79	1.45	0.09	651	57.13
T 6	47	1.47	1.45	0.11	678	43.59
T7	154	33.8	1.94	0.62	651	181.2
T 8	216	8.87	1.77	0.14	686	43.83
T 9	2	0.08	0.32	0.03	213	19.79

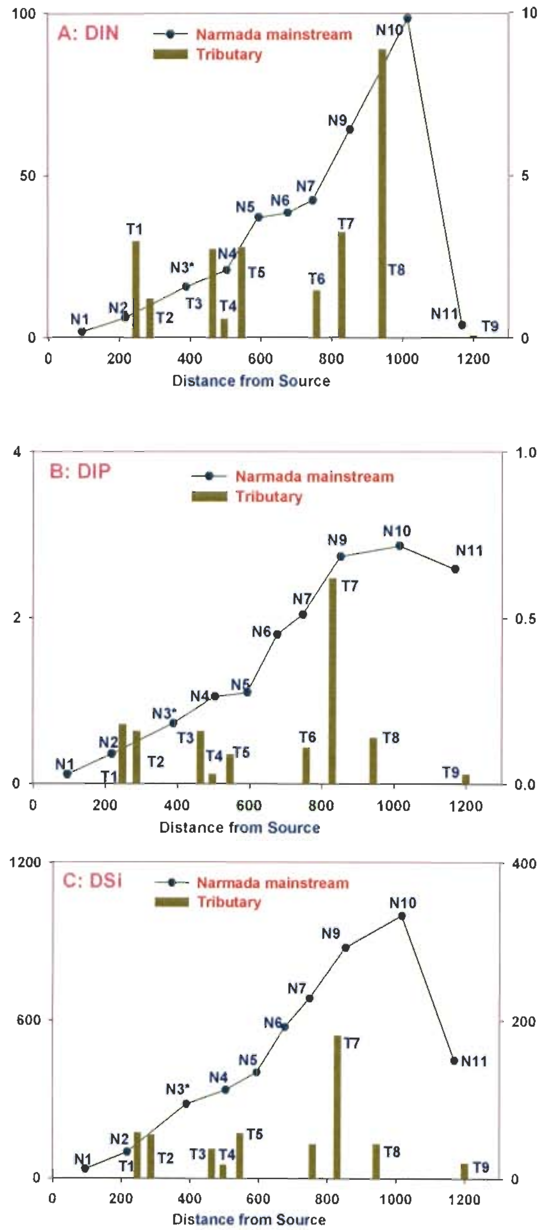


Fig. 4.46 Spatial variations in water flux (km^3 yr^{-1}) and nutrient flux (k tons yr^{-1}) in the Narmada mainstream (from upstream to down stream) and contribution from major tributaries (AW- water discharge, A- DIN, B-DIP and C- DSi)

Similar to nutrient concentrations, nutrient loads also show inter annual variations. The annual variations in nutrient loads at three locations, representing upstream (Manot, N2), midstream (Hoshangabad, N6) and downstream (Garudeshwar, N11) and a tributary in upstream (Burhner, T1) are shown in Fig. 4.47. Water year 1990-91 consistently recorded high nutrient flux at all of the locations, whereas the water year 1994-95 recorded high flux at Hoshangabad, Garudeshwar and Mohgaon, but not at Manot. Similarly in the year 2000-01, location Manot recorded high nitrate and silica loads.

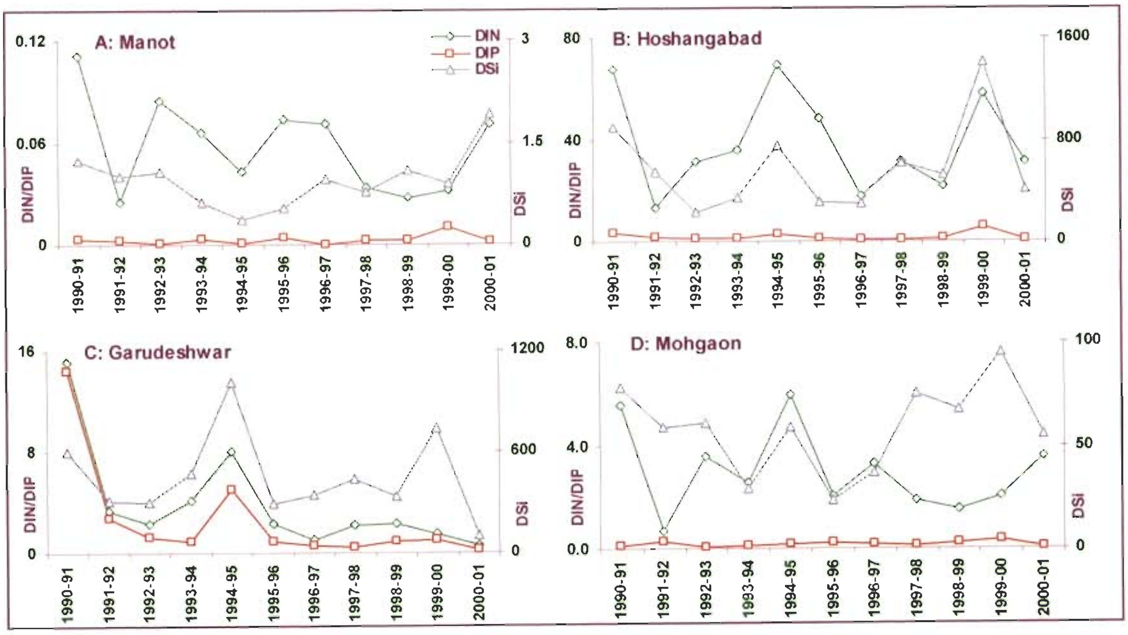


Fig. 4.47 Temporal variations in nutrient loads (kg tons yr^{-1}) at four locations (A-Manot, N2; B-Hoshangabad, N6; C-Garudeshwar, N11; and D-Mohgaon, T1) (nitrate/phosphate- primary Y- axis; silica-secondary Y - axis)

4.11.3 Influence of monsoon

A significant amount of nutrient loads are transported from the watershed during the monsoon period. From upstream to down stream, the nutrient loads show a sequential decrease. The Burhner river (T1), shows more than 90% nitrate and phosphate and approximately 86% of dissolved silica loads being transported during the monsoon season only. This shows that tributaries transport significant amounts of nutrients in monsoon season and hence play a vital role in controlling nutrient concentrations and subsequently the total loads of the mainstream. Similar findings for other river basins were also reported by various authors (Duda and Johnson 1985; Chowdhury et al., 1992). Table 4.23 presents the percentage of water flux, sediment and nutrient loads being transported during the monsoon season. If we compare the nutrient concentrations during the monsoon at all four locations, with the average nutrient concentration, nitrate and phosphate (except Garudeshwar) show relatively higher concentrations and silica (except tributary Burhner) shows low concentrations.

Table 4.23 Monsoon contribution of water discharge, sediment and nutrient flux (in percentage)

Code	Location	Water Flux %	Sediment Load %	Nutrient Concentration (monsoon)			Nutrient Concentration (average)			Nutrient loads % (monsoon)		
				DIN	DIP	DSi	DIN	DIP	DSi	DIN	DIP	DSi
N2	Manot	85.6	94.5	59	1.61	465	58	1.45	471	90.1	90.8	86.6
N6	Hoshangabad	66.4	93.2	54	1.29	377	52	1.13	402	69.5	78.7	63.0
N10	Garudeshwar	78.5	98.7	3	0.97	185	3	0.97	215	55.5	68.5	66.3
T1	Mohgaon	87.2	94.0	45	1.29	421	43	1.13	373	91.3	91.3	86.3

Rainfall is a major source of several elements to the Earth's surface and consequently it is imperative to determine the rainwater composition. In addition to rainfall, dry deposition of aerosols is another important source of atmospheric contribution. Table 4.24 presents the concentrations of nitrate and phosphate in rainwater. Maximum concentrations of nitrate were recorded from the rainwater sample collected on June 13th, 2004 from Mandleshwar (128 μM), followed by Kogaon (113 μM; June 13th, 2004) and Gadarwara (86 μM; June 14th, 2004). Nitrate concentrations in rainwater of three consecutive days 16th, 17th and 18th June 2004 are 73, 54 and 38 μM respectively at Barmanghat. The decreasing concentrations on successive days show the atmospheric flushing out of the chemical components. Concentrations of phosphate in rainwater vary from nil to 15 μM, whereas mean concentrations vary from 0.2 to 13 μM in the basin. Similar to nitrate, highest concentration of phosphate in rain water in the basin were recorded on June 14th 2004 at Gadarwara (15 μM). It is obvious that initial rains contain higher chemical components as compared to later rains. According Berner and Berner (1987), the typical concentration of nitrate and phosphate in terrestrial rains is between 6 to 21 and 0.2 to 0.6 μM mg l^{-1} respectively. Both nitrate and phosphate in rains in the basin show high concentrations may be attributed to high dust/aerosol in the atmosphere, resulting from the un-metalled roads at many places and heavy traffic. Forest fires could also be an important source for N-species. Likens et al. (1979) observed that in some remote areas, precipitation inputs were greater than the dissolved river input. Our rainwater results show 6-38% nitrate and 5-17% phosphate concentrations present in the river water are contributed from rains. The rain water flux to the river is very significant.

Table 4.24 Rainfall contribution of nitrate and phosphate in the Narmada river

Code	Station	Mean concentration (μM)	% contribution
Nitrate			
N 1	Dindori	23	46
N 2	Manot	29	50
N 5	Barman	24	48
N 6	Hoshangabad	29	56
N 7	Handia	21	42
N 8	Mandleshwar	26	41
N 9	Rajghat	38	43
T 1	Mohgaon	19	44
T 3	Patan	24	29
T 5	Gadarwara	24	31
T 8	Kogaon	22	10
Phosphate			
N 1	Dindori	0.97	8.89
N 5	Barman	0.81	7.14
N 6	Hoshangabad	0.48	13.3
N 7	Handia	0.00	7.14
N 8	Mandleshwar	0.32	16.7
N 9	Rajghat	0.48	11.3
T 1	Mohgaon	0.00	7.14
T 2	Hirdaynagar	0.16	5.56
T 3	Patan	0.16	6.43
T 5	Gadarwara	0.32	5.56
T 8	Kogaon	0.32	8.18

Mean fortnight concentrations of nitrate, phosphate and silica at Hoshangabad are coupled with mean water discharge ($m^3 s^{-1}$) (Fig 4.48) The results display concentrations of nitrate and phosphate show a positive correlation with water flow, indicating the minor role played by dilution. Dissolved silica concentrations show negative correlation, may be due to dilution of available silica by high water flow during monsoon.

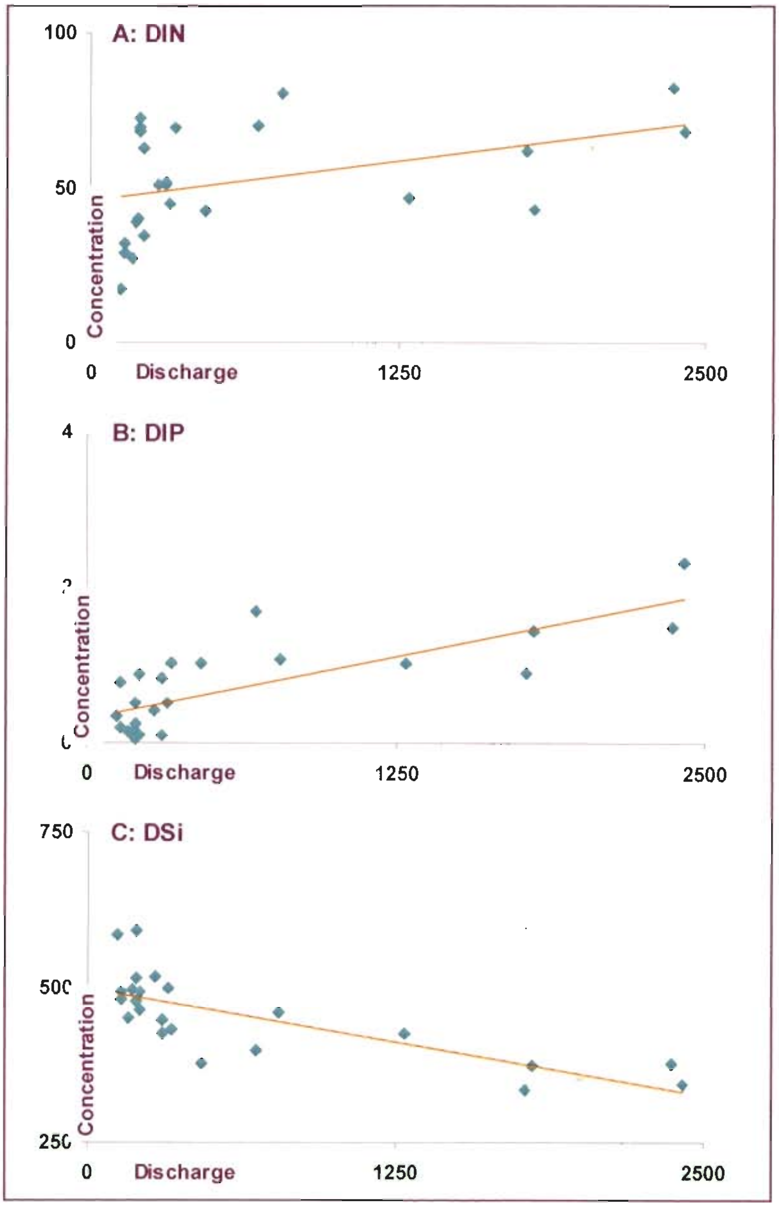


Fig. 4.48 Nutrient concentrations (μM) in relation to water discharge ($m^3 s^{-1}$)

Factor analysis of the water quality parameters and nutrients in the Narmada river at Hoshangabad (Table 4.25) shows that, the ions Na^+, Ca^{2+}, Mg^{2+}, HCO_3^- and Cl^- are derived from rock source, nitrogen and phosphorus are derived from application of fertilizers and probably also rainwater whereas, silica is derived from silicate rock weathering.

Table 4.25 Factor analysis of various dissolved constituents at Hoshangabad

	Variance Rotated Matrix			
	F 1	F 2	F 3	Communalities
DIN	0.23	0.75	0.27	0.69
DIP	-0.24	0.75	0.08	0.63
DSi	0.34	-0.25	-0.68	0.64
K^+	0.12	-0.09	0.83	0.72
Na^+	0.81	-0.08	-0.06	0.67
Ca^{+2}	0.81	-0.02	-0.05	0.67
Mg^{2+}	0.65	0.04	-0.18	0.46
HCO_3^-	0.90	0.09	-0.08	0.82
Cl^-	0.57	0.07	0.17	0.36
SO_4^{2-}	0.11	0.48	-0.24	0.30

4.11.4 Temporal Variations

Fig. 4.49 shows long term plot (1990-2001) of the nutrients at three locations (N2, N6 and N11) on the Narmada river. Large variations are observed in nutrient loads in upstream, midstream and down stream locations during different years. Data of three locations upstream, midstream and downstream of the basin, are analyzed to show the various alterations taking place in the Narmada main stream. There is an appreciable variation in the concentrations of the nutrients. Time series data at Manot show slight increase in silica and phosphate and decrease in nitrate over the study period. At Hoshangabad silica and nitrate show slight increase in concentrations whereas phosphate shows significant reduction in concentrations. Significant changes can be observed at

Garudeshwar, where all three nutrients show negative trends but the trend of nitrate and phosphate show significant reduction in nutrient concentrations. The variation is more focused for nitrate and phosphate, whereas silica variation is minimal. Silica is derived from rock weathering, whereas the signatures of anthropogenic controls are clearer in case of nitrate and phosphate. This may also be possible, because of the effective utilization for P and N and also its adsorption to sediment particle during the enhanced residence time of water in reservoir, whereas Si may not have a good sink in sediments.

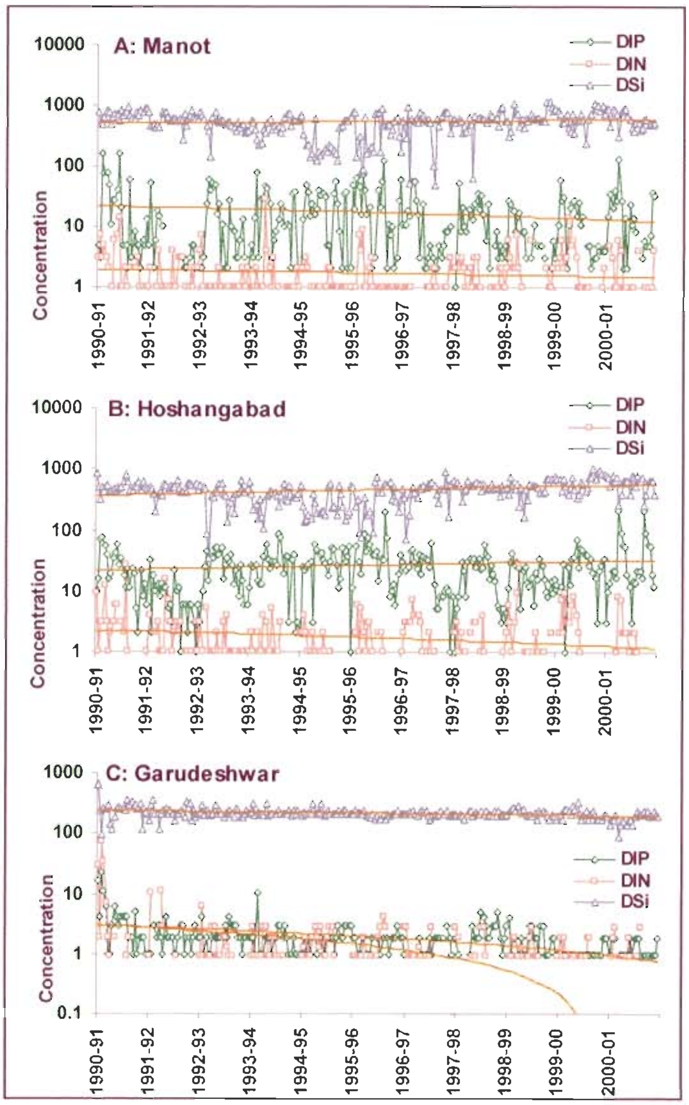


Fig. 4.49 Long term variation of nutrients at Manot (N2; upstream), Hoshangabad (N6; midstream) and Garudeshwar (N11; downstream)

4.11.5 Growth limiting nutrients

The N/P and Si/N ratio are suggestive of the type of organisms that thrive in aquatic systems and also determine whether Si, N or P is a limited nutrient. Redfield et al. (1963) and Elser et al. (1996) postulated that there were stoichiometric and physiological limits to phytoplankton community composition and food web structure. It is also suggested that for the optimal algal growth in any aquatic system, N/P and Si/N ratio must be 16:1 and 1:1 respectively. Table 4.25 shows the N/P and Si/N ratio for the Narmada main stream and its major tributaries. The N/P ratios suggest phosphate as a growth limiting nutrient for the Narmada river basin except at, Garudeshwar (N11) on the Narmada river, Banjar at Hirdaynagar (T2) and Orsang at Chandwara (T9). At these three locations, nitrate is the growth limiting nutrient. High nitrate concentrations and the associated high N/P ratio may result mainly from the combined effects of use fertilizers in agriculture in the basin and the low flow during dry season. Between Si and N, N is the growth limiting nutrient for diatom algae.

Table 4.26 N/P and Si/N ratios at different locations in NRB

Location	N/P ratio	Si/N ratio
Dindori	17.7	16.0
Manot	19.3	15.5
Jamtara	24.7	16.5
Barmanghat	22.2	16.1
Sandia	37.2	10.5
Hoshangabad	24.3	14.5
Handia	21.8	15.5
Mandleshwar	25.6	12.8
Rajghat	34.6	10.1
Garudeshwar	1.80	129
Mohgaon	19.4	16.5
Hirdaynagar	7.77	44.4
Patan	18.5	11.8
Belkheri	17.0	32.9
Gadarwara	27.3	15.9
Chhidgaon	16.7	27.1
Ginnore	40.5	8.05
Kogaon	62.3	6.01
Chandwara	0.30	213

Fig. 4.50 (A, B and C) shows nutrients concentration in relation to dissolved oxygen (DO), pH and temperature at Hoshangabad (midstream). Silica and nitrate do not show any significant change with increase in DO concentrations; however phosphate reduces significantly with increase in DO concentrations.

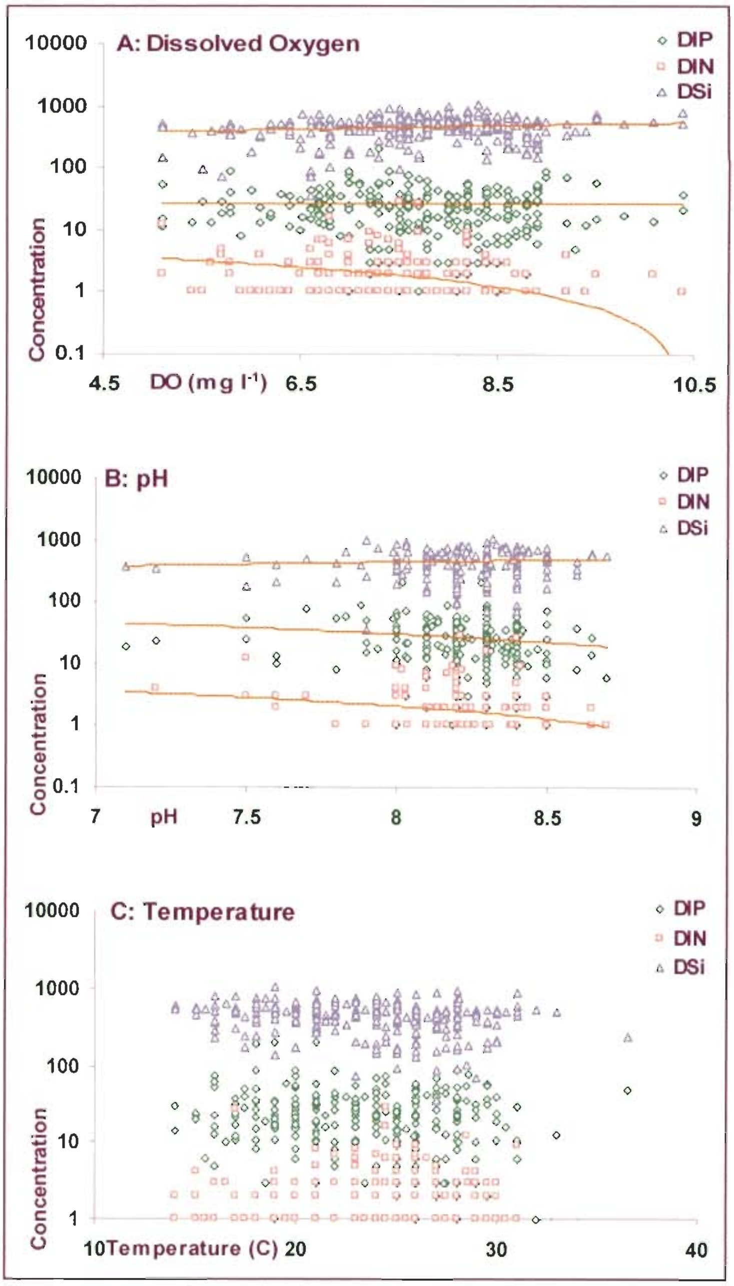


Fig. 4.50 Nutrients in relation to DO, pH and temperature in NRB at Hoshangabad (midstream)

The Narmada river water is characterized mostly, by dissolved oxygen levels of 5-8 mg l^{-1}, and most phosphate and nitrate values are centered around this value, whereas dissolved silica is widely scattered. Silica shows an increase whereas nitrate and phosphate show decrease in concentration level with increase in pH values. The solubility of particulate amorphous silica is related inversely to pH between approximately 3 and 7 and increase somewhat at alkaline values to a pH 9 (Marshall, 1964). With increase in temperature, silica and nitrate show reductions in concentrations, whereas phosphate increases with increase in temperature. The Narmada river basin is characterized by alkaline water and along with higher temperatures makes the nutrients to remain in dissolved state for a longer time.

4.11.5 Dams - a sink for nutrients

Similar to lakes, reservoirs also work as huge wetland ecosystems (Wetzel, 1983; Gunnison, 1985; Straskrabova et al., 1990; Thornton et al., 1990). Studies by Jossette et al. (1999), on reservoirs in Seine Basin (France) and Friedel et al. (2004), on Iron Gate I reservoir in Danube river basin have addressed large alteration in mass balance of various bio-essential elements in reservoirs. Milliman and Syvitski (1992), Vorosmarty et al. (2003), Gupta and Chakrapani (2005), accentuated the role of dams in suspended sediments retention. From all of these studies, it has been established that reservoirs work as a major sink for suspended and dissolved loads. Retention of suspended sediments and dissolved loads by reservoirs/dams has been observed all over the world. At the same time, global riverine nitrogen and phosphorus inputs into the ocean have trebled due to human activities, whereas inputs of dissolved silicate from natural sources has been significantly reduced (Conley et al., (1993); Humborg et al., (1997); Rabalais, (1999)).

Sardar Sarovar Dam/Reservoir (SSR), traps a large part of suspended sediments, a study of over 20 years annual sediment loads showed trapping of near about 30% sediments (Gupta and Chakrapani, 2005), whereas during ten years (1990-2000), 50% of upstream sediment loads have been trapped in the reservoir. To identify the impact of the dam on nutrient mass balance of the Narmada river, we calculated the difference in the concentrations and loads of nutrients in between an upstream location Rajghat (N10) and down stream location Garudeshwar (N11), which are intervened by the SSR. Although Rajghat lies in the catchment area of the reservoir, yet this location is not under submerged condition and the location Garudeshwar lies eight km down stream of the Dam.

Fig. 4.51 Changes in nutrient concentrations in upstream and downstream of Sardar Sarovar Dam

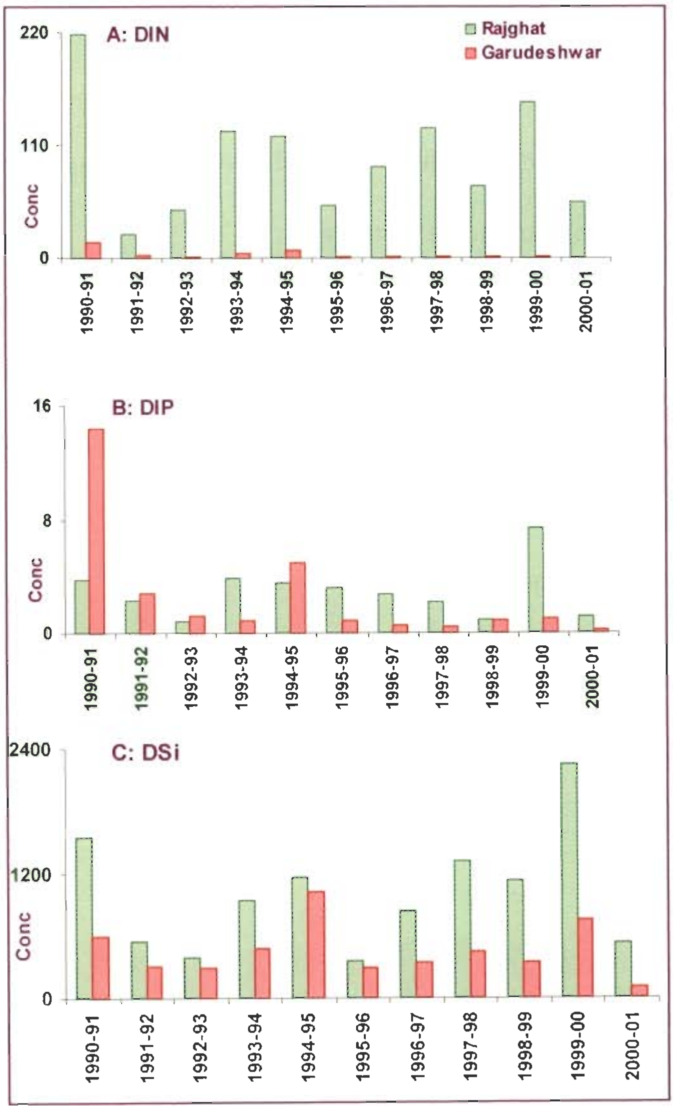


Fig. 4.52 Changes in the nutrient loads during the study period

Fig. 4.51 (A, B and C) shows changes in fortnight nutrient concentrations (year 2000-01) in between Rajghat and Garudeshwar, which show noticeable decline in nutrients at Garudeshwar, after the river has passed through the dam. Fig. 4.51 (D, E and F) also shows the long term changes in average nutrient concentrations for 11 years. Concentrations of nitrate, phosphate and silica at Rajghat and Garudeshwar are 88.2-3.2, 1.29-0.97 and 470-215 (μM). For the water year 2000-01, 99% nitrate, 78% phosphate and 81% silica were trapped by the dam. On a decadal scale, almost 96% nitrate, 55% silica and 10%

phosphate were trapped by Sardar Sarovar dam. The trapping is very high compared to 40-60% in Seine river (Jossette et al., 1999). The reason could be the role of precipitation mechanism in different climatic conditions and also depends on the amount and concentrations of nutrients in river water.

Fig. 4.52 (A, B and C) shows detailed account of amount of total nutrient loads at Rajghat and Garudeshwar. Differences in nitrate loads are very significant compared to phosphate and silica. For inorganic nitrate, phosphate and silica, the average amounts of nitrate retained in SSR are 94.29, 0.28 and 548.65 k tons yr^{-1} respectively. During the water year 2000-01, the amount of nutrients retained are 329.67, 5.34 and 2535.76 k tons for nitrate, phosphate and silica respectively.

Chapter 5

CONCLUSIONS

The Narmada river at Rajghat

CONCLUSIONS

The important conclusions from the study are,

Water Discharge

- The water flow in the Narmada river shows significant temporal and spatial variations and span >1 order of magnitude.
- Monsoon rainfall is a major factor in contributing water flow to the river. Water discharge in the basin is primarily influenced by rainfall patterns and associated runoff, although other catchment characteristics (catchment area, soil properties, topography and vegetation cover) also modify the water flow.
- Monsoon months observe higher water flow and comprise the bulk of annual discharge (60 - 80%). A few days during monsoon season are responsible for huge amounts of water flow in the river. Low water flow in the river is observed during peak summer months of April, May and June.
- The water discharge ratio of monsoon to non-monsoon show large variations and vary from ~10 to over 100. Presence of dams regulates the natural flow patterns of water.
- The final water flux (mean discharge) of the Narmada river to the Arabian sea is approximately 37 $km^3\ yr^{-1}$.
- Forty-one tributaries drain their water to the Narmada river and contribute approximately 70% of the water flow.
- The left bank tributaries, which originate from the Satpuras, act as the main source of water to the Narmada river.
- The monsoon season contributions for water flow are 70 - 92% and 87 - 99% for the Narmada mainstream and the tributaries respectively.

- Runoff in the Narmada river varies between 247 mm to 742 mm.

Suspended Sediments

- The Narmada river shows large temporal and spatial variations in daily sediment concentrations and the variations are predominantly significant for monsoon period. Sediment concentrations in the basin are intimately coupled with water discharge patterns.
- Only "a few days" carry sediment concentrations of more than 1000 mg l^{-1} and the number of such days in a year varies from 1 day to 40 days for different locations. The monsoon months (July, August and September) observe maximum suspended sediment concentrations whereas, lowest suspended sediment concentrations are observed during the months of February, March, April and May.
- The "long term" sediment concentrations of two decades show conspicuous difference (6-50% changes) in sediment concentrations. The previous decade (1990-2000) recorded reduced concentrations as compared to the decade 1980-90.
- More than 90% annual sediment loads in the Narmada river are transported during the monsoon season. Approximately, 70 - 90% of annual loads in the Narmada river are transported during 14 - 24 days of the year.
- More than 90% of suspended sediment loads in the basin are carried in finer sizes (< 0.075 mm) whereas, transport of coarse and medium size sediments (diameter above 0.075 mm) is more pronounced during monsoon season as compared to the non-monsoon.

- The annual sediment loads of Narmada river vary from 3.33×10^6 tons to 41.5×10^6 tons, at different locations in the basin. The tributaries contribute significant amounts of the total suspended sediments to the river. The ultimate flux of the Narmada river to the Arabian sea is approximately 30×10^6 tons.
- The Narmada river shows a good linear between water discharge and sediment concentrations. Similarly, annual water flux and sediment loads show good correlations in the entire river.

Factors controlling water and sediment transport

- Water flow and sediment load patterns in the river suggest that rainfall, catchment area, relief, basin geology and soil characteristics and presence of reservoir/dam are the major controlling factors.
- Presence of reservoir/dams along the course of the Narmada mainstream and the tributaries significantly modify the natural sediment loads in the basin. Among the dams, Bargi (upstream), Indra Sagar (midstream) and Sardar Sarovar (downstream) are the large dams on the Narmada river. Sardar Sarovar alone traps approximately 60-80% of monsoon sediment loads. Long term data suggest, nearly 30% of sediments are being trapped by the Sardar Sarovar Dam.

Physical Weathering Rates

- Physical weathering rates in the basin vary between 208 and 1320 tons km^{-2} yr^{-1}.
- In the upstream part of basin, relief dominantly controls the physical weathering process.

Water Chemistry

- The pH of Narmada river water varies from almost neutral to mild alkaline (6.9 to 8.5) with most of samples in the range of 7.0 - 8.0. The ionic strength varies between 3 - 5 x 10^{-3} (mol l^{-1}). Chemical compositions of water in the river show extreme temporal and spatial variations.
- (Ca^{2+}+Mg^{2+}) and HCO_3^- are the most abundant ions in the river water. The dissolved silica concentrations in the river are high and vary from 149 to 592 μM.
- Ternary plots of multi-annual data suggest, the control of geology over water composition, whereas scattering of data is mainly controlled by the climatic (rainfall and temperature) factors.
- Major ions in the Narmada river show variations at different sampling locations. Change in lithology and soil characteristics exert strong influence on the water composition in the basin.
- All the dissolved species show a strong dependence on water discharge and indicate the effect of dilution during peak flow.
- The final dissolved loads of the Narmada river to Arabian sea are approximately 7.40 x10^6 tons yr^{-1}. Among the major ions, alkalinity alone, constitutes between 57- 63% of total loads, whereas, Ca^{2+} varies between 11-14% and dissolved silica 6 - 16%. Bulk of the annual loads of the dissolved constituents are carried during monsoon season
- The chemical weathering rates in different sub-catchment areas in the Narmada river vary between 20 - 49 tons km^{-2} yr^{-1} with an average of ~30

tons km^{-2} yr^{-1} and approximately 84% of chemical load is transported during the monsoon season.

- Physical and chemical weathering rates in the basin show good correlation. The chemical weathering rates seldom exceed one-tenth of physical weathering rates. Sediment load dominates over chemical load in the basin by a factor of 17.5.
- The total weathering rates in the Narmada river basin vary between 212 and 1353 tons km^{-2} yr^{-1}.
- Tight coupling between physical and chemical weathering rates in the basin suggest, more or less similar factors, such as climate (rainfall and temperature), runoff, basin geology and soil characteristics, relief, catchment area and presence of dams control weathering rates in the basin.
- Dissolved strontium concentrations in the Narmada river vary between 0.77 and 2.62 μM, whereas the $^{87}Sr/^{86}Sr$ isotopic ratios vary between 0.70823 and 0.71964.
- The specific flux of strontium derived from the weathering of Deccan traps in the Narmada basin range between 333 and 973 mol km^{-2} yr^{-1}. The total flux of strontium delivered by the Narmada river to the Arabian sea is approximately 4.05×10^{7} mol yr^{-1}

Nutrients

- Temporal and spatial variations indicate several factors controlling nutrient concentrations. The major factors identified are, (i) lithology (ii) atmospheric contribution (iii) land use and fertilizer consumption (iv) biological controls and, (v) presence of dams and reservoirs.

- Agricultural runoff and domestic sewage are potential sources of nitrate and phosphate. Silicate rock weathering is the major source of dissolved silica and agricultural runoff and domestic/industrial sewage are significant source for phosphate and nitrate.
- The nutrient concentrations are high in lean period, however due to heavy water flow during monsoon (almost 90% of annual water flow), nutrient flux become very high.
- The N/P ratios suggest phosphate as a growth limiting nutrient in the Narmada river.
- Mean concentrations of nitrate, phosphate and silica in the river basin vary from 1.90 to 216, 0.32 to 1.94 and 214 to 686 μM respectively.
- Loads of nitrate, phosphate and silica vary from 1.76-98.2, 0.11-2.87 and 32.7-999 k tons yr^{-1} respectively. The nutrients load show significant increase towards downstream.
- The final flux of nutrients to the Arabian sea at Garudeshwar (farthest downstream location of the river for the present study) are about 3.95, 2.62 and 470 k tons yr^{-1} for nitrate, phosphate and dissolved silica respectively.
- The flux of the nutrients are very low in comparison to the upstream site at Rajghat, because of obstructions at many reservoir sites along the river. The Sardar Sarovar Dam located between Rajghat (upstream) and Garudeshwar (downstream), traps huge amounts of nutrients. Approximately 96% nitrate, 55% silica and 10% phosphate was retained by the reservoir itself.

- N/P and Si/N ratios suggest that phosphate is growth limiting nutrient for primary yield, whereas nitrate is growth limiting nutrient for diatom algae in the Narmada river.

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