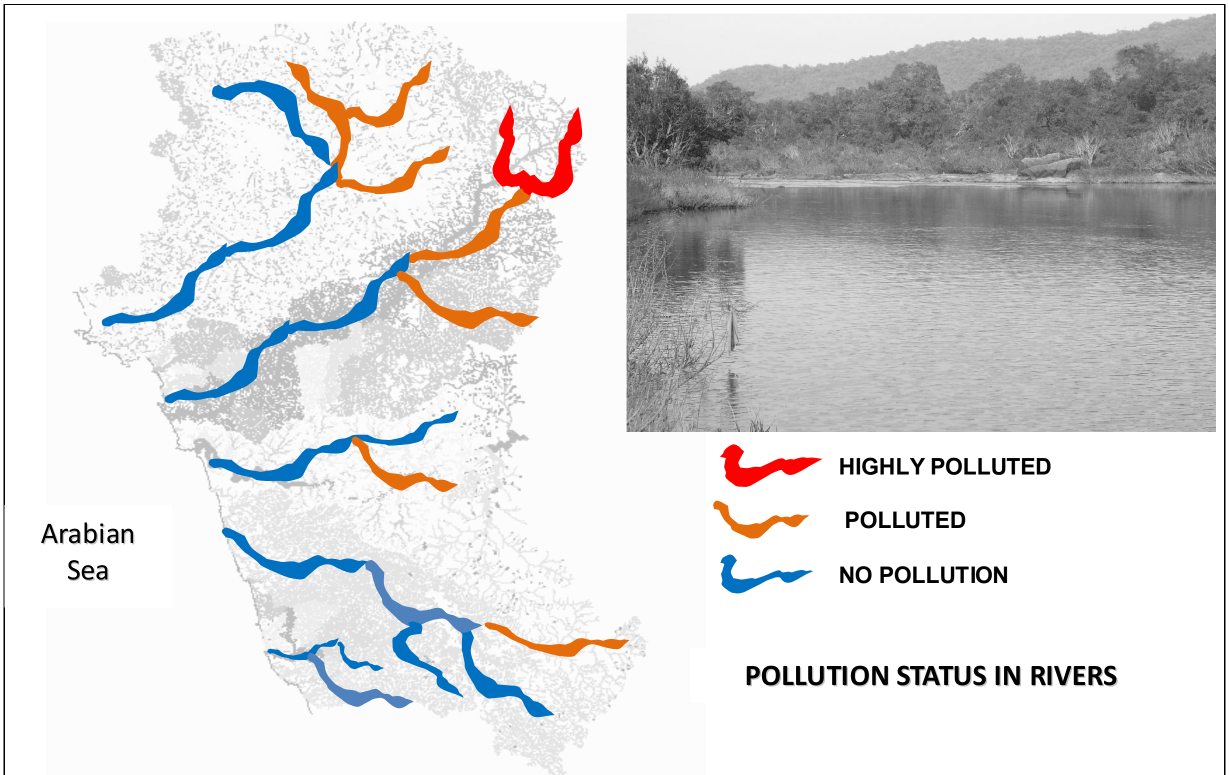
Sahyadri Conservation Series 14

Ecohydrology of Lotic Ecosystems of Uttara Kannada, Central Western Ghats

Ramachandra T.V. **Subash Chandran M.D** **Joshi N.V.**
Karthick B. **Sameer Ali** **Vishnu D. Mukri**



POLLUTION STATUS IN RIVERS

Western Ghats Task Force, Government of Karnataka
Karnataka Biodiversity Board, Government of Karnataka
The Ministry of Science and Technology, Government of India
The Ministry of Environment and Forests, Government of India

ENVIS Technical Report: 40

March 2012

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Centre for Ecological Sciences,
Indian Institute of Science,
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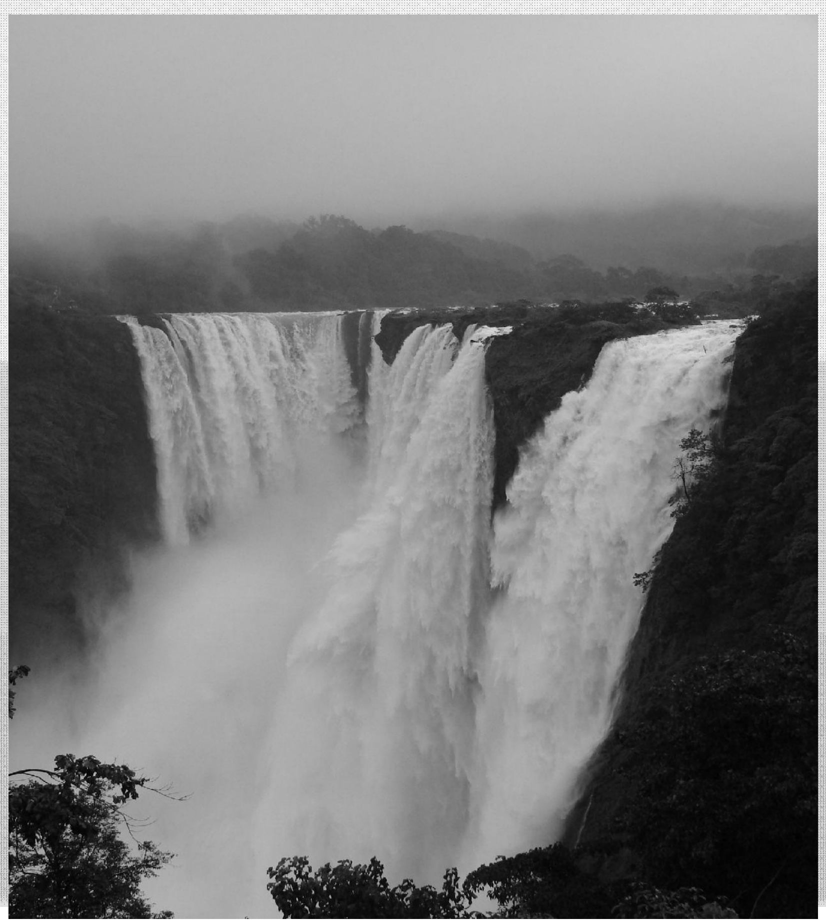
Contents



Ecohydrology of Lotic Ecosystems of Uttara Kannada, Central Western Ghats

Abstract

Western Ghats is the primary catchment for most of the rivers in peninsular India. Pristine forests in this region are rich in biodiversity and are being cleared due to unsound developmental activities. This has given rise to concerns about land use/land cover changes with the realization that land processes influence climate. Rapid land-use changes have undermined the hydrological conditions, there by affecting all the components in the hydrological regime. The development programmes based on ad-hoc decisions, is posing serious challenges in conserving fragile ecosystems. Considerable changes in the structure and composition of the land use and land cover in the region have been very obvious during the last four decades. Pressure on land for agriculture, vulnerability of degraded ecosystems to the vagaries of high intensity of rainfall and high occurrence of steep erosion and landslide-prone areas, lack of integrated and coordinated land use planning are some of the reasons for rapid depletion of the natural resource base. These changes have adversely affected the hydrological regime of river basins resulting in diminished river / stream flows. This necessitates conservation of ecosystems in order to sustain the biodiversity, hydrology and ecology. In this situation, in order to resolve present problems and to avoid a future crisis, a comprehensive assessment of land use changes, its spatial distribution and its impact on hydrological regime was carried out and accordingly, appropriate remedial methods are being explored for the sustainable utilization of the land and water resources of the catchment. The current research focusing on five rivers in central Western Ghats monitors water quality along with diatoms, land use in the catchment and threats faced by these ecosystems.

Keywords: Western Ghats, Lotic Ecosystems, water quality, diatoms

Ecohydrology of Lotic Ecosystems of Uttara Kannada, Central Western Ghats

Introduction

Freshwater ecosystems around the world have been classified into lotic and lentic systems, that is systems comprising of flowing or standing water. There are varieties of plant and animal communities in these ecosystems and these have adapted to the physical conditions around them. Fishes, aquatic invertebrates, amphibians, crustaceans, diatoms, plankton and some aquatic plants form the important communities in these ecosystems. Fishes also form a very crucial part of the food chain in aquatic ecosystems, and occupy various levels in the trophic hierarchy.

Environmental pollution, mainly of water sources, has become of public interest (Niemi *et al*., 1990). Not only the developed countries have been affected by environmental problems, but also the developing nations suffer the impact of pollution (Listori and World-wide Bank, 1990), due to unplanned developmental activities associated with the exploration of virgin natural resources. Surface waters are vulnerable to pollution due to their accessibility for disposal of polluted runoff and wastewaters. Quality of the surface waters are altered by both the natural processes, such as precipitation inputs, erosion, weathering and the anthropogenic influences such as agricultural activities, urban, industrial and increasing exploitation of water resources (Jarvie *et al.,* 1998). Rivers play a major role in assimilation or carrying off the municipal and industrial wastewater and run-off from agricultural land. The surface run-off is a seasonal phenomenon, largely affected by climate in the basin. Seasonal variations in precipitation, surface run-off, interflow, groundwater flow and pumped in and outflows have a strong effect on river discharge and subsequently on the concentration of pollutants in river water (Vega *et al.,* 1998). Since, rivers constitute the main inland water resources for domestic, industrial and irrigation purposes, it is imperative to prevent and control the rivers pollution and to have reliable information on quality of water for effective management. These impacts reduce both water quality (Sweeting, 1994) and biological diversity of aquatic ecosystems (Maddock, 1999). In view of the spatial and temporal variations in hydrochemistry of rivers, regular monitoring programs are required for reliable estimates of the water quality and conservation of riverine biodiversity. The integrated aquatic ecosystem management requires proper study for sound understanding and effective management of water systems and their internal relations and hence an attempt has been done in the present study to determine the water quality status and application of diatoms as a bioindicator in the rivers of central Western Ghats.

The Western Ghats of India, is one of the global biodiversity hotspot, is a chain of mountains on the Western Coast with about 1600km long and about 100km wide stretch (between 8°N-21°N). The region has varied forest types from tropical evergreen to deciduous to high altitude sholas. It is also an important watershed for the peninsular India with as many as 37 west flowing rivers, three major east flowing rivers and innumerable tributaries. The current research focusing on five rivers in central Western Ghats monitors water quality along with diatoms, land use in the catchment and threats faced by these ecosystems.

Objectives

1. To study the current water quality status of five rivers of Uttara Kannada district, Karnataka.
2. To study the seasonality of diatoms and application of diatoms in biomonitoring in Western Ghats.
3. To study the impact of catchment land-use and land-cover on water quality and diatom community in streams.
4. To identify stretches with major water pollution and provide recommendation for mitigation and conservation of rivers of Uttara Kannada.

Lotic Ecosystems of Central Western Ghats: Overview

Rivers of the central Western Ghats are unique in their geomorphology, due to the presence of ‘river capture’ in most of the rivers. When the Indian plate moved away from the Gondwana land, peninsular portion experienced an eastward tilt, which changed the pattern of drainage in many rivers. In many cases, like the river Sharavathi and Kali in Uttara Kannada, the western faulting led to 'river capture' and diversion of the easterly drainage to the west (Radhakrishna, 1991). There are abrupt drops as water falls such as Jog Falls, Unchalli, Magod through gorges and cascades of rivers flow along the upper reaches of the Western Ghats.

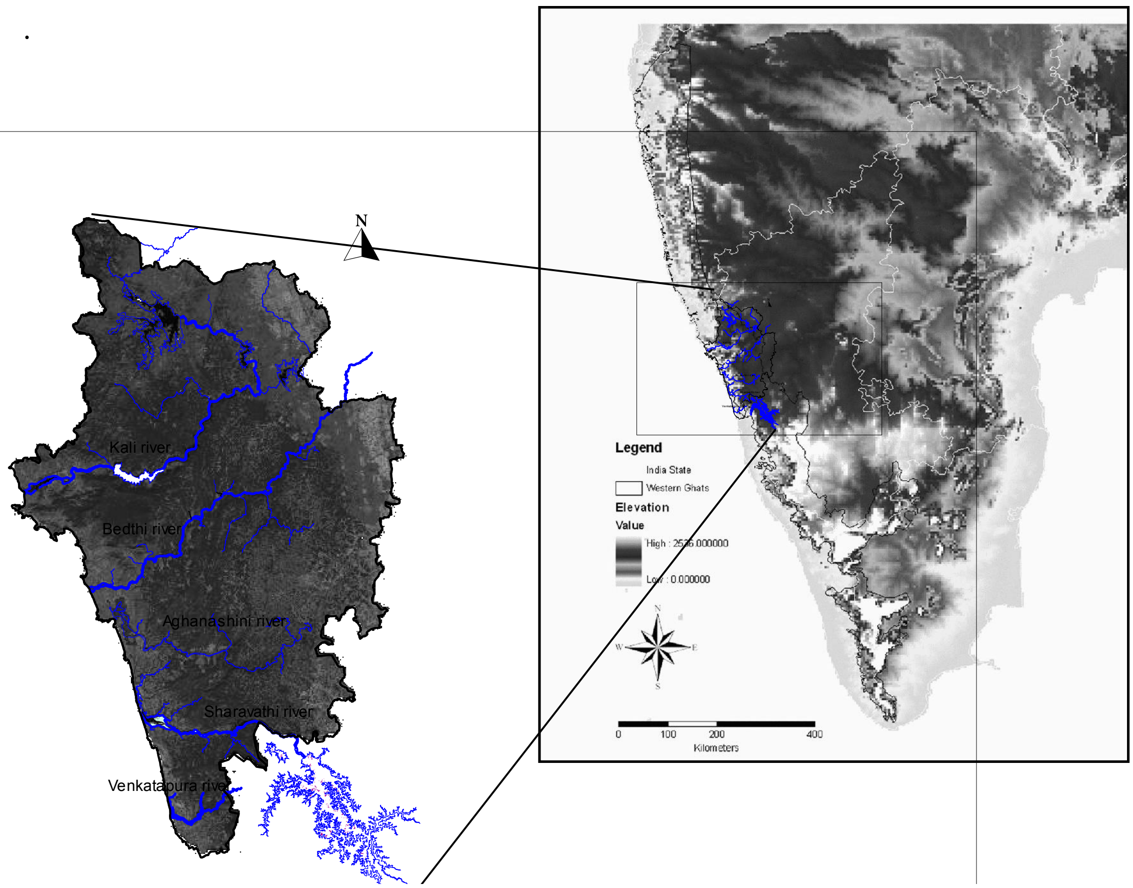


Figure 1: False colour composite image of Uttara Kannada district with rivers

Kali River: Kalinadi (Fig. 2), which extends to a length of 184 km, earlier originated near the village Diggi in Supataluk, as Karihole. After the construction of the dam near Supa, the entire region is now submerged in the reservoir. Pandri and Ujli are the two main feeders to this river in the North and the stream Tattihalla also joins near Haliyal. The Kaneri and the Vaki are its two main tributaries joins later at Dandeli and Anshi Tiger Reserve. Later near Kadra, Thananala joins the main river. In all, the catchment area of the river is about 5,179 sq. km and the annual river discharge is 6,537 million cu. M (Bhat, 2002). There are four major dam projects on this river - the Supa reservoir near the headwaters, the Bommanhalli reservoir near the Dandeli Wildlife Sanctuary, the Kodasalli dam near Ganeshgudi and finally, one at Kadra (which is the part of the Kaiga project).

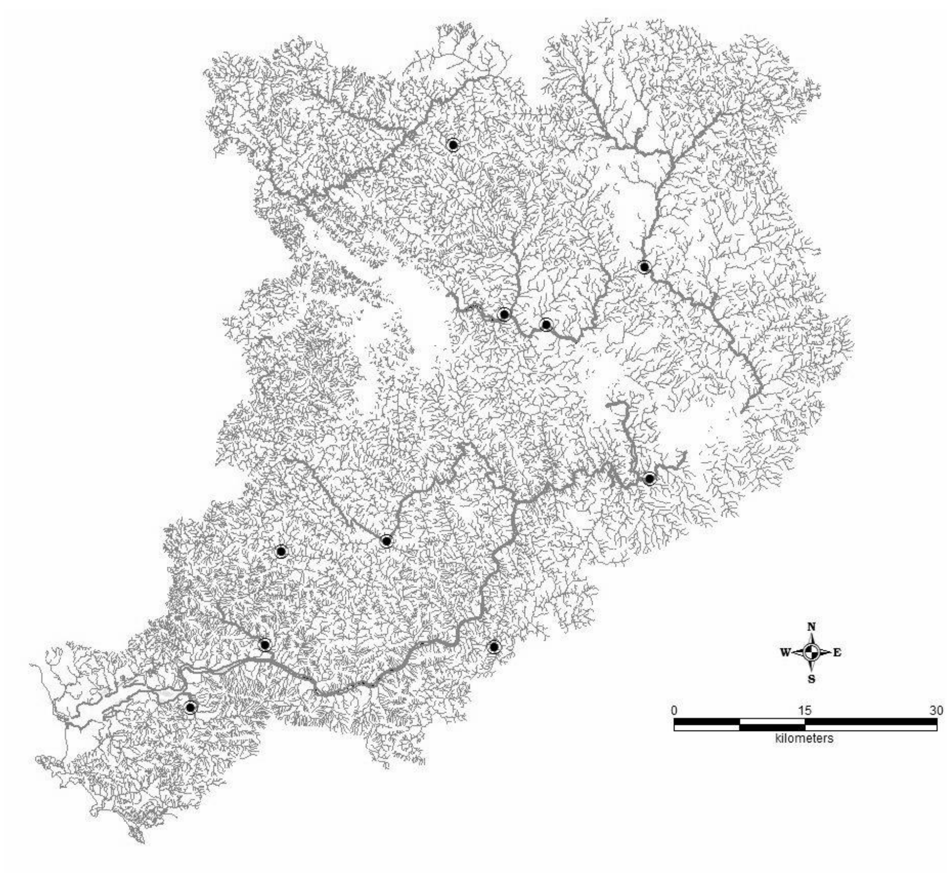
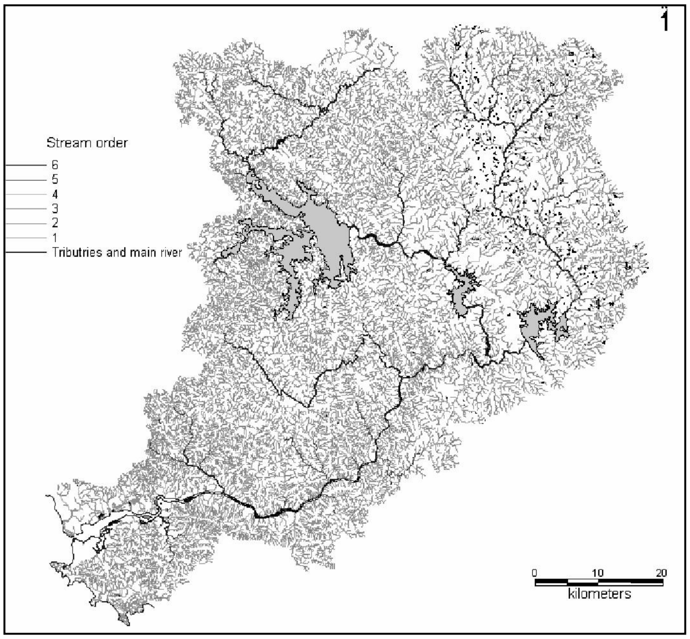
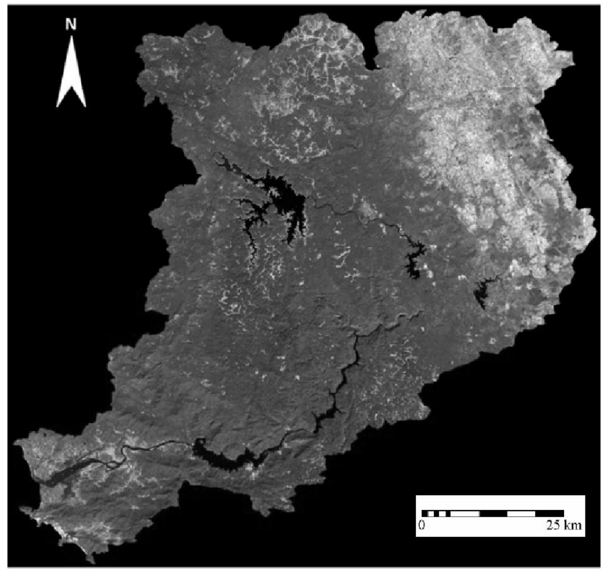


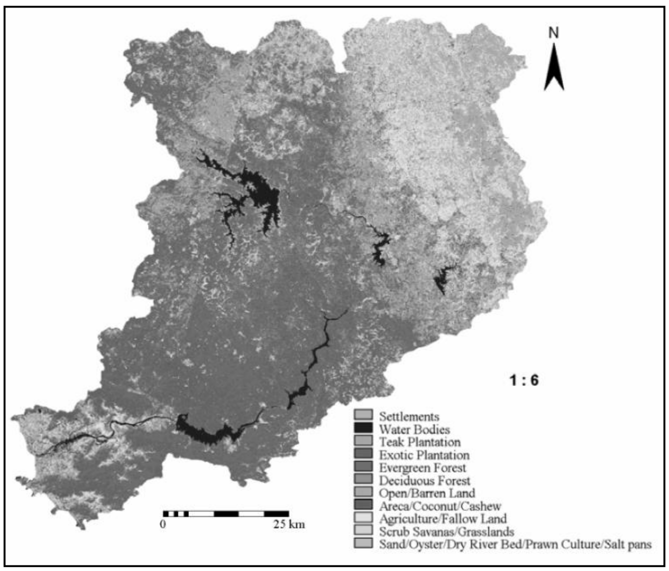
Figure 2: River Kali with sampling sites

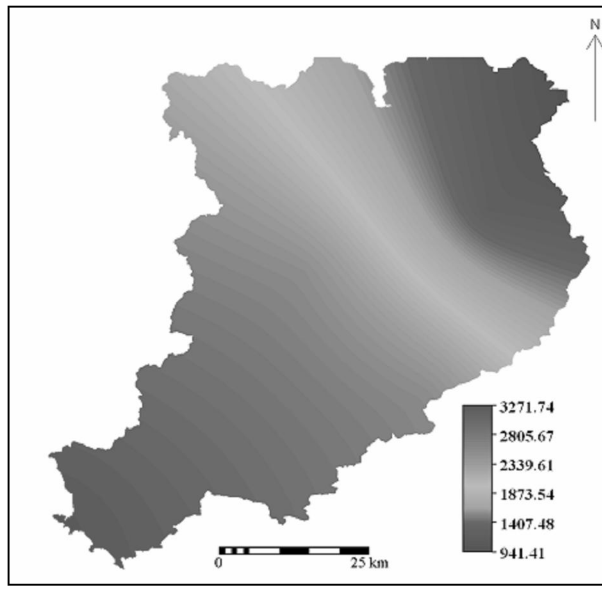
K A L I





Drainage network, land use, rainfall





Bedthi River: River Bedthi (Fig. 3) is a result of the confluence of two major streams, and the Bedthi stream, which originates near Hubli taluk. They join near Kalghatgi and the river flows for about 25 km westwards and enters the district of Uttara Kannada. After a southwesterly course of about 32 km, it falls into the sea. The united river extends about 8km south east to the border of Uttara Kannada and flows in the district for a length of 96km. The river, which extends to 152 km with a. catchment area of 3902 sq. km and discharges 4,925 million cu. m of water annually.

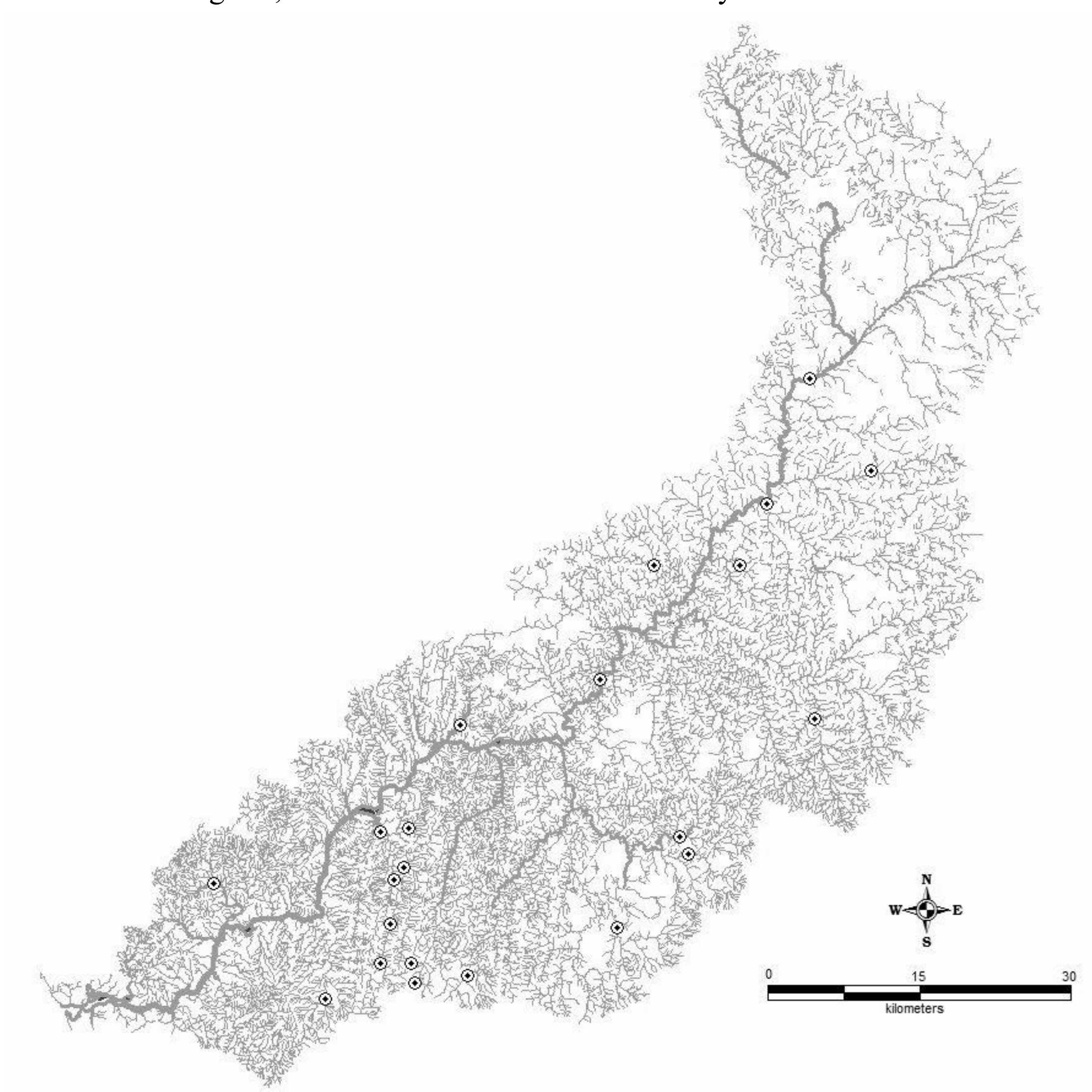
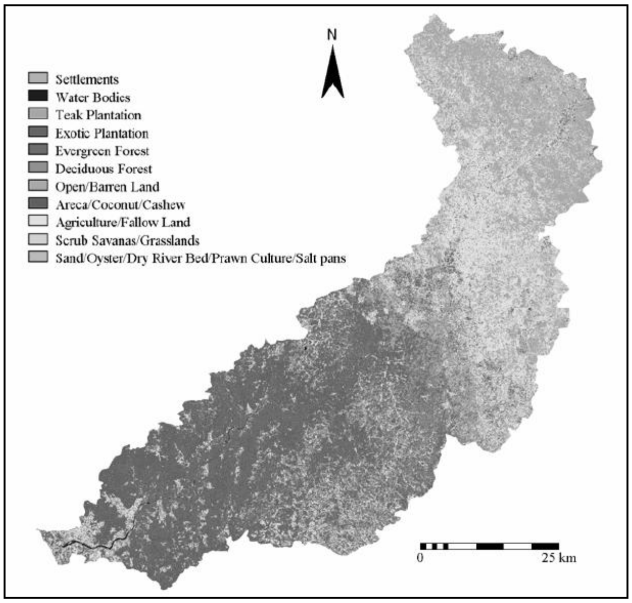
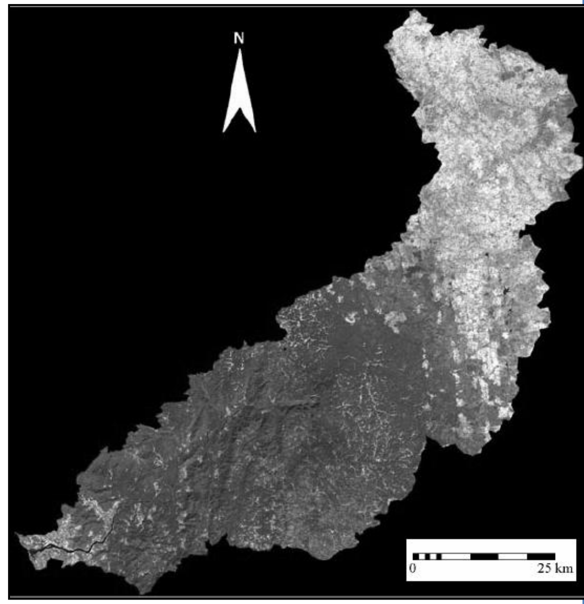
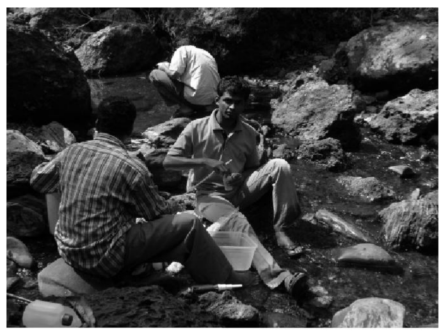


Figure 3: River Bedthi with sampling sites

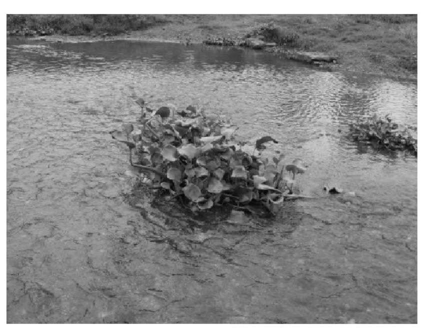

N
Settlements
Water Bodies
Teak Plantation
Exotic Plantation
Evergreen Forest
Deciduous Forest
Open/Barren Land
Areca/Coconut/Cashew
Agriculture/Fallow Land
Scrub Savanas/Grasslands
Sand/Oyster/Dry River Bed/Prawn Culture/Salt pans
0
25 km

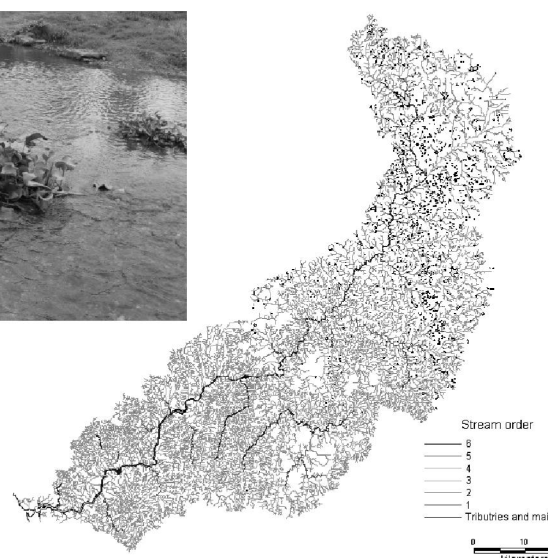

N
0
25 km

BEDTHI



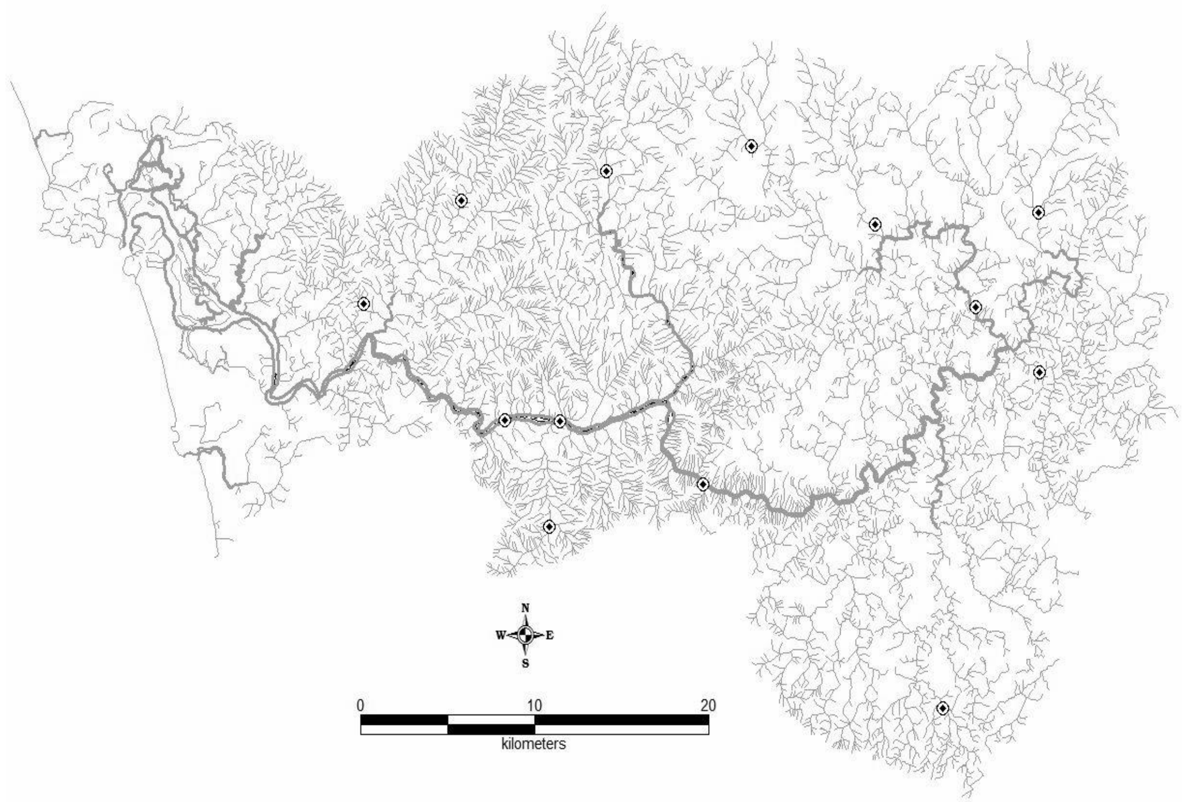

N
3593
3017
2442
1866
1290
0
25 km

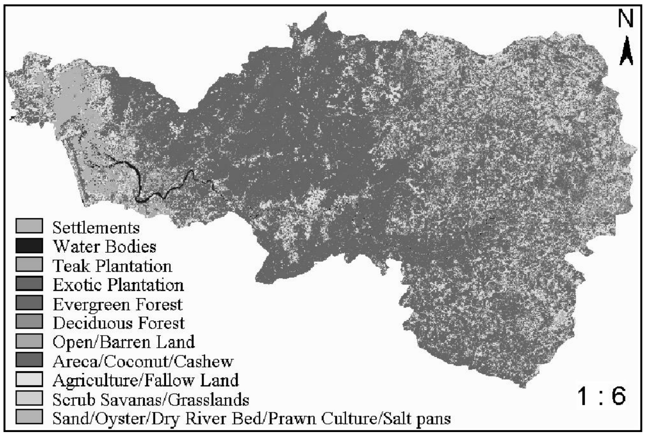


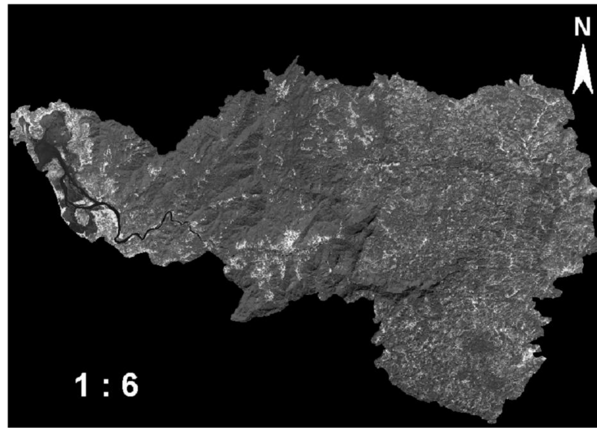

Stream order
6
5
4
3
2
1
Tributaries and main
0
10
kilometers

Aghanashini River: Aghanashini river (Fig. 4) arises at Manjguni near Sirsi. After a winding westerly course of about 70 km, it falls off into the sea about 10km south of Bedthi. The river has two sources - a tributary called Bakurhole, rising at Manjguni, about 25km west of Sirsi and Donihalla, which is close to Sirsi. The two streams meet at Mutthalli about 16 km south of Sirsi. Under the name Donihalla, it flows about 25 km south of Sirsi westwards to Sahyadri's west face and at Heggarne in Siddapur, it falls off a height of about 116 m as the Lushington (or the Unchalli) falls. Further down 6 km from Bilgi near Hemanbail, it flows down again as the Burdejog. It finally meets the tide at Uppinpatna. The Aghanashini covers a catchment area of 2,146 sq. km, with an annual discharge of 966 million cu. m.

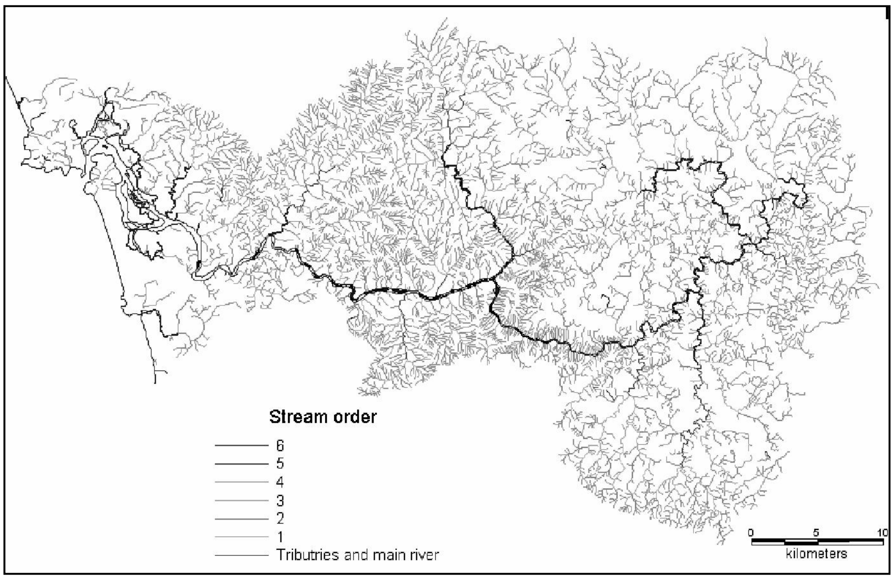
Figure 4: River Aghanashini with sampling sites







AGHANASHINI



Sharavathi River: Sharavathi river (Fig. 5) originates at Ambutirtha in Tirthahallitaluk of Shimoga district. After a northerly course of about 64 km from Sagar, it forms the southeastern border of the Uttara Kannada district for about 13km and flows a further 32 km west in all, it flows 128 km to join the sea at Honnavar. Soon after touching the Uttara Kannada border the river falls off the western face of the Ghats in Jog falls at a height of 252 m into a pool 117 m deep. About 30km west, it reaches Gersoppa. The Sharavathi extends to a length of 122 km, with a catchment area of 2,209 sq. km and an annual discharge of 4,545 million cu.m.

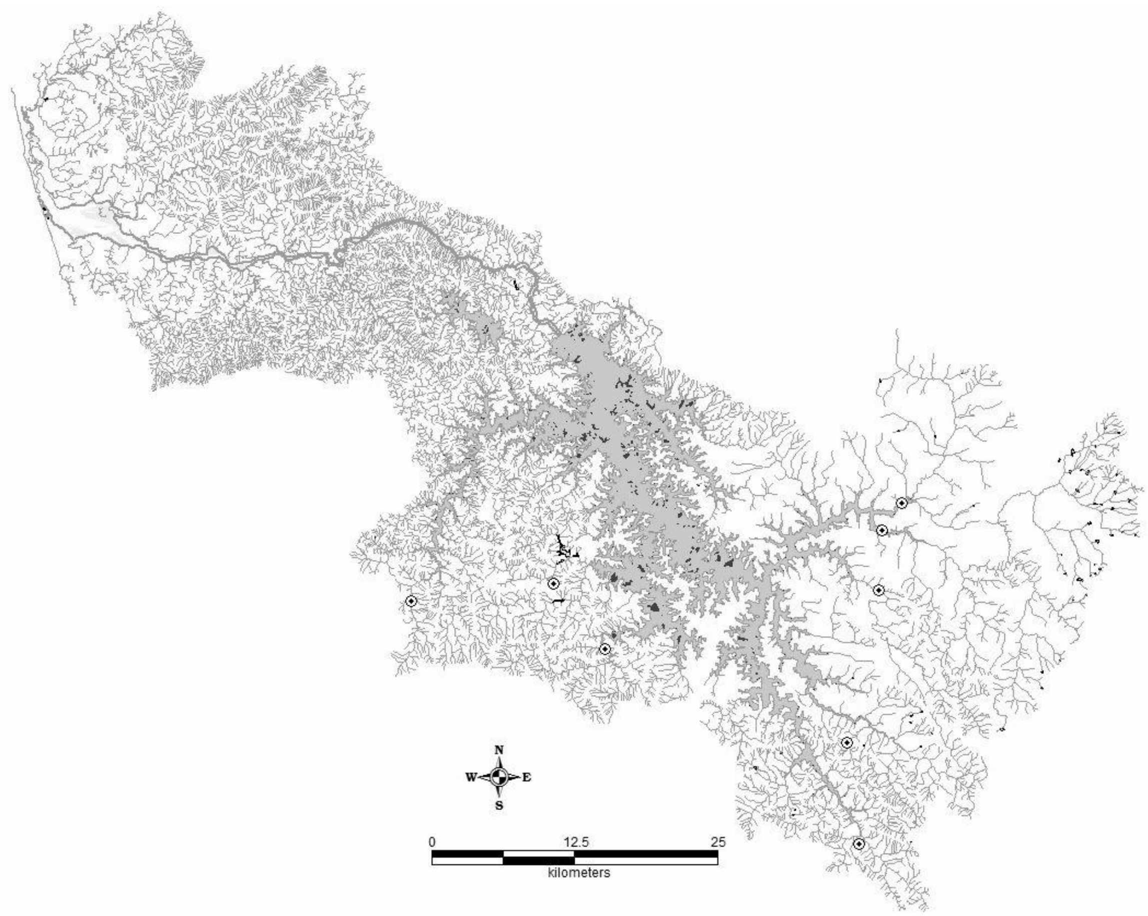
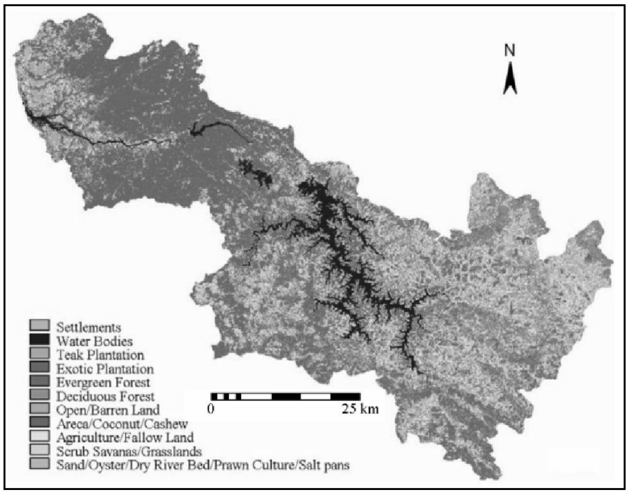
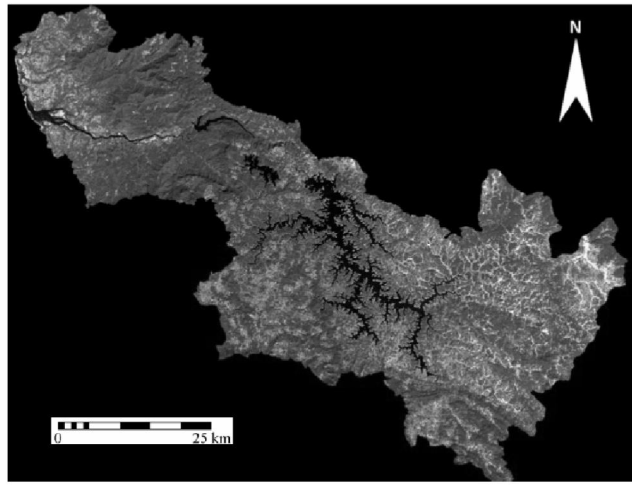
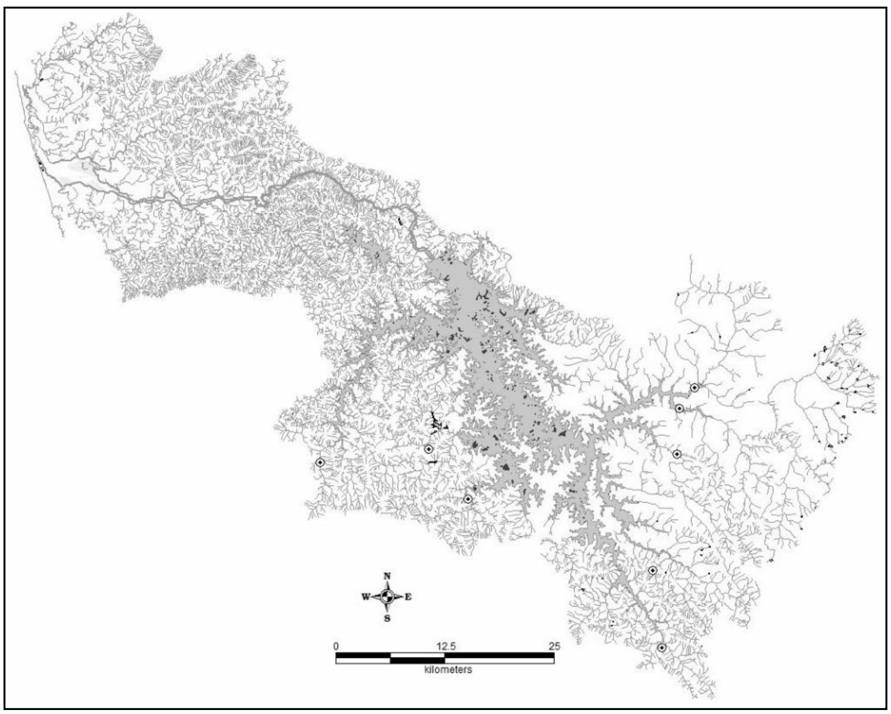


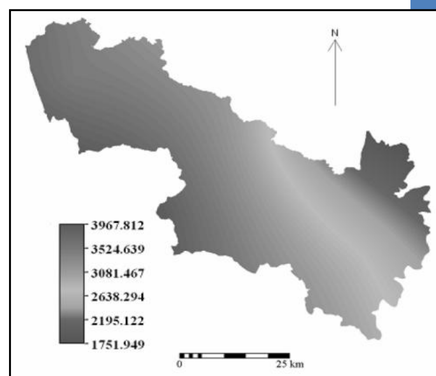
Figure 5: River Sharavathi with sampling sites


N
Settlements
Water Bodies
Teak Plantation
Exotic Plantation
Evergreen Forest
Deciduous Forest
Open/Barren Land
Areca/Coconut/Cashew
Agriculture/Fallow Land
Scrub Savanas/Grasslands
Sand/Oyster/Dry River Bed/Prawn Culture/Salt pans
0
25 km


N
0
25 km

SHARAVATHI


N
W
E
S
0
12.5
25
kilometers


N
3967.812
3524.639
3081.467
2638.294
2195.122
1751.949
0
25 km

Venkatapura River: Venkatapura river (Fig 6) is located between 13.98° - 14.15° N and 74.48°- 74.73° E in the southern part of Uttara Kannada district of Karnataka, India (Figure 1). It originates in Western Ghats and confluence into Arabian Sea after a course of 45 km near Venkatapura with a catchment of 335 km^2. Forest and agriculture are the major land use in the catchment. The river basin is divided in to six sub basins namely Venkatapura tributary, Chitihalla, KatagarNala, BastiHalla, Kitrehole and Venkatapura River based on major tributaries.

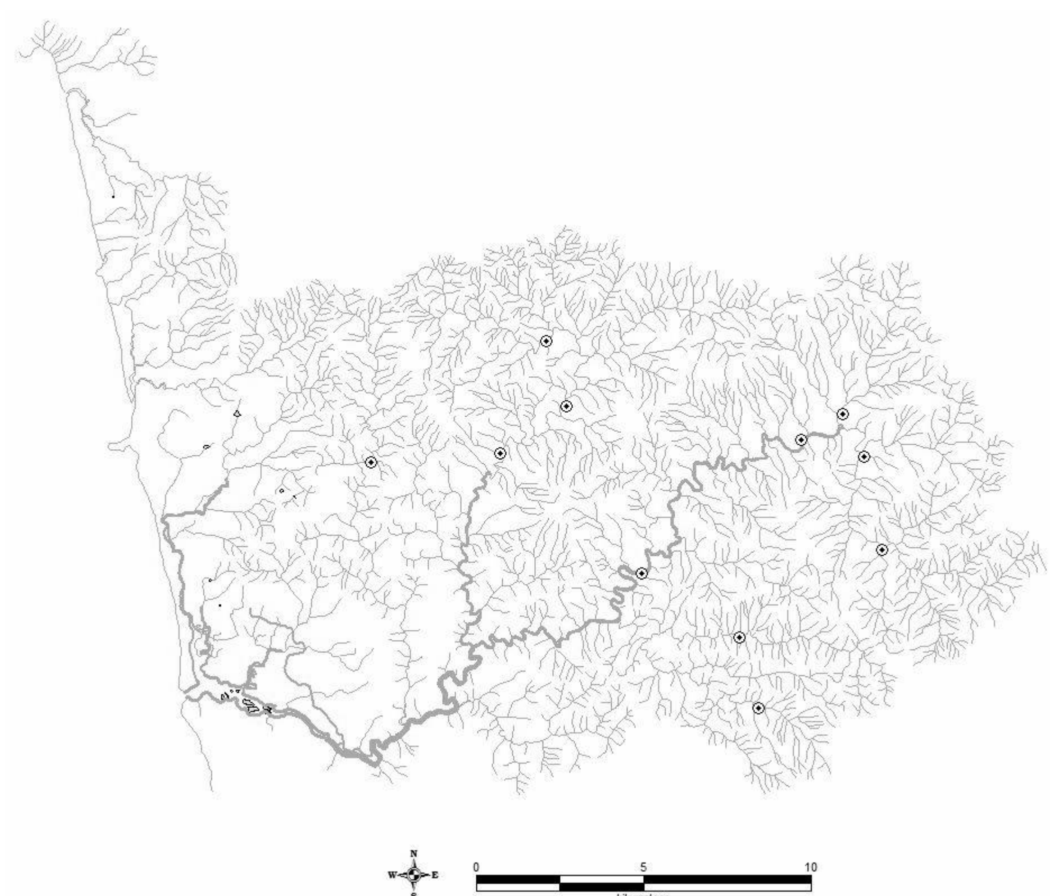


Figure 6: Venkatapura River with sampling sites

Water Quality Monitoring: Materials and Methods

Water Quality Monitoring: Water samples were collected at each sampling locations (Table 1) from each source in clean polythene containers of 2.5 L capacity. The sample containers were labeled with a unique code and date of collection. pH, water temperature, Total Dissolved Solids, Salinity and Nitrates were recorded on spot using EXTECH COMBO electrode and Orion Ion Selective Electrode. Other parameters like chloride, hardness, magnesium, calcium, sodium, potassium, fluoride, sulphate, phosphates, and coliform bacteria were analyzed in lab. All analyses were carried out as per methodologies in Standard Methods for the examination of water and wastewater APHA (1998). Detailed Methods are listed in Table 2. Figures 7 to 10 depicts the field data collection involving hydrological parameters (water velocity, duration of water flow, width of the stream, water quality, etc.).

Table 1: Details of the sampling sites (river basin-wise)

SITES	CODE	LATITUDE	LONGITUDE
Aghanashini River Basin (ARB)			
Sonda	**A1**	74.4834	14.4868
Nellimadke	**A10**	74.8431	14.5289
Neralamane	**A11**	74.8439	14.4554
Balur	**A12**	74.8098	14.4853
Baillalli	**A13**	74.7920	14.3013
Hulidevarakodlu	**A2**	74.6643	14.4040
Donehole	**A3**	74.5878	14.4330
Deevalli	**A4**	74.5584	14.4332
Ullurmatha	**A5**	74.5823	14.3844
Yanahole	**A6**	74.5355	14.5344
Jalagadde	**A7**	74.6127	14.5480
Kurse	**A8**	74.6900	14.5595
Sappurthi	**A9**	74.7562	14.5234

Bedthi River Basin (BRB)			
Mathigadda	**B1**	74.5926	14.6730
Vajgadde	**B10**	74.6154	14.6213
Nycti.Site	**B11**	74.6120	14.6390
Angadibail	**B12**	74.5332	14.6067
Daanandhi	**B13**	74.8667	14.7358
Hemmadi	**B14**	74.8586	14.7510
Attiveri	**B15**	75.0357	15.0759
Yerebail	**B16**	74.9395	15.0470
Gunjavathi	**B17**	74.9140	14.9921
Chitgeri	**B18**	74.9834	14.8557
Karadrolli	**B19**	74.8356	14.9918
Kammani	**B2**	74.5958	14.7132
Dabguli	**B20**	74.6572	14.8508
Ramanguli	**B21**	74.6054	14.1238
Kalghatghi	**B22**	74.9785	15.1586
Manchiker	**B23**	74.7861	14.8910
Apageri	**B3**	74.5840	14.6389
Hasehalla	**B4**	74.5840	14.7551
Kaleswara	**B5**	74.6095	14.7587
Andhalli	**B6**	74.8016	14.6701
Makkigadde	**B7**	74.4299	14.7095
Kelaginkeri	**B8**	74.5926	14.6730
Devanahalli	**B9**	74.6635	14.6281
Kali River Basin (KRB)			
Beegar	**K1**	74.5818	14.9163
Astolli	**K10**	74.5383	15.4289
Kervada	**K2**	74.6368	15.2454
Mavlangi	**K3**	74.5923	15.2561
Tatwala	**K4**	74.7466	15.0879

Sakathi	**K5**	74.3378	14.9185
Naithihole	**K6**	74.2593	14.8543
Kesrolli	**K7**	74.7412	15.3037
Kaneri	**K8**	74.4676	15.0247
Badapoli	**K9**	74.3560	15.0144
Sharavathi River Basin (SRB)			
Nandiholé	**S1**	75.1245	14.0418
Haridravathi	**S2**	75.1084	14.0209
Mavinaholé	**S3**	75.1055	13.9735
Sharavathi	**S4**	75.0804	13.8532
Hilkunji	**S5**	75.0896	13.7730
Nagodiholé	**S6**	74.8839	13.9269
Hurliholé	**S7**	74.8428	13.9786
Yenneholé	**S8**	74.7268	13.9650
Venkatapura River Basin (VRB)			
Badabhag	**V1**	75.6293	14.0588
Bachochodi	**V10**	74.6907	14.0901
Kelanur	**V11**	74.6959	14.0653
Undalakatle	**V2**	74.5900	14.0910
Midal	**V3**	74.5543	14.0888
Arkala	**V4**	74.6563	14.0415
Galibyle	**V5**	74.6085	14.1038
Nagoli	**V6**	74.6735	14.0946
Ondalasu	**V7**	74.6028	14.1213
Hegganamakki	**V8**	74.6848	14.1018
Kurandura	**V9**	74.6616	14.0227

Table 2: Methods used for analysing water samples

Parameters	**Units**	**Methods**	**Section no. APHA, 1998.**
pH	-	Electrode Method	4500-H^+ B
Water Temperature	ºC		2550 B
Salinity	ppm		2520 B
Total Dissolved Solids	ppm		2540 B
Electrical Conductivity	µS		2510B
Dissolved Oxygen	mg/L	Iodometric method	4500-O B
Alkalinity	mg/L	HCl Titrimetric Method	2320 B
Chlorides	mg/L	Argentometric Method	4500-Cl^- B
Total Hardness	mg/L	EDTA Titrimetric Method	2340 C
Calcium Hardness	mg/L	EDTA Titrimetric Method	3500-Ca B
Magnesium Hardness	mg/L	Calculation Method	3500-Mg B
Sodium	mg/L	Flame Emission Photometric Method	3500-Na B
Potassium	mg/L	Flame Emission Photometric Method	3500-K B
Fluorides	mg/L	SPADNS method	4500-F- D
Nitrates	mg/L	Nitrate Electrode method and Phenol Disulphonic Acid Method	4500-NO3- D
Sulphates	mg/L	Turbidimetric method	4500-SO_4^{2-} E
Phosphates	mg/L	Stannous Chloride Method	4500-P D

Figure 7: Collection and analysis of water samples onsite

Figure 8: Collection and analysis of water samples onsite at BRB

Figure 9: Measuring hydrological variables in a turbid stream at BRB

Figure 10: One of the sampling site with Water level indicator

Diatom Collection, Preparation and Enumeration

Figure 11 illustrates the habitat of diatoms – diatom colonies on stones, sand, etc. At each site, three to five stones were randomly selected across the stream and diatoms were scraped off the exposed surface of the stones using a tooth brush. Fresh samples were carefully checked to assure that majority of the diatom frustules were alive prior to acid combustion. A hot HCl and $KMnO_4$ method was used to clean frustules of organic materials. The cleaned diatom samples were dried on 18x18 mm cover slips and mounted with Pleurax. A total of 400 frustules per sample were enumerated and identified using compound light microscope (Lawrence & Mayo LM-52-series, with 1000× magnification) following methods described by Taylor et al. (2005) and Karthick et al. (2010). Diatoms were identified primarily to the species level according to Gandhi, (1957a,b,c; 1958a,b; 1959a,b,c; 1960a,b,c); Krammer and Lange-Bertalot (1986–1991) and Taylor et al. (2007).

Figure 11: Diatoms on stone in streams

Land Use Land Cover (LULC) Analysis

The remote sensing data are processed to quantify the land use of respective basins broadly into 6 classes – forest and vegetation; agriculture and cultivated area; open scrub and barren; water bodies; built-up; and others (includes categories like rocky outcrop, *etc.*). The multi-spectral data of Indian Remote Sensing (IRS) LISS-III with a spatial resolution of 23.5m were analyzed using IDRISI Andes (Eastman, 2006; http://www.clarklabs.org). The image analyses included image registration, rectification and enhancement, false colour composite (FCC) generation. The image analyses were undertaken for each of the scenes cropping with respect to the extent of basins falling within each scene. The classification of the multi-spectral remote sensing data was carried through a multi-stage classification process: unsupervised and supervised. In the unsupervised classification the number of clusters for classification is identified through the number of distinct peaks obtained from the histogram. For the supervised classification the signatures were derived from the training data obtained in the field using Global Positioning System (GPS) for distinctive land cover and some of the land cover features obtained from unsupervised classification. FCC aided in the identification of heterogeneous locations. Attribute data (type of heterogeneous patches/vegetation, number of individuals per unit area, etc.) corresponding to these heterogeneous locations (training polygons) using hand held pre-calibrated GPS (Global Positioning System), These data (spatial location of training polygons with attribute data) were used to classify the remote sensing data corresponding to the respective river basins. The signatures generated for each of the land use were also verified with the false color composite image and Google Earth (http://www.googleearth.com). Based on these signatures, corresponding to various land features, supervised image classification was carried out using Gaussian Maximum Likelihood Classifier (GMLC) to the final six categories.

Data Analysis

Compiled data were tested for normality before performing statistical analyses. Statistical analyses comprised Kruskal-Wallis test (H), Principal Component Analysis (PCA) and Non-Metric Multi Dimensional Scaling (NMDS). All tests were performed using the R-software (R Development Core Team, 2006).Box plots are used throughout this report to visually summarize data. These graphs depict the following statistical measures: median, upper and lower quartiles. The box plot is interpreted as follows: The box itself contains the middle 50 percent of the data. The upper edge of the box indicates the 75th percentile of the data set, and the lower edge of the box indicates the 25^{th} percentile. The line in the box indicates the median value of the data. If the median line within the box is not equidistant from the edges of the box, then the data are skewed. "Gridding" is the operation of spatial interpolation of scattered 2D data points onto a regular grid. Gridding allows the production of a map showing a continuous spatial estimate. The spatial coverage of the map is generated automatically as a square covering the data points. Non-metric multidimensional scaling is based on Bray-Curtis distance matrix was performed for classifying the sites across river basins. In NMDS, data points are placed in 2 or 3 dimensional coordinates system preserving ranked differences.

Data were tested for normality before performing statistical analyses. Statistical analyses comprised Kruskal-Wallis test (H), Principal Component Analysis (PCA) and Non-Metric Multi Dimensional Scaling (NMDS). All tests were performed using the R-software (R Development Core Team, 2006). The non-parametric Kruskal-Wallis test was used to assess whether species richness, species diversity and turnover across water quality regimes were significantly different. Temporal variation in diatom assemblages in each site was analyzed by NMDS using absolute abundance data. NMDS is an ordination method well suited to data that are non-normal or are arbitrary or discontinuous and for ecological data containing numerous zero values (Minchin, 1987; McCune & Grace, 2002). Results were visualized showing the most similar samples closer together in ordination space (Gotelli & Ellison, 2004). A final stress value, typically between 0 and 15, was evaluated as a measure of fitted distances against the ordination distance, providing an estimation of the goodness-of-fit in multivariate space. Changes in species composition or percentage turnover (T) were used to indicate community persistence. T was calculated as $T=(G + L)/(S1 + S2)$ times 100 where G and L are the number of taxa gained and lost between months respectively, and S1 and S2 are the number of taxa present in successive sampling months (Diamond & May, 1977; Brewin et al. 2000; Soininen & Eloranta, 2004). The relationship between local population persistence, local abundance in terms of relative abundances, and regional occupancy were examined using correlation analysis (Soininen & Heino, 2005). For the species distribution model the species were classified as core species as species that occurred in over 90% of sites, and satellite species as species that occurred in fewer than 10% of sites (McGeoch & Gaston, 2002, Soininen & Heino, 2005). Local occupancy of each diatom species was calculated by their percentage of occurrence at each site across the seasons. Seasonal diatom community was related to the water quality parameters using multiple linear regressions. Finally, water quality variables were used in PCA to elucidate the spatial water quality variation.

Results and Discussions

pH:

The pH of river water is the measure of how acidic or basic the water is on a scale of 0-14. It is a measure of hydrogen ion concentration. Most of the peninsular rivers falls between 6.5 and 8.5 on this scale with 7.0 being neutral. The optimum pH for river water is around 7.4. Water's pH can be altered by industrial and agricultural runoff. Vajgadde at BRB has recorded low pH of 6.9 and Kalghatghi from the same river basic has recorded highest pH of 8.27. In the current study the low range of pH observed in forested streams and high alkaline pH observed in sites contaminated with agricultural and urban runoff (figure 12 and 13). A pH of 8.0 should be sufficient to support most river life with the possible exception of snails, clams, and mussels, which usually prefer a slightly higher pH. The average pH in the study was 6.9, a value that is only sufficiently basic for bacteria, carp, suckers, catfish, and insects. BRB and KRB records most of the alkaline sites, where as ARB, SRB and VRB sites records neutral to near acidic sites.

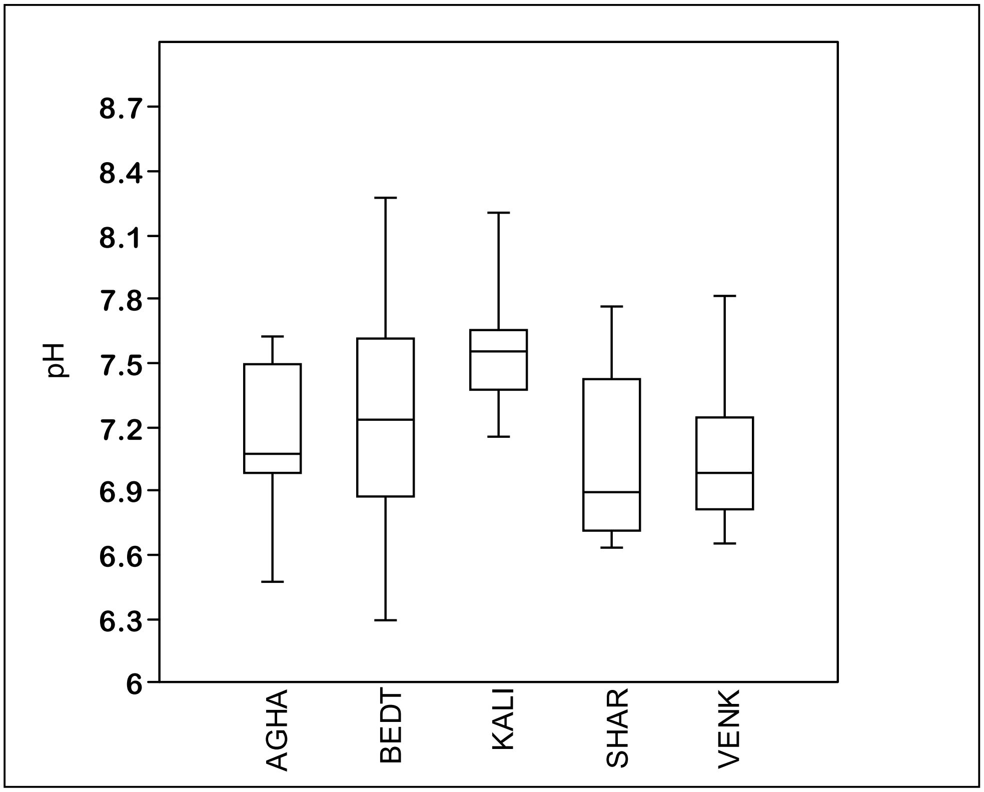


Figure 13 Box-plot of pH across river basins

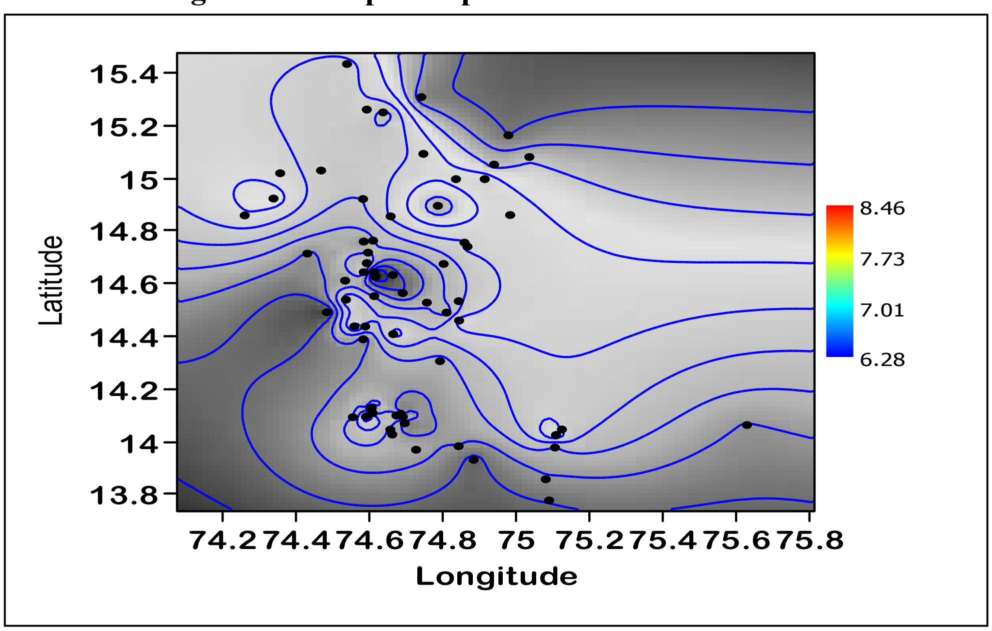


Figure 13 Spatial representation of pH across sites

Electrical Conductivity and Total Dissolved Solids: Conductivity is a measure of the ability of water to pass an electrical current. Conductivity in water is affected by the presence of inorganic dissolved solids such as chloride, nitrate, sulfate, and phosphate anions (ions that carry a negative charge) or sodium, magnesium, calcium, iron, and aluminum cat ions (ions that carry a positive charge). Organic compounds like oil, phenol, alcohol, and sugar do not conduct electrical current very well and therefore have a low conductivity when in water. Conductivity is also affected by temperature: the warmer the water, the higher the conductivity. Low level of electrical conductivity is observed at Vajgadde at BRB (22.5 µS/cm) and highest value was recorded from Kalghatghi of the BRB (1038.95 µS/cm), as illustrated in Figure 14. Sites of BRB showed high levels of variation when compared to the SRB and VRB. KRB sites recorded comparatively high levels of conductivity and total dissolved solids due to sedimentation from the monoculture plantations of its catchment area in the north part of the river basin (Figure 15).

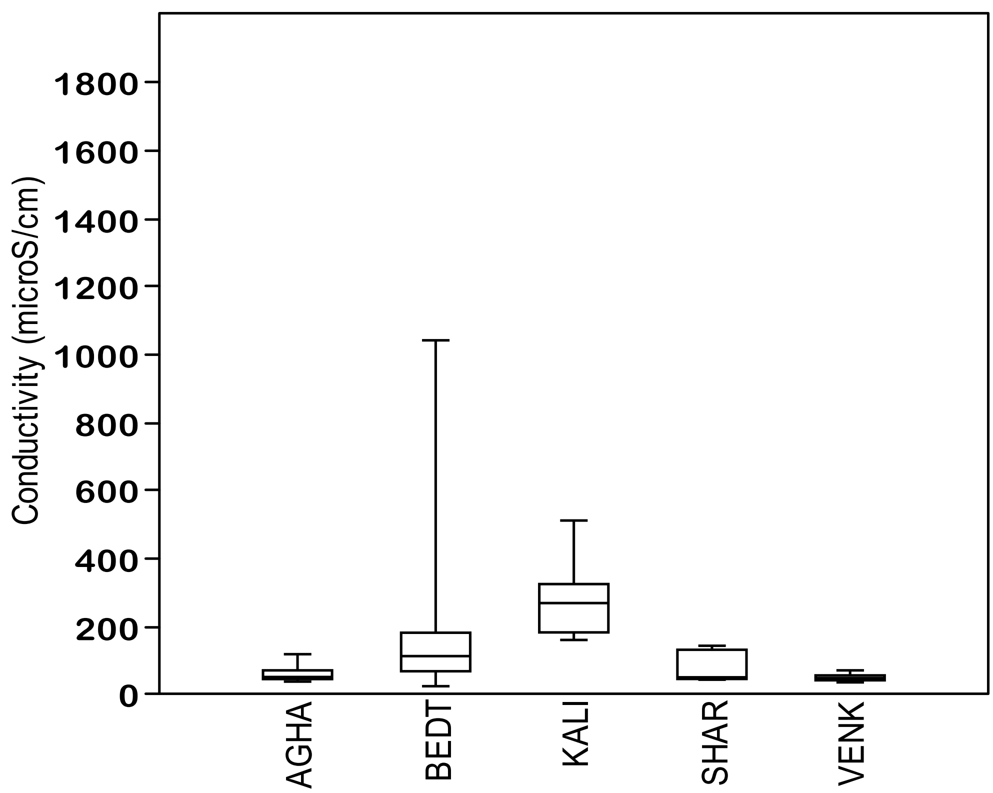


Figure 14: Boxplot of electrical conductivity across river basins

Discharges to streams can change the conductivity depending on their make-up. A failing sewage system would raise the conductivity because of the presence of chloride, phosphate, and nitrate; an oil spill would lower the conductivity.

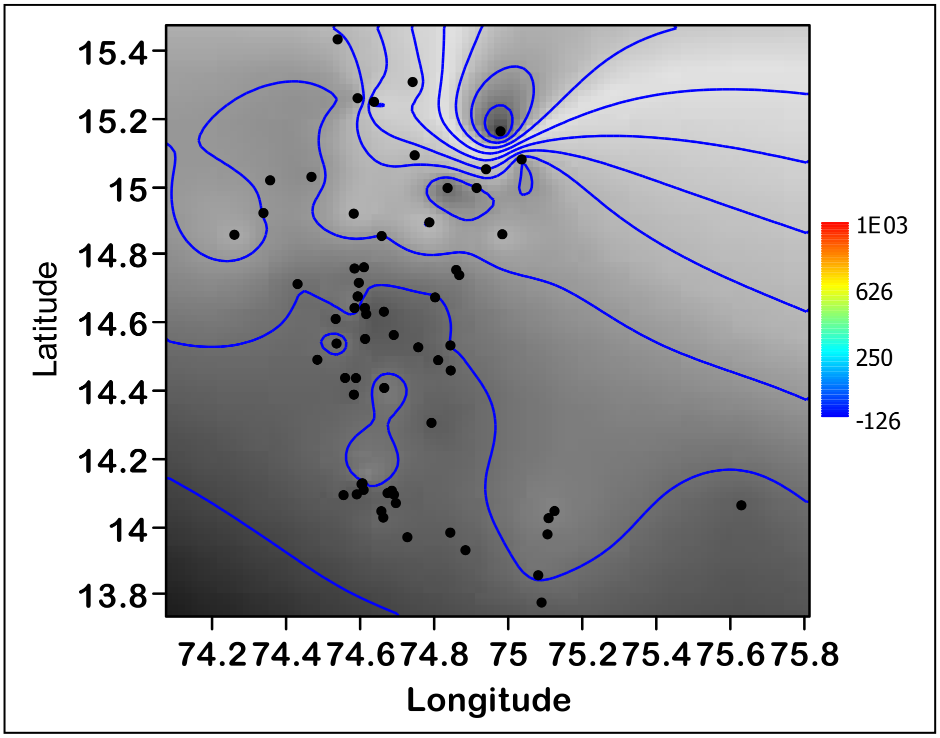


Figure 15: Spatial representation of electrical conductivity across sites

Dissolved Oxygen: An adequate supply of dissolved oxygen gas is essential for the survival of aquatic organisms. A deficiency in this area is a sign of an unhealthy river. There are a variety of factors affecting levels of dissolved oxygen. The atmosphere is a major source of dissolved oxygen in river water. Waves and tumbling water mix atmospheric oxygen with river water. Oxygen is also produced by rooted aquatic plants and algae as a product of photosynthesis.

In the present study lowest dissolved oxygen levels were observed in Kervada (3.67 mg/L) from KRB. **This site is located next to the point where the Paper mills effluent confluence with the main river**. The paper mill effluent is characterized with high levels of organic content, which consumes most of the oxygen for its degradation with help of the bacteria. Bacteria which decompose plant material and animal waste consume dissolved oxygen, thus decreasing the quantity available to support life. Ironically, it is life in the form of plants and algae that grow uncontrolled due to fertilizer that leads to the masses of decaying plant matter. This site is also infested with marsh crocodiles (*Crocodylus palustris*), which prevails as a major threat to the humans and cattle in the surrounding s. Crocodiles are attracted to this particular place due to availability of the solid organic contents present the paper mill effluent. Sites at SRB recorded saturated levels of dissolved oxygen in the streams and all other sites recorded with high variation. Apart from the organic pollution other reason for low levels of dissolved oxygen is lack of mixing in water. In most of the middle reaches of all the rivers water is stopped by the small to moderate levels of check dams for agricultural activities. Stagnated water lack gas mixing, which lead to low levels of dissolved oxygen.

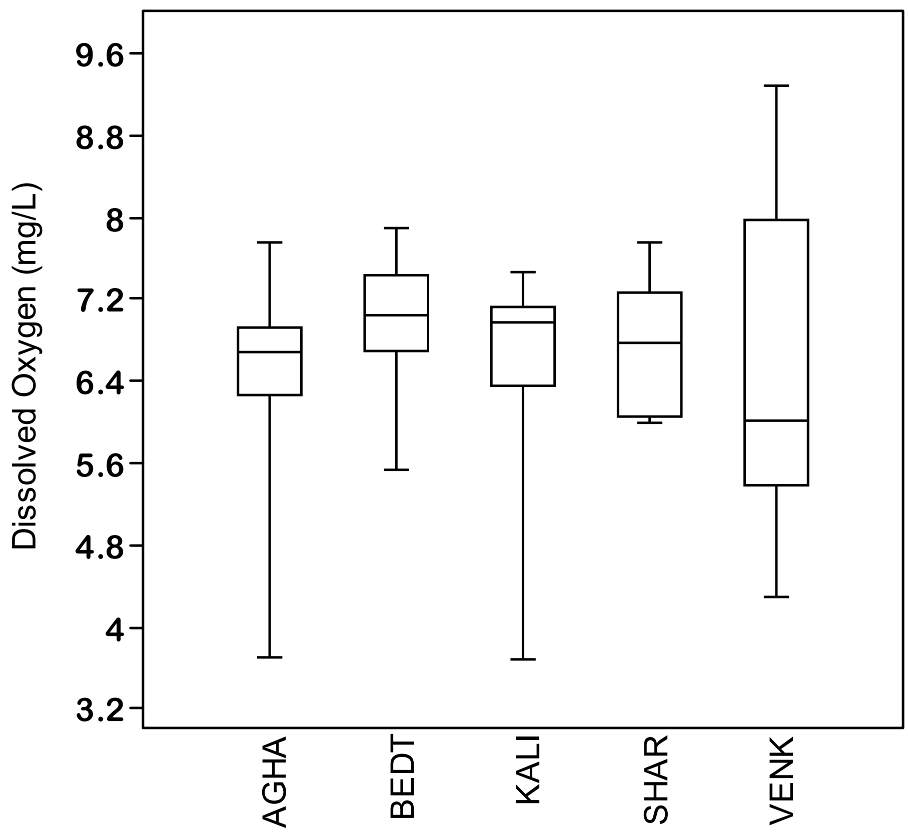


Figure 17: Dissolved Oxygen levels across rive basins

Nutrients

Unlike temperature and dissolved oxygen, the presence of nitrates usually does not have a direct effect on aquatic insects or fish. However, excess levels of nitrates in water can create conditions that make it difficult for aquatic insects or fish to survive. Nitrate-nitrogen is important because it is biologically available and is the most abundant form of nitrogen in Central Western Ghats streams. Like phosphorus, nitrate can stimulate excessive and undesirable levels of algal growth in water bodies. Nitrates come to the streams mainly from the runoff from the agriculture farms and sedimentation. Runoff from the agriculture farms carries huge amount of fertilizer residues. Among the study river basins, KRB and BRB recorded high levels of nitrates from its upstream region. Both KRB and BRB possess intense agriculture and limited water area in its upstream regions which leads to high levels of nitrates.

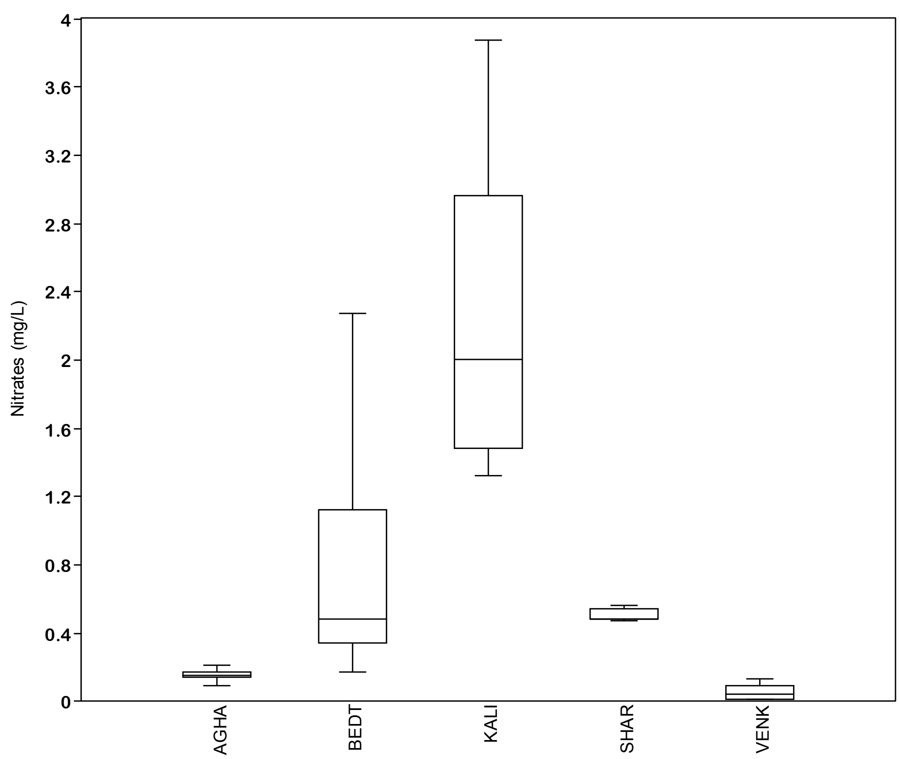


Figure 17: Boxplot showing the Nitrate valve across river basins

Along with the nitrates, phosphates also play a important role in the river hydrobiology. Phosphorus is an important nutrient for plant growth. Total phosphorus is the measure of the total concentration of phosphorus present in a water sample. Excess phosphorus in the river is a concern because it can stimulate the growth of algae. Excessive algae growth, death, and decay can severely deplete the oxygen supply in the river, endangering fish and other forms of aquatic life. Urban runoff is the major source for phosphates in the streams. In the current study regions, BRB receives considerable amount of urban sewage from Hubli city. The impact of high levels of phosphates leads to algal blooms in many reaches of the Bedthi River. Manchikeri site located in between Sirsi and Yellapur have a check dam for pumping water for drinking water supply. Recently a check dam was constructed near the Manchikeri Bridge for storing water for Yellapur drinking water supply. Check dam paves a way to stores the severely polluted water and reduces the dilution of pollution. Stagnated water with heavy nutrient content leads to algal bloom. Preliminary investigations suggest that the algal bloom was created by algal genus *Microcystis*. *Microcystis* is a type of blue-green algae (also referred to as Cyanobacteria). This genus is colonial, which means that single cells can join together in groups which tend to float on the water surface. Colony sizes will vary from a few to hundreds of cells. It is a common bloom-forming algae found primarily in nutrient enriched river and lake waters. Any large algal bloom has the potential to result in fish kills by depleting the water of oxygen. The dead algal cells sink down and consume huge amount of oxygen for their decomposition. In such situations, there may not be enough oxygen remaining in the water to support fish in the vicinity. Furthermore, as these large blooms die and sink to the bottom, they commonly release chemicals that can produce a foul odor and musty taste. Some strains of *Microcystis* may produce toxins that have been reported to result in health problems to animals that drink the water, and minor skin irritation and gastrointestinal discomfort in humans that come in contact with toxic blooms. Uncontrolled growth of single species of algae will also lead to death of aquatic invertebrates and fishes due to unavailability of food, which in turn affects the aquatic food chain.

Lotic Ecosystems: Intra basin variations in quality

Principal component analysis reveals that BRB (Bedthi River Basin) contains sites with pristine to heavily polluted waters. Most of the sites in BRB in the northern portion stand out separately in ordination space due to their very high amount of ions and nutrients. SRB (sharavathi River Basin), KRB (Kali River Basin) and ARB (Aghanashini River Basin) sites seem to fall in the same quality of water, where as the VRB (Venkatapura River Basin) stands out separately with very pristine water quality status (Fig 18, 20). NMDS plot of the water quality variables shows that ionic and physical parameters have the same origin, where as nutrients arise from different source (Fig. 19)

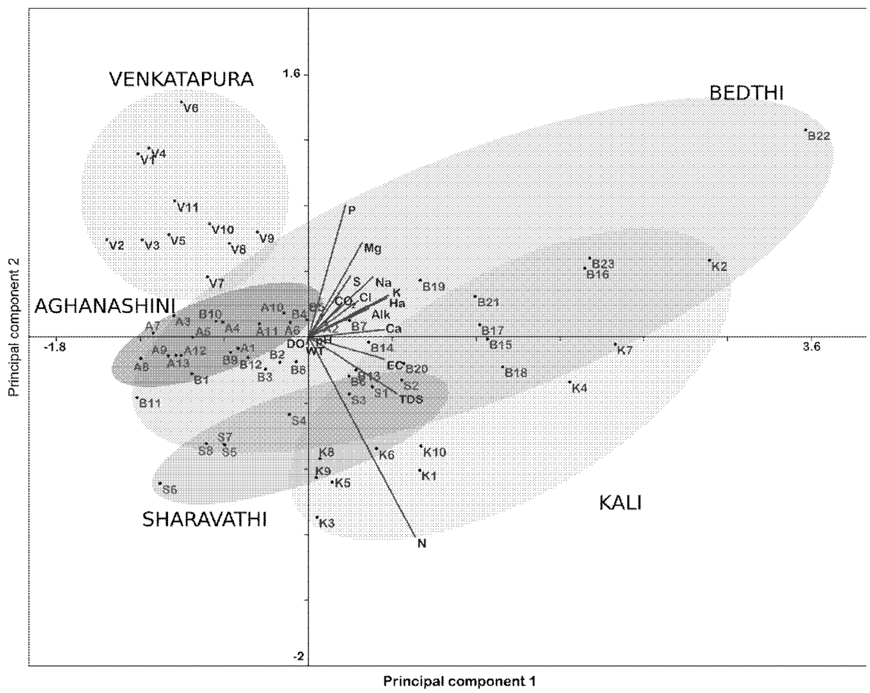


Figure 188: PCA plot for water quality variables across the river basins

Seasonality of Benthic Diatoms and water quality

The water chemistry data along the Bedthi River showed high annual variation across sites. Stream water chemistry differed between the three groups of sites (Figure 16). The parameters which showed significant different among the groups were pH, conductivity, chlorides, hardness, calcium, magnesium, sodium and potassium. All the above mentioned parameters were high in HPAS, moderate in MPPS and very low in LPFS.

Irrespective of the pollution status, dissolved oxygen (DO) levels across water quality regimes were roughly similar with mean DO levels (Mean±S.D) of 7.51±1.67, 7.08±2.21, 6.43±2.91. However an anoxic DO level of 0.86 mgL^{-1} was observed in one sample from the HPAS (KAL) (Refer the Table 2 for detailed water chemistry data). PCA results indicated that water quality differed markedly among sampling sites and across seasons (Figure 3) with the first component explaining 84.6% of the total variation. Three distinct clusters were observed along a pollution gradient. Sample scores from HPAS (KAL and MAN) were positioned to the right along PCA axis 1, and were characterized by higher conductivity, phosphates, nitrates, alkalinity, hardness, calcium, sodium and potassium levels. MPPS (AND, DAN) were positioned along the PCA axis 2. In contrast, samples from the LPFS (HAS, KAM) were located to the left along PCA axis 1, and were characterized by higher DO and low levels of ions and nutrients. Water chemistry parameters like pH, carbon dioxide, alkalinity, nitrates, sulphates were positively loaded while dissolved oxygen was negatively loaded with principal axes. These results indicate that water chemistry between the sites was strongly different throughout the year.

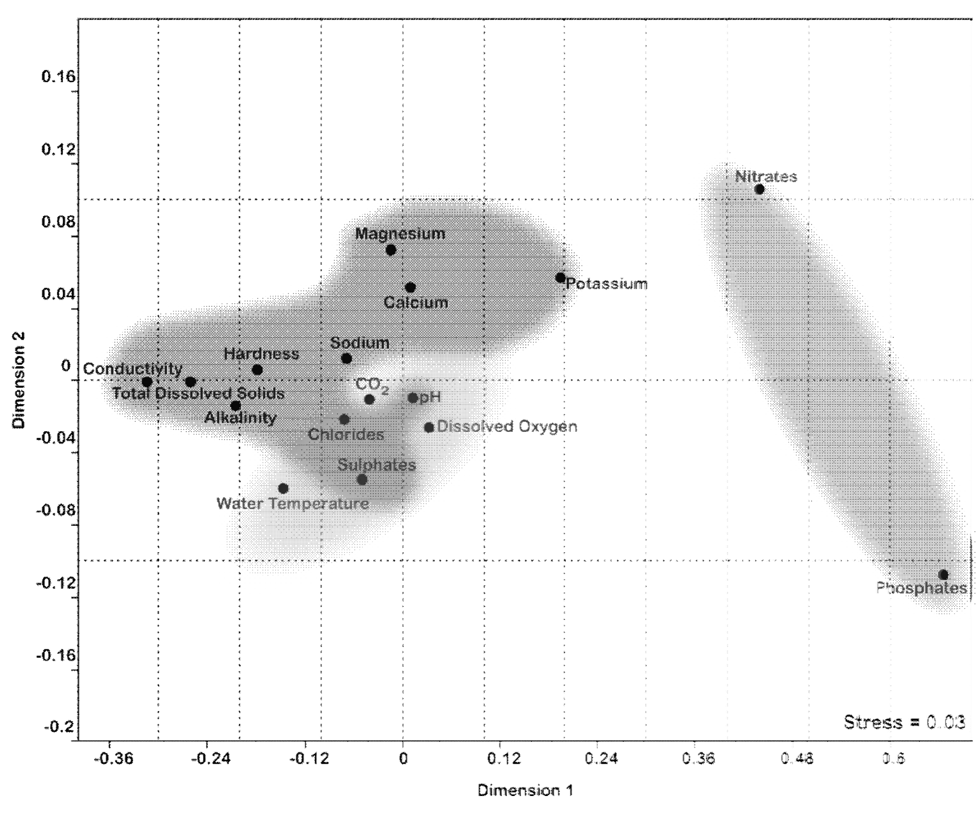


Figure 19: NMDS plot of Water quality variables across river basins

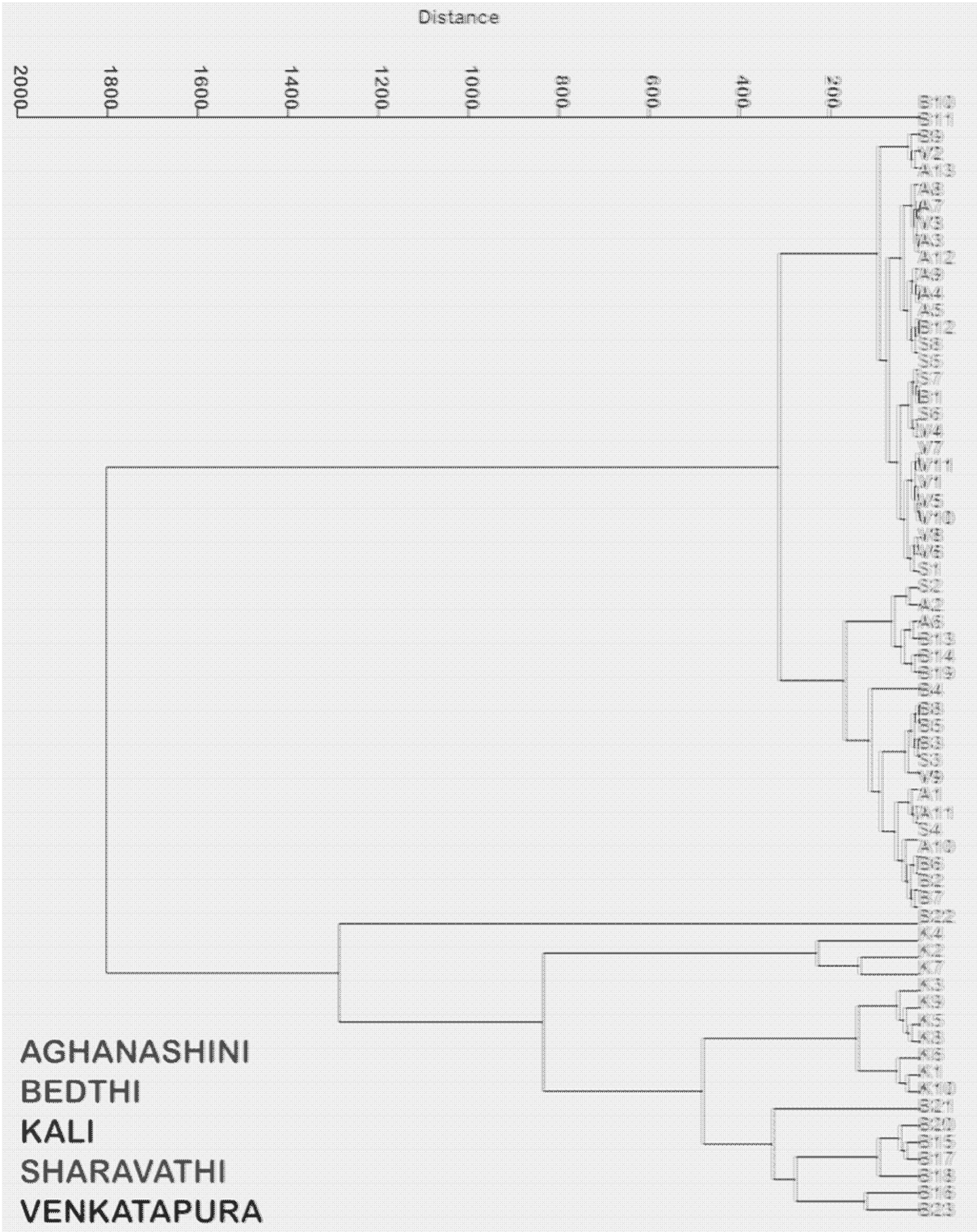


Figure 20: Cluster Analysis of sampling sites across river basins based on water quality

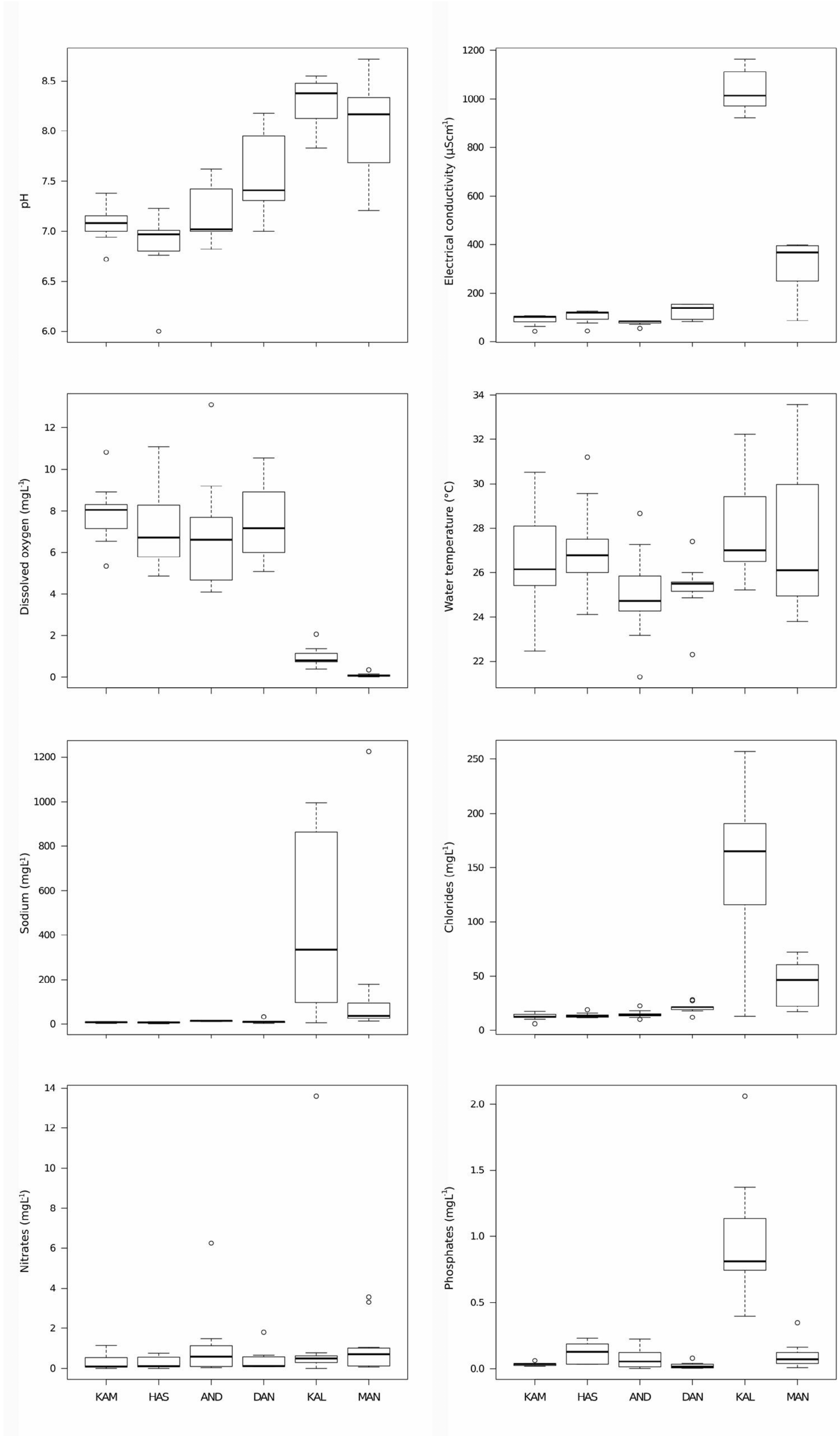


Figure 201: Water chemistry at sampled sites during the study period Jan 2006 - Dec 2006 at BRB

One hundred and three species of diatoms were recorded from all the six sites during the study period, with a flora typical of oligotrophic to eutrophic condition. Among the taxa recored, the most abundant diatom species were *Achnanthidium minutissimum*(Kϋtz) Czarn., *Gomphonema gandhii*Karthick & Kociolek, *G. difformum* Karthick & Kociolek, *Nitzschia palea*(Kϋtz) W. Sm., *Nitzschia frustulum*(Kϋtz) Grun., *Cymbella sp.* and *Navicula sp. Achnanthidium minutissimum*, *Gomphonema gandhii* and *G. difformum*, were present throughout most of the study in LPFS and MPPS, while *Nitzschia palea* and *Nitzschia frustulum* were dominant in HPAS. In contrast, *Cymbella* sp. was the only diatom present at the MAN site during the month of April. The samples from headwater oligotrophic streams (often with low pH and conductivity) were characterized by the occurrence of *Gomphonema gandhii*, *Achnanthidium minutissimum and Gomphonema difformum*. Assemblages from eutrophic streams (HPAS) were characterized by dominance of *Nitzschia palea*, *N. frustulum and* occasionally with *Cyclotella meneghiniana*.

The species richness was highest at three sites; KAM, DAN and MAN, even though each one inherited different water chemistry regimes. All six sites were characterized with very low species richness during the monsoon season (Table 3). In all sites across the study, the diversity (H') ranged between the highest 2.34 in DAN during the month of February to lowest of 0 in KAM and KAL during the monsoon months. Kruskal–Wallis results showed that the species diversity across three water chemistry regimes were significantly different (Kruskal–Wallis, $H = 6.97$; $p = 0.03$).

Species abundances across season suggested trends within community composition in ordination space (Figure 22). In sites KAM and KAL communities of post monsoon season aggregated in ordination space, however this trend were not seen in HAS, DAN, MAN and AND sites. In LPFS (KAM and HAS) and MPPS (AND and DAN) diatom assemblages were identical for pre-monsoon, monsoon and post-monsoon seasons respectively, whereas the assemblages in HPAS (KAL and MAN) were not identical across seasons. Though there are trends on community composition, it looks like there is a strong relation with the seasonally dynamic environmental variables. The difference in the species richness among sites were not significant (Kruskal–Wallis H = 6.07; p = 0.29). Species richness from highest to lowest within water quality regimes, followed the order LPFS > MPPS > HPAS. Overall, species richness was lowest during the monsoon months in all the sites. Changes in species composition or percentage turnover (T) did not follow any trend irrespective of site water chemistry. The highest mean turnover (94.44%±11.11) was observed in MAN, indicating the lowest persistence (Figure 5), followed by DAN (79.08±14.47), HAS (70.46±27.64) and AND (64.77±23.71). The mean species turnover was less than 50% in KAL (47.96±38.1) and KAM (44.03±20.85). Interestingly, KAL showed a wide range of turnover with a minimum of 9% during the post monsoon and a maximum turnover of 100% during the monsoon months. In LPFS sites 25% of the species were persistent across seasons and in MPPS sites 30% of the species were persistent. However in the HPAS sites a minimum persistence of 7.14% was observed for KAL and 80% persistence in MAN. The differences in turnover were significant across sites (Kruskal–Wallis H = 17.52; p = 0.0036).

Table 3: Species richness and diversity across space and time at BRB sites

MONTHS	LPFS		HPAS		MPPS	
	KAM	HAS	KAL	MAN	AND	DAN
JAN	14 (1.10)	10 (1.04)	7 (1.58)	-L-	4 (0.81)	14 (2.27)
FEB	10 (1.58)	6(1.10)	7 (1.65)	9 (1.63)	4 (1.04)	19 (2.34)
MAR	4 (1.25)	6 (0.85)	8 (1.73)	14 (1.90)	6 (0.95)	-D-
APR	7 (1.47)	7 (0.67)	9 (1.65)	1 (0)	8 (0.93)	-D-
MAY	11 (1.40)	4 (0.47)	3 (0.92)	8 (1.34)	11 (1.76)	-D-
JUN	9 (1.16)	3 (0.15)	4 (1.02)	-M-	3 (0.98)	5 (1.14)
JUL	4 (0.77)	-M-	1 (0)	-M-	6 (1.19)	7 (1.46)
AUG	-M-	-M-	-M-	-M-	5 (0.79)	5 (1.35)
SEP	1 (0)	-M-	1 (0)	-M-	2 (0.69)	9 (1.67)
OCT	4 (0.78)	5 (0.77)	5 (1.34)	5 (1.15)	9 (1.29)	9 (1.35)
NOV	4 (0.82)	4 (0.94)	6 (1.54)	-L-	-L-	4 (0.84)
DEC	4 (0.87)	-L-	8 (1.76)	16 (2.02)	2 (0.69)	10 (1.39)

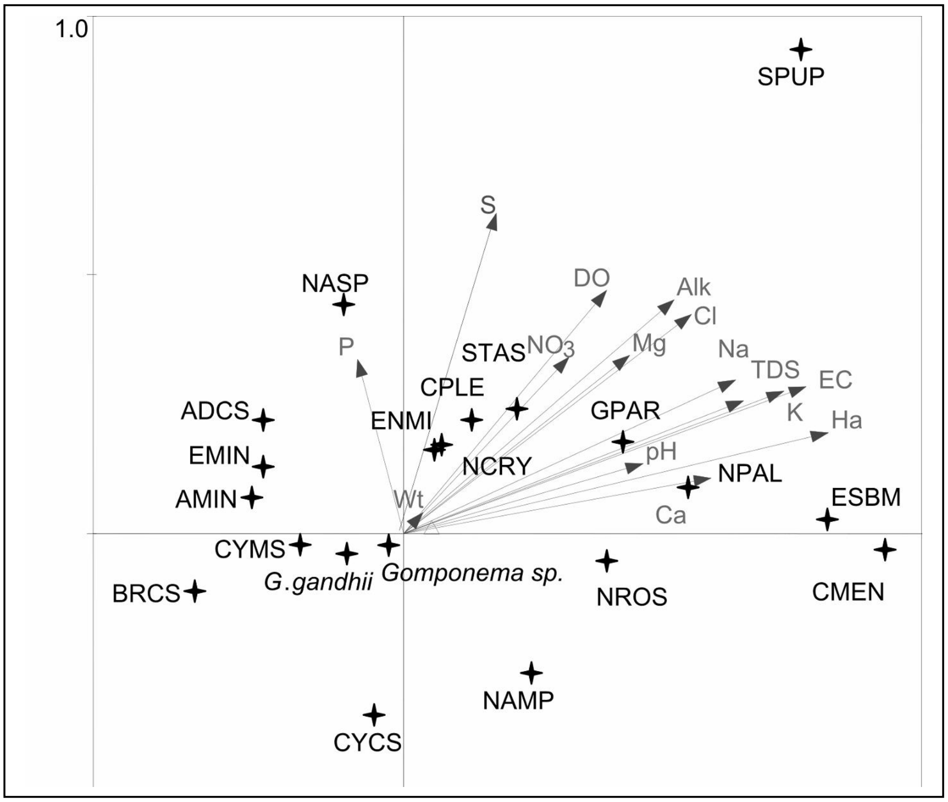


Figure 22: CCA biplot showing the relationship between water chemistry variables and dominant species assemblages

Percentage occupancy showed a significant relationship with local maximum species abundance ($r = 0.49$; $P = <0.0001$) and local mean species abundance ($r = 0.37$; $P = <0.0001$). This positive correlation was slightly stronger for the local maximum abundance; however it was highly significant for both the local abundance measures. Species that occurred locally with more frequency also tended to be abundant across the sites. The species–occupancy frequency distribution (Figure 23) followed a "satellite-mode" (Hanski, 1982) of species distribution, where a high proportion of species occurred at a small number of sites. Sixty-three species occurred in only one site, twenty two species in two sites, eleven species occurred in three sites; five species occurred in four sites, three species occurred in five sitesand none of the species occurred in all the six sites.

Diatom Based Biomonitoring

A total of 140 diatom taxa were identified across sites, 61 of them reaching a relative abundance of over 5% in at least one site. Annexure 1 provides the checklist of diatoms. The species compositions were dominated by *Gomphonema gandhii* Karthick and Kociolek, *Achnanthidium minutissimum* Kützing, *Achnanthidium* sp., *Gomphonema* sp., *Gomphonema parvulum* Kützing, *Nitzschia palea* (Kützing) W.Smith, *Nitzschia frustulum* (Kützing) Grunow var. *frustulum*, *Navicula* sp., *Navicula cryptocephala* Kützing, *Cyclostephanos* sp., *Cymbella* sp., *Eolimna subminuscula* (Manguin) Moser Lange-Bertalot and Metzeltin, *Sellaphora pupula* (Kützing) Mereschkowksy, *Eunotia minor* (Kützing) Grunow in Van Heurck, *Nitzschia amphibian* Grunow f. *amphibia*, *Cyclotella meneghiniana* Kützing, *Gomphonema difformum* Karthick and Kociolek, *Navicula rostellata*Kützing, *Cocconeis placentula* Ehrenberg var. *euglypta* (Ehr.) Grunow, *Brachysira* sp., *Stauroneis* sp., *Encyonema minutum* (Hilse in Rabh.) D.G. Mann, *Cyclotella* sp. and *Nitzschia* sp. The species composition contains cosmopolitan to possible Western Ghats endemic species and in general species from oligotrophy to highly eutrophic condition were also observed. The current study also documents some of the species for the first time in Western Ghats and many new species descriptions are underway. Waters were circumneutral throughout the whole study area (Table 4), with certain tendency towards alkalinity in the streams drained from agriculture and urban catchment. The highest ionic and nutrient values correspond to the agriculture catchment dominated streams, particularly in the leeward side of the mountains. Oxygenation was generally close to saturation; the lowest values are due to wastewater water inflows in few localities. The most oligotrophic sites were located in mountain watercourses, while downstream sites were generally more polluted, becoming eutrophic in condition. The detailed water chemistry variables are presented in Table 5.

The results of correlation performed between diatom indices and water chemistry variables are presented in the table 6. It is observed that significant correlations exist to varying degrees between most of the diatom indices and water chemistry variables. Diatom indices IPS, EPI and SID showed correlation with more number of water chemistry variables when compared to the other indices. TDI and IPS are negatively correlated with pH, EC, TDS, alkalinity, calcium, magnesium, sodium and potassium. Percent pollution tolerant diatoms were positively correlated with most of the ionic variables. None of the indices were correlated with water temperature. The first four axis of CCA explains 70.1% variance of species-environment relation and the ordination plot reveals two distinct clusters of species.

The species composition contains cosmopolitan to possible Western Ghats endemic species and in general species from oligotrophy to highly eutrophic condition were also observed. Among the species observed in this study, two species were possibly endemic to Western Ghats (*G. gandhii*, *G. difformum* and few other species yet to identify). In few sites these species were very dominant reaching more than 80% of the total assemblages. The remaining dominant taxa were cosmopolitan and well documented in international literatures (Krammer and Lange Bertalot, 1986-1991). It is important to note that the indices that were developed and tested in European rivers, lacks Western Ghats endemic taxa. Most sites were oligo-mesotrophic and only a few of the streams were eutrophic. The differences in the water quality of these rivers were reflected in the values for the diatom indices, by the relative abundances of indicators of trophic/saprobic stage and by different types of diatom community. Classification of stream sites according to the IPS score is given in Table 6.

Table 4: Summary of the Canonical correspondence analysis for the stream sites from Central Western Ghats.

Variables	**Axis order**			
	1	**2**	**3**	**4**
Eigen value	0.275	0.193	0.162	0.119
Species-environment correlations	0.815	0.755	0.890	0.754
Cumulative percentage variance of species data	10.0	17.0	22.9	27.2
Cumulative percentage variance of species-environment relation	25.8	43.8	59	70.1

Table 5: Summary table of water chemistry variables in 45 sites of CWG streams.

Variables	Mean	Std. dev	Median	Min	Max
pH	7.22	0.49	7.14	6.03	8.16
WT (°C)	25.31	2.70	25.07	19.00	33.00
EC (µScm^{-1})	160.55	207.10	107.67	41.55	1164.67
TDS (mg L^{-1})	122.24	204.98	60.30	20.88	1299.67
Alkalinity (mg L^{-1})	54.55	50.32	30.00	6.81	180.00
Chlorides (mg L^{-1})	32.39	40.40	22.72	5.90	220.24
Hardness (mg L^{-1})	51.26	71.05	28.00	10.00	348.00
Calcium (mg L^{-1})	13.88	16.14	8.02	1.60	78.56
Magnesium (mg L^{-1})	16.35	16.73	9.36	1.17	65.95
DO (mg L^{-1})	6.96	1.68	7.23	2.93	10.87
Phosphates (mg L^{-1})	0.36	0.56	0.04	0.00	2.30
Nitrates (mg L^{-1})	0.74	1.10	0.13	0.03	4.30
Sulphates (mg L^{-1})	25.73	20.84	16.87	0.00	74.10
Sodium (mg L^{-1})	25.77	72.18	9.09	4.11	370.00
Potassium (mg L^{-1})	6.33	15.72	1.30	0.19	75.00

Table 6: Pearson correlation coefficients between measured water chemistry variables and diatom index scores in 45 sites of CWG streams

INDICES	pH	WT	EC	TDS	Alk	Cl	Ha	Ca	Mg	Na	K
SLA	-0.33*	-	-0.59**	-0.52**	-0.49**	-	-0.62**	-0.43**	-	-0.51**	-0.58**
DESCY	-0.32*	-	-0.54**	-0.46**	-0.41**	-	-0.65**	-0.47**	-	-0.49**	-0.52**
IDSE/5	-0.32*	-	-0.60**	-0.50**	-0.46**	-	-0.63**	-0.45**	-	-0.55**	-0.60**
SHE	-	-	-0.52**	-0.38**	-0.38*	-	-0.56**	-0.41**	-	-0.43**	-0.56**
WAT	-	-	-	-	-	-	-0.36*	-	-	-0.34*	-0.44**
TDI	-0.32*	-	-0.64**	-0.54**	-0.46**	-	-0.69**	-0.53**	-0.30*	-0.52**	-0.58**
%PT	0.36*	-	0.68**	0.62**	0.35*	0.43**	0.66**	0.50**	0.41**	0.65**	0.58**
GENERE	-	-	-0.49**	-0.39**	-0.30*	-	-0.54**	-0.41**	-	-0.41**	-0.41**
CEE	-	-	-	-	-	-	-0.36*	-	-	-	-0.40**
IPS	-0.36*	-	-0.68**	-0.59**	-0.42**	-	-0.66**	-0.46**	-0.31*	-0.56**	-0.58**
IBD	-		-0.56**	-0.43**	-0.34*	-	-0.61**	-0.46**	-	-0.46**	-0.51**
IDAP	-	-	-0.51**	-0.38*	-0.38*	-	-0.56**	-0.40**	-	-0.44**	-0.53**
EPI-D	-0.33*	-	-0.58**	-0.51**	-0.41**	-0.31*	-0.59**	-0.44**	-	-0.53**	-0.55**
DI_CH	-	-	-0.54**	-0.43**	-0.45**	-	-0.58**	-0.39**	-	-0.41**	-0.53**
IDP	-	-	-0.48**	-0.35*	-0.39**	-	-0.58**	-0.42**	-	-0.43**	-0.49**
SID	-0.36*	-	-0.50**	-0.45**	-0.40**	-0.38**	-0.47**	-0.37*	-	-0.43**	-0.46**
TID	-	-	-0.53**	-0.43**	-0.47**	-	-0.59**	-0.41**	-	-0.40**	-0.48**
Evenness	-	-	0.39**	0.40**		-	0.41**	-	-	-	-

Note: WT-Water Temperature, EC-Electric Conductivity, TDS-Total Dissolved Solids, ALK-Alkalinity, Cl-Chlorides, Ha-Total Hardness, Ca-Calcium hardness, Mg-Magnesium hardness, Na-Sodium, K-Potassium. Diatom Indices: SLA-Sládeček's index, DESCY-Descy's pollution metric, SHE-Steinberg and Schiefele trophic metric, WAT-Watanabe index, TDI-Tropical diatom Index, GENRE-Generic Diatom Index, CEE-Comission for economical community Index, IPS-Specific Pollution Sensitivity Metric, IBD-Biological diatom index, IDAP-IndiceDiatomique Artois Picardie, EPI-D-Eutrophication/pollution Index, IDP-Pampean Diatom Index,%PT-Percentage Tolerant).

In general, the diatom indices show significant correlations to water quality. The correlations obtained in the present study are comparable to those demonstrated by Taylor *et al*., (2007c) in South Africa and by Kwandrans *et al*., (1998), Prygiel and Coste (1993) and Prygiel *et al*., (1999) in Europe. Significant correlations emphasize that diatom indices can be used to reflect changes in general water quality (Table 6). No correlation of temperature with any of the indices observed that may be due to differing temperature regime in tropical when compared to temperate streams. Similar observation has been recorded by Taylor *et al*., (2007) from South African rivers. Canonical correspondence analysis (Figure 22) demonstrates that certain widely distributed taxa have similar ecological characteristics in widely separated geographic areas. Species commonly associated with poor water quality in Europe *e.g.,Eolimna subminuscula* Lange-Bertalot, *Nitzschia palea* (Kützing) W. Smith, *Sellaphora pupula* (Kützing) Mereschkowksy, *Gomphonema parvulum* (Kützing) ordinate on the right hand side of the CCA together with elevated levels of ionic and nutrients. Taxa typical of cleaner, less impacted waters ordinate out on the left hand side of the diagram e.g., *Gomphonema difformum* Karthick and Kociolek. However *Gomphonema gandhii* Karthick and Kociolek seems to have a wider ecological tolerance when compared to its morphologically related species. *Achananthidium minutissimum* group from Western Ghats streams contains morphologically three distinct taxa with wide ecological preferences. Despite the reevaluation of this genus multiple times (Lange-Bertalot and Krammer, 1989, Krammer and Lange-Bertalot, 1991, Potapova and Hamilton, 2007) there are still major gaps in taxonomy and ecology apart from non-inclusion of specimens from tropical rivers. The similar problem holds good for some of the other genus like *Gomphonema*. This analysis helps to demonstrate that the widely distributed species encountered in the streams of Western Ghats which are not identical only with morphology also have similar environmental tolerances *G. gandhii* and *G. difformum* are one among the dominant taxa in this data set but not included in any of the index calculations and their omission could result in an under or overestimation of the index scores. Taylor *et al*., (2007d) cautioned about the associated problems with usage of European indices in South African rivers. These suggest that European diatom indices can be used in India provided indices address the issues concerned with ecology of endemic species. Hence, the list of taxa included in the indices needs to be adapted according to the study region with giving more importance to the local endemic flora which encourages taxonomic and ecological studies in tropics. The structure of benthic diatom communities and the use of diatom indices yield good result in water quality monitoring in India. It is also evident from the current study that many widely distributed diatom species have similar environmental tolerances to those recorded for these species in Europe and elsewhere. However, the occurrence of possible endemic species will necessitate the work towards diatom index unique to India. In the mean time considerable amount of importance should be paid for taxonomic and ecological understanding of endemic flora for development of improved biomonitoring program.

LULC Analysis: LULC showed considerable variability among catchments, with forest/vegetation land cover as a dominant class (mean = 64.36%, range = 0.13–95.45%), followed by agriculture/cultivation area (mean = 24.27% range = 2.55-63.63%), among the 24 catchments. The mean percentage area covered by open scrub/barren land, water bodies, built up and other classes were 6.65±9.16 (0.16-31.48), 1.68±1.76 (0.01-5.61), 0.47±0.4 (0.06-1.52), and 2.58±2.51 (0.07-9.58) respectively. LULC analysis shows that natural vegetation is poor towards the leeward side of the mountains (eastern region), due to intense anthropogenic activities. This region has more of agriculture, open scrub/barren land, and built-up area. In the entire study region the class forest/vegetation covers predominantly moist deciduous type, with small isolated patches of semi-evergreen vegetation in the eastern region and the western region (windward side) with rugged hilly terrain and heavier rainfall (~5000 mm) having characteristic evergreen to semi-evergreen forests. The detailed LULC for each catchment is given in the Table 7 and the land cover images are given in Figure 23. The dendrogram of sites based on LULC obtained by Ward's method is shown in Figure 18a. Three well differentiated clusters can be seen, with forest cover decreasing and agriculture/cultivable land cover increasing from top to bottom. The third cluster from top includes sites SAN, KAL, MAN, SAP and GUN, which are characterized with high amount of agricultural activities (>50%). The group in center is characterized by more forest cover (>50%) with moderate amount of agricultural land. Another top most group is dominated by forest land cover of more than 80%.

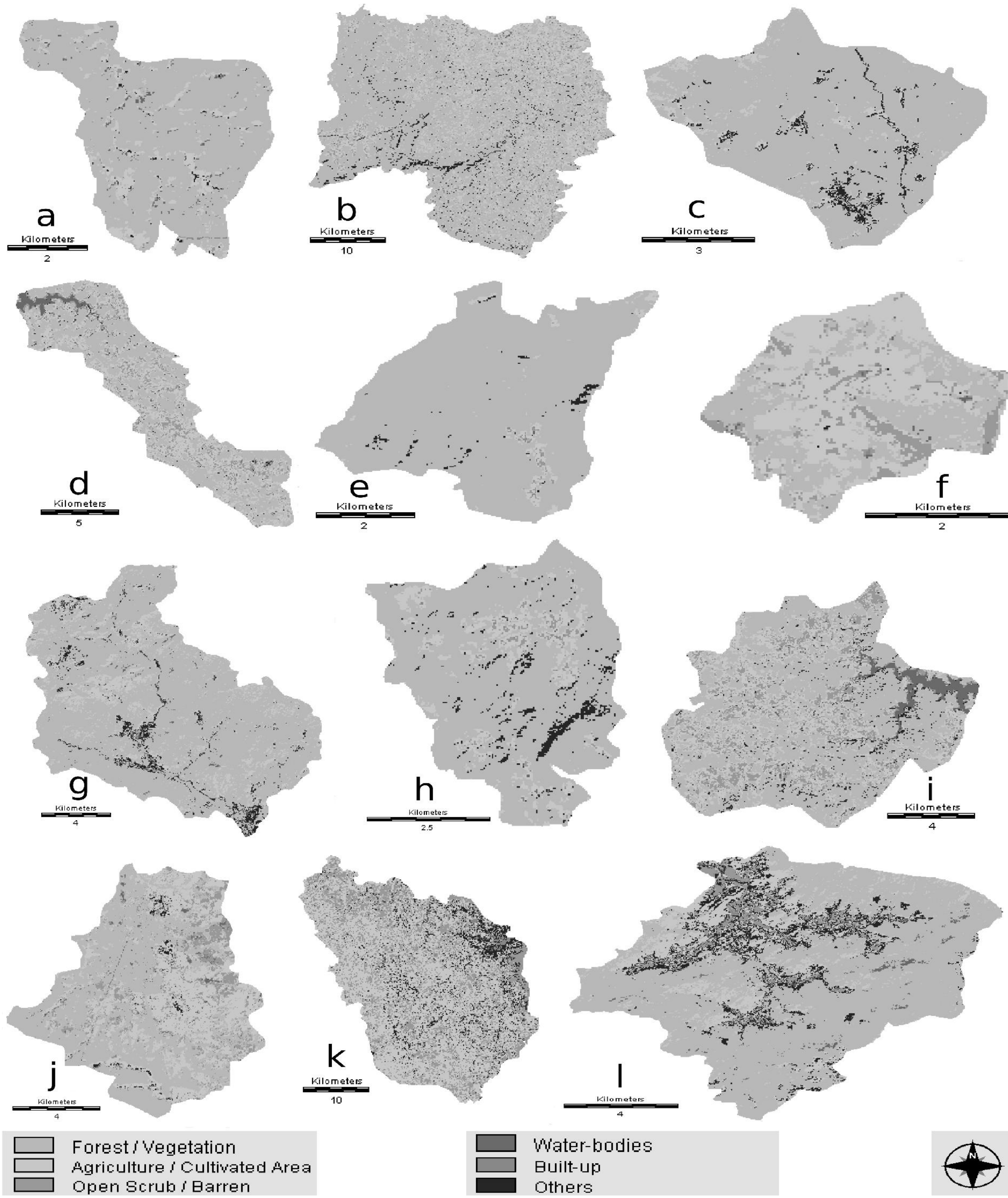


Figure 23: Classified land use images of study catchments in Central Western Ghats. a - Daanandhi, b - Deevalli, c - Badapoli, d - Mavinahole, e - Makkegadde, f - Gunjavathi, g – Sakathihalla, h – Angadibail, i – Hurlihole, j – Chitgeri, k - Kalghatghi, l – Naithihole

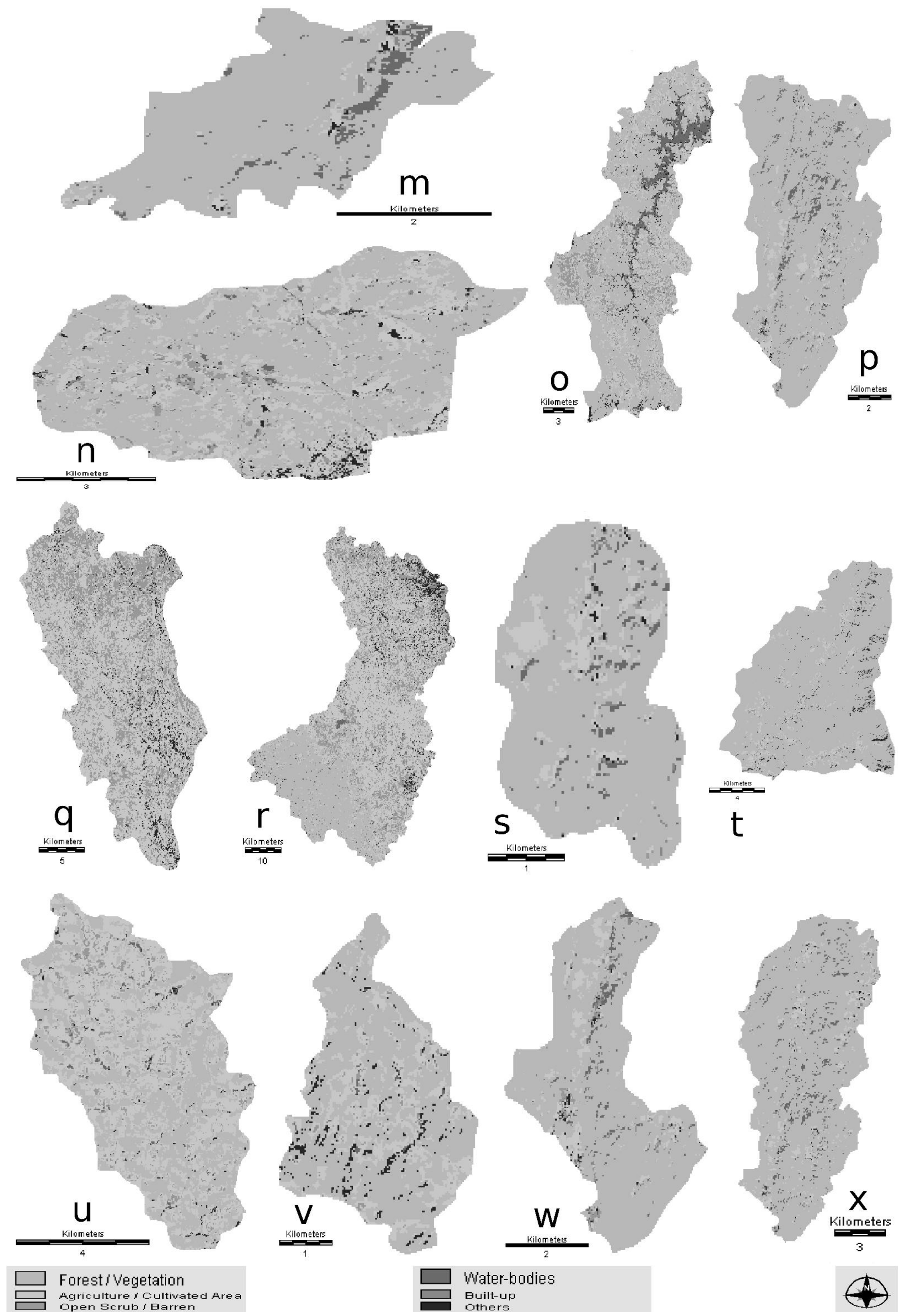


Figure 23 (cont.): Classified land use images of study catchments in Central Western Ghats. m - Beegar, n - Andhalli, o – Yennehole, p - Kammani, q - Sangadevarakoppa, r - Machikere, s - Melinakeri, t - Yanahole, u - Sapurthi, v - Bailalli, w - Kelaginakere, x – Hasehalla.

Water Chemistry: Water chemistry was characterized by high spatial variability in nutrients and ionic strength among the 24 sites. Nutrients like nitrates showed a many fold variability from 0.07 to 4.24 mgL^{-1}. Sites in the mountain range and wind ward side were characterized by low nutrient and ionic variables; where as the sites on the lee ward sides of the mountains were characterized with high nutrients, ions and low dissolved oxygen levels. The dendrogram of sites based on the water chemistry is shown in Figure 25. Two well differentiated clusters can be seen, with sites containing moderate to low levels of nutrient and ions in the top cluster and two severely polluted sites at bottom. The top cluster further divide in to four sub cluster based on the ionic and nutrient values. Clustering of most of the sites in cluster based on water chemistry variables are similar to the cluster of sites based on the land cover variables. A PCA bi-plot of water quality variables and LULC for all sample sites is given in Figure 26. The two-dimensional bi-plot describes 65% of the variation in data, where 52% displayed on the first axis and 13% is displayed on the second axis. Among water chemistry variables, ionic variables were positively correlated with first axis and among the LULC variables percentage agriculture and scrub land cover were positively related to the first axis. Sites with more than 50% of agriculture land cover were separated from other sites on the PC2 axis indicating trends in water quality may be related to land use. Agriculture dominated sites were placed due to the higher conductivity, ionic and nitrates levels relative to the forest dominated sites, which are characterized by low ionic and nutrient in nature**.**

Diatom Assemblages: Among the 113 taxa the most common and dominant diatom taxa are *Eolimna subminuscula, Achnanthidium* sp., *Navicula* sp., *Nitzschia palea, Gomphonema parvulum, Gomphonema* sp., *Gomphonema gandhii, Achnanthidium minutissima and Cyclostephanos* sp. The list of species with their abundance is presented in the Appendix 1. Species richness varied from 4 to 29 with an average of 15. Shannon-Wiener diversity varied from 0.71 to 2.94 with an average of 1.76. According to the pH classification, diatom assemblages were characterized by a high proportion of neutrophilous diatom species (64.62%) followed by alcaliphilous species (26.64%). Salinity classification based on the diatom species assemblages infer the fresh to brackish water species were the dominant form with 86.16% followed by brackish to freshwater (7.84%) and exclusively freshwater (5.3%) flora.

Nitrogen autotrophic taxa, which tolerate elevated concentrations of organically bound nitrogen, were dominant with 53.31%. Species which require 100% oxygen saturation were prevailing community with 42.98% followed by low level (30% oxygen saturation) oxygen requirement species by 29.08%. The composition of diatom community with respect to saprobity in the order or oligosaprobous, β-mesosaprobous, α-mesosaprobous, α-meso-/polysaprobous and polysaprobous were 7.8%, 46.09%, 10.58%, 26.56% and 8.97% respectively. The species occurs in the eutraphentic and oligo to eutraphentic were equally dominant with respect to the trophic state explained by diatoms.

Relationship of LULC with water chemistry and diatom assemblages

Correlation between percentage agricultural land cover with water chemistry variables and diatom autecological indices revealed the role of landscape level drivers in natural forest cover due to creation of new settlement for relocation of people and associated increase in cultivation of crops (Hegde *et al.,* 1994). Earlier studies confirm that agricultural expansion as one of the major driver for deforestation (Menon and Bawa, 1998) in Western Ghats determining the environmental condition of streams and diatom assemblages (Figure 27). The gradient of percentage agriculture land cover were positively correlated with water chemistry variables like electrical conductivity (r = 0.67), total dissolved solids (r = 0.62), nitrates (r = 0.60) and pH (r = 0.52). Gradient of percentage agriculture land cover were positively correlated with percentage pollution tolerant diatoms (r = 0.65, Figure 28). Relation between the diatom autecological indices with land cover and water chemistry variables are given in Tables 7 and 8 respectively. Most of the diatom autecological parameters were positively correlated with forest/vegetative cover and negatively correlated with agriculture/cultivable and scrub land cover. All the diatom indices were normalized to a range of 0-20, where <9 indicates bad water quality, 9 to 12 indicates poor water quality, 12 to 15 indicates moderate water quality, 15 to 17 indicates good quality and >17 indicates high quality. The present study shows that within a similar ecoregion, the diversity and community composition of diatoms changes with LULC pattern. Among all the 24 catchments, most of the catchments were dominated by forest/vegetation land cover. However, forest cover in the leeward side catchment was very low owing to anthropogenic activities. Hydro power projects commenced in the study area since 1960s seem to have lost.

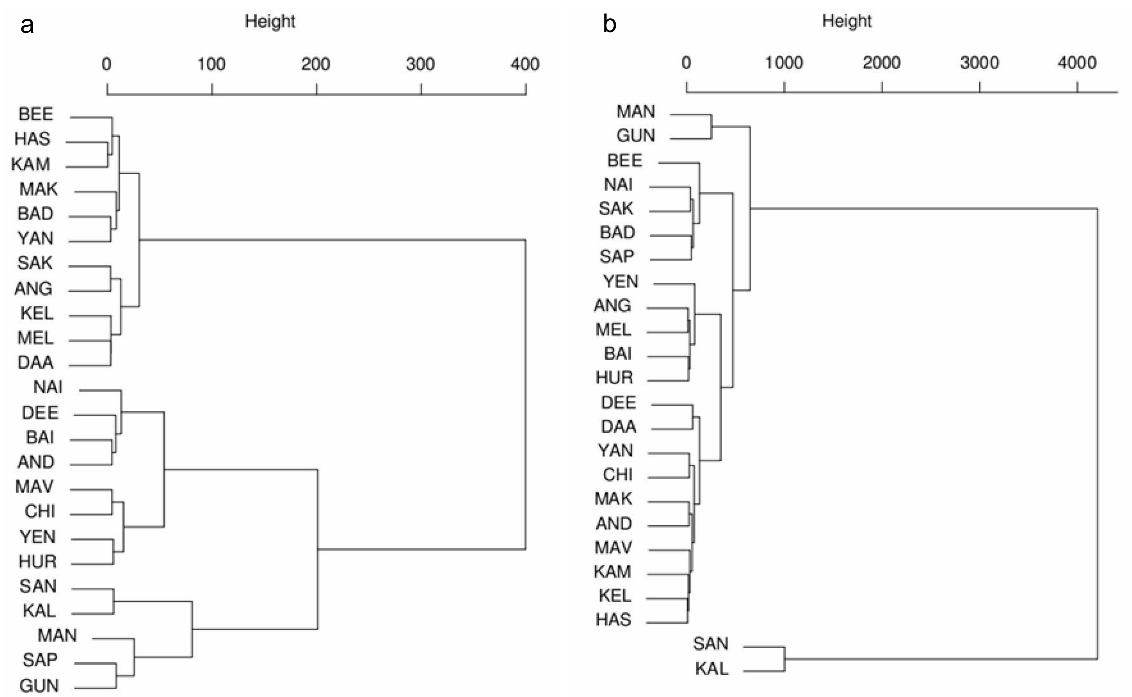


Figure 25: Dendrogram of the cluster analysis based on (a) LULC and (b) water quality, according to the 24 sampling sites of the Central Western Ghats

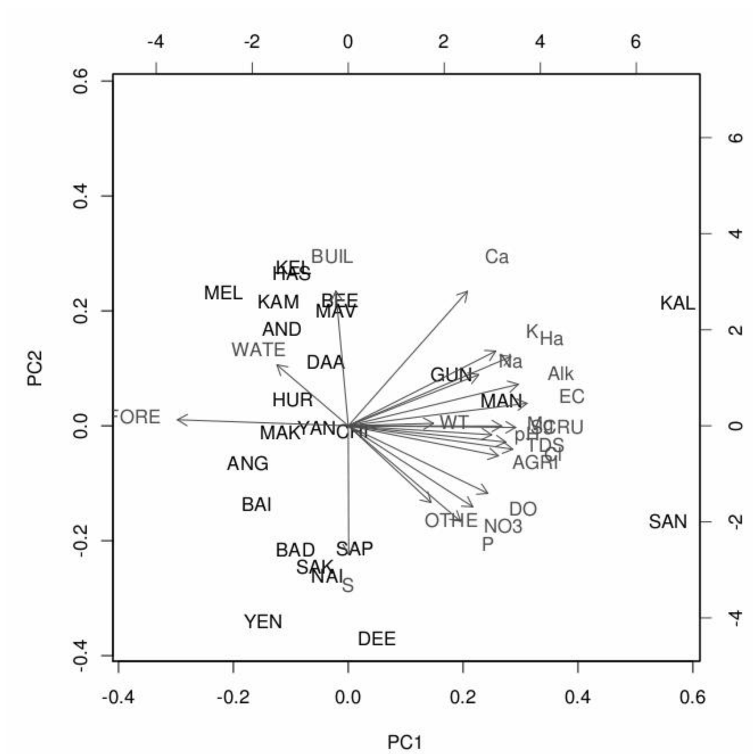


Figure 26: PCA bi-plots of water chemistry and LULC variables in study sites in Central Western Ghats streams

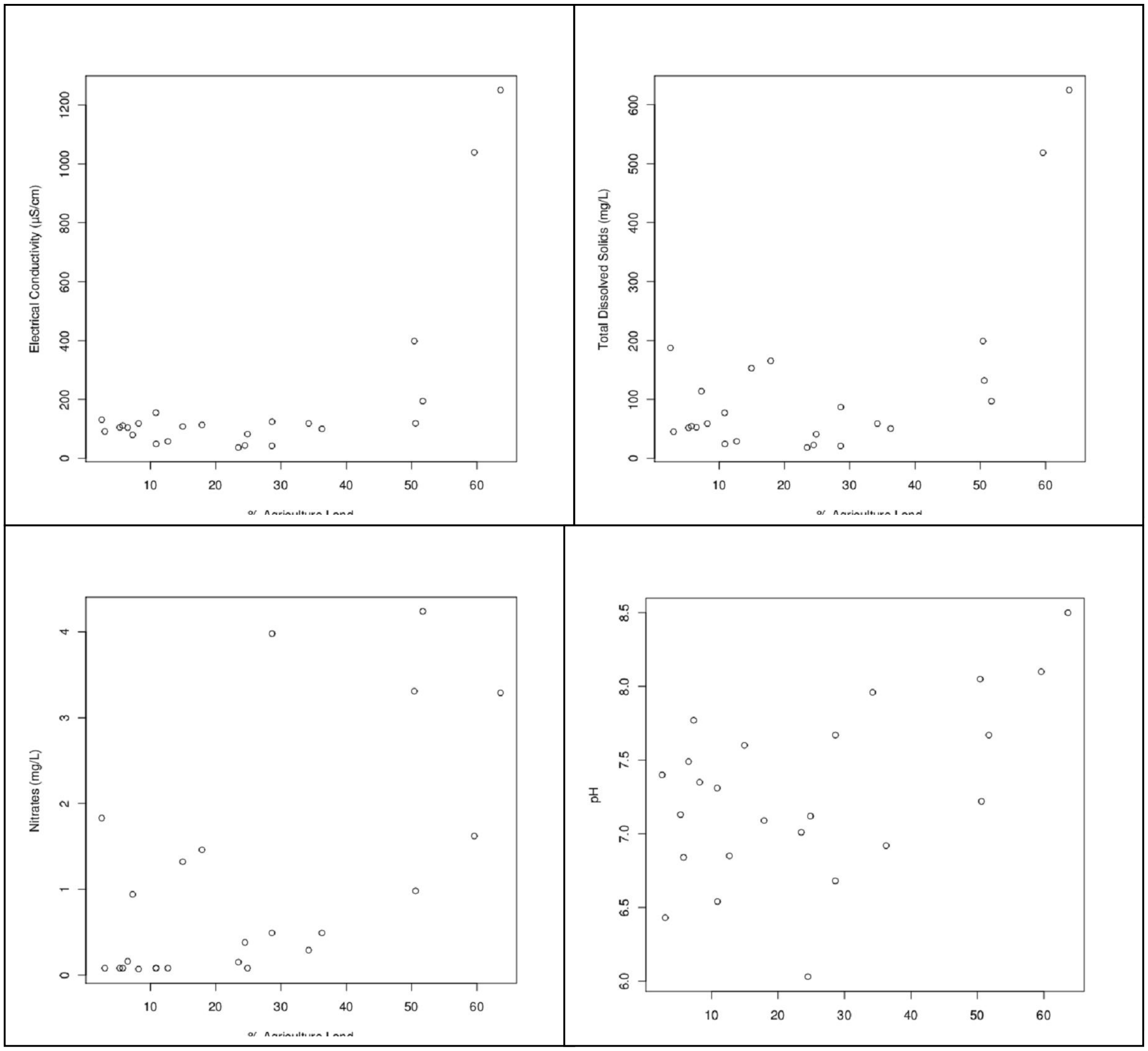


Figure 27: Changes in water quality variables along a gradient of percentage agricultural land cover in Central Western Ghats.

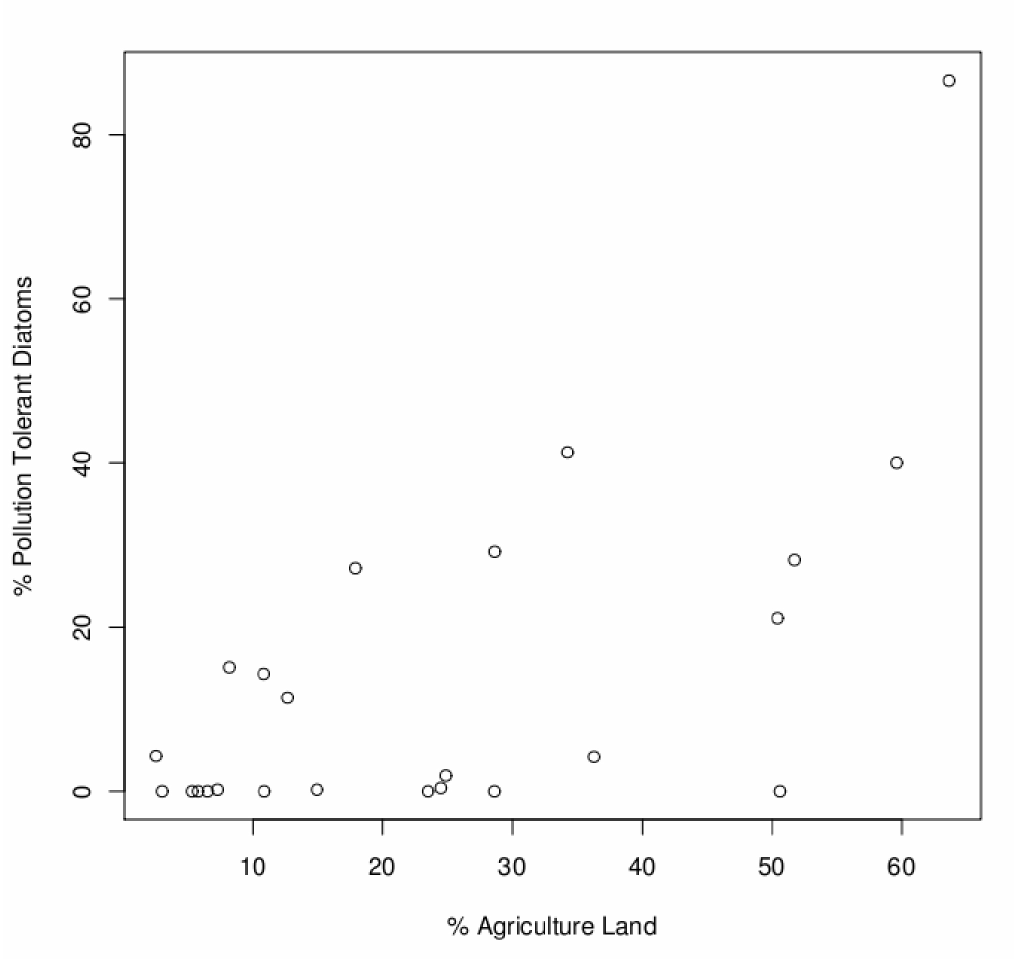


Figure 28: Relations between percentage pollution tolerant diatoms with gradient of percentage agricultural land cover in Central Western Ghats

The streams drained from catchment with agriculture and scrub land cover were characterized with ionic and nutrient rich, which notify that the water chemistry variables were decided by the land cover types. Many studies have reported that urban and agricultural land use play a primary role in degrading water quality in adjacent aquatic systems by altering the soil surface conditions, increasing the impervious area and generating pollution (Tong and Chen, 2002; White and Greer, 2006).

Table 7: Percentage LULC classes for each catchment in the study area

	Forest/ Vegetation	Agriculture/ Cultivation	Open Scrub/ Barren Land	Water Bodies	Built Up	Others
CHI	52.5	34.24	10.9	1.18	0.14	1.04
MEL	83.58	10.88	0.57	2.84	1.52	0.61
KEL	85.83	8.19	1.4	3.03	0.92	0.62
BEE	90.41	2.55	0.16	5.11	1.16	0.61
ANG	81.54	12.67	1.38	0.08	0.18	4.14
MAK	95.45	3.02	0.38	0.01	0.13	1.01
HUR	52.84	28.62	11.89	3.91	0.1	2.64
MAV	48.85	36.26	10.79	2.94	0.43	0.73
YEN	56.15	24.49	10.47	5.61	0.16	3.12
BAI	70.85	23.49	0.99	0.58	0.2	3.89
DEE	64.34	28.64	3.62	0.51	0.2	2.69
YAN	90.83	6.52	0.56	0.02	0.08	1.98
SAP	42.8	50.61	4.5	0.97	0.31	0.81
BAD	88.36	7.29	0.24	0.11	0.06	3.94
NAI	67.43	17.89	3.65	1.03	0.44	9.58
SAK	80.08	14.94	0.26	0.92	0.24	3.58
AND	68.1	24.87	3.36	0.93	0.98	1.77
DAA	86.29	10.84	0.58	1.26	0.41	0.63
HAS	88.6	5.77	0.42	3.96	0.88	0.37
KAM	88.8	5.31	0.6	4.01	0.89	0.39
MAN	23.46	50.42	20.69	0.67	0.52	4.25
KAL	0.53	59.6	30.22	0.02	0.84	8.79
SAN	0.13	63.63	31.48	0.02	0.16	4.59
GUN	36.82	51.72	10.52	0.52	0.35	0.07

Our results conform to earlier studies, suggesting better water quality tendencies in watersheds having less urbanization with more natural vegetation region. Percent agriculture in the catchment ranged from 2 to 63% with an average of 24.27% so the sites we selected covered a good range of the land-use gradient. An aggregated measure of LULC such as percentage agriculture in catchments may only represent the potential of LULC effects on streams. Percentage agriculture lands in catchments were positively correlated with the ionic and nutrient variables. Studies have shown that the percentage of agriculture at watershed scale is a primary predictor for nitrogen and phosphorus (Ahearn *et al.,* 2005).

Table 8: Water chemistry variables of the sampling sites in Central Western Ghats

Water Chemistry variables (Units)	Mean±S.D	Range
pH	7.28±0.58	6.03-8.50
Water Temperature (°C)	26.09±2.52	22.10-35.43
Electrical Conductivity (μScm^{-1})	199.00±301.44	37.17-250.67
Total Dissolved Solids (mgL^{-1})	120.26±149.68	18.67-624.67
Alkalinity (mgL^{-1})	70.44±111.46	12.00-421.07
Chlorides (mgL^{-1})	35.25±62.36	4.99-255.92
Hardness (mgL^{-1})	69.49±96.94	12.00-376.00
Calcium (mgL^{-1})	14.76±17.33	1.60-84.97
Magnesium (mgL^{-1})	15.72±18.58	1.17-71.01
Dissolved Oxygen (mgL^{-1})	7.58±1.77	4.81-11.52
Phosphates (mgL^{-1})	0.18±0.36	0.01-1.30
Sulphates (mgL^{-1})	19.94±18.07	2.91-67.91
Sodium (mgL^{-1})	52.92±201.09	1.05-996.03
Potassium (mgL^{-1})	11.01±35.01	0.41-168.33
Nitrates (mgL^{-1})	1.06±1.33	0.07-4.24

Diatom community structure in streams of the CWG was strongly related to land use practices as in many other regions (Stevenson *et al.,* 2009; Walsh and Wepener, 2009). The nutritional changes in the streams triggered by the LULC analysis stands as a determining factor in structuring the diatom species composition. Effects of nutrient are commonly identified as one of the most important determinants of diatom species composition in lentic and lotic ecosystems (Pan and Stevenson, 1996). However the diatom species composition at CWG stream were controlled more by the ionic variables than the nutrient concentration, which is evident by the dominance of fresh to brackish water diatom species in agriculture catchments. More of pollution tolerant species were seen in the streams in agriculture dominated catchments. Blinn (1993, 1995) found that higher salinities (≥ 35 $mScm^{-1}$) tend to override other water quality parameters in structuring diatom communities in salt lakes. Agriculture dominated sites like SAN and

KAL represented water quality with high nutrient concentration along with elevated levels of total dissolved solids, and pH (Figures 25 and 26) which is also supported by positive correlation of percentage agriculture land cover with percentage pollution tolerant diatoms (Figure 28). Correlation analyses between measured land cover of the watersheds and water quality parameters reveal a number of interesting aspects of the pattern effects of land uses on water quality. The application of indices on the diatom communities revealed significant correlation of only percent pollution tolerant diatoms with land use variables. The significant positive correlation of all the water chemistry variables with agriculture land use represents more human induced activities, whereas water temperature did not correlate significantly with any of the variables. This may be due to varying depth and different water regimes (Taylor, 2004). As would be expected streams in catchments with intensive agriculture were characterized by increased concentrations of nutrients and ions, which is evident from the principal component analysis. Clear differences in community composition were seen in NMDS analysis, where diatom community from streams with agriculture land cover was clustered out separately, except one site. According to NMDS analysis, diatom communities were significantly different in streams with different catchment nature. Diatom community in the forested streams were dominated by endemic diatom flora (*Gomphonema gandhii* Karthick and Kociolek, *G. difformum* Karthick and Kociolek, *G. diminutum* Karthick and Kociolek and many unidentified species from genus *Navicula*), whereas the streams from agricultural dominated landscapes were dominated by cosmopolitan species (*Gomphonema parvulum* Kützing, *Nitzschia palea* (Kützing) W.Smith, *Achnanthidium minutissima* Kützing v. *minutissima* Kützing).

Conclusions

These results offer insight into our three objectives for this study: (1) all the three water quality regimes shows changes in water quality across seasons, (2) diatom species assemblages changes strongly in all the water quality regimes, due to seasonal water quality conditions, where physical forces are more significant over longer scales of study while eutrophication and regional landuse is moreover evident within climatic seasons, and (3) the species distribution across the sites followed the satellite-mode due to the specific ecological niches of the diatoms. This study also concludes that Western Ghats streams can be monitored during the post monsoon months for biomonitoring ventures and compared to other water monitoring programs. This study also hints that the diatom community in this region is rich with possible endemic taxa; hence considerable amount of importance has to be given for the taxonomy of the lesser-known species before starting the biomonitoring programs.

The analyses and results described here provide insights to the linkages between land use practices and water quality in the streams of CWG and the relative sensitivity of water quality variables to alterations in land use. Agricultural activities in stream catchments are closely linked to increasing nutrient and ionic concentrations. Water quality in the eastern leeward regions was most strongly influenced by agriculture land uses, whereas the western windward catchments were dominated by natural forests. The diatom indices and water chemistry variables relation clearly shows the impact of land use on stream ecosystem. Comparison of community structure for diatoms taken from sites with varying land uses using NMDS analysis reflected differences attributing to LULC. In conclusion, this study highlights the role of landscape and proximate factors in the regulation of diatom species assemblages. Understanding the relative importance of natural and anthropogenic variations on diatom species composition is essential for conservation of lesser known organisms like diatoms

It has been evident from our findings that the causes and sources of water pollution in the 5 River Basins are due to agricultural land use, anthropogenic activities and industrialization. The major occupation in the study area is agriculture, which is main source of increase in nitrates and ionic components in streams. Domestic and industrial sewage discharges in to rivers are responsible for the observed high concentration of electrical conductivity, total dissolved solids, total hardness and other ionic components. Proper treatment of effluent from the industrial processes to the acceptable levels and discouraging stagnation of water through small dams are the two major recommendations to minimize the river ecosystem damage in the central Western Ghats.

River ecosystems of Uttara Kannada: Threats

Dams: Large to small sized dams used for hydroelectricity production and small sized local check dams for intense agriculture purposes. Both large and small check dam affects the riverine biodiversity and water quality.

Figure 29: Site showing check dam and loss of riparian vegetation. Site: Beegar, Yellapura Taluka.

Loss of riparian vegetation: Removal of riparian vegetation is observed in all river basins (figure 29). In particular streams flows next to the agriculture lands shows significant removal of riparian vegetations.

Water pollution due to domestic sewage: Bedthi River Basin, in particular upper reaches of Bedthi shows high level of water quality degradation due to the domestic sewage disposal in the main streams (Figure 30). Certain portion of the domestic sewage of Hubli town is disposed into upper Bedthi River (Figure 31). Sewage contaminants flows in to Bedthi River and later gets diluted by the water from tributary like Hasehall, which drains more water even during the summer months. Some of the sites, which are severely affected by the water pollution in Bedthi River basin are Sangadevarakoppa, Kalghatghi and Manchikeri (Yellapura).

Figure 30: Site showing sewage flowing in tributary of Bedthi.

Figure 31: Site showing sewage flowing in tributary of Bedthi

Industrial Pollution: Kali River Basin is under the influence of industrialization in Uttara Kannada, in particular Dandeli region with polluting industries. The West Coast Paper Mills Ltd situated in the bank of River Kali pollutes the water and surrounding riparian environment by letting partially treated or untreated effluents into the river. Kervada village, next to Dandeli witness severe water and air pollution due to the effluent of paper mill. Paper mill waste increases total dissolved and suspended solids, turbidity and ionic content. In addition to the effluents the river also receives sewage. Organic waste let in to the river decreases the dissolved oxygen, which eventually causes threat to aquatic biodiversity. Site where confluence of sewage is also witnessed soaring population of Mugger crocodiles (Figure 32) resulting in the higher instances of human wildlife conflicts.

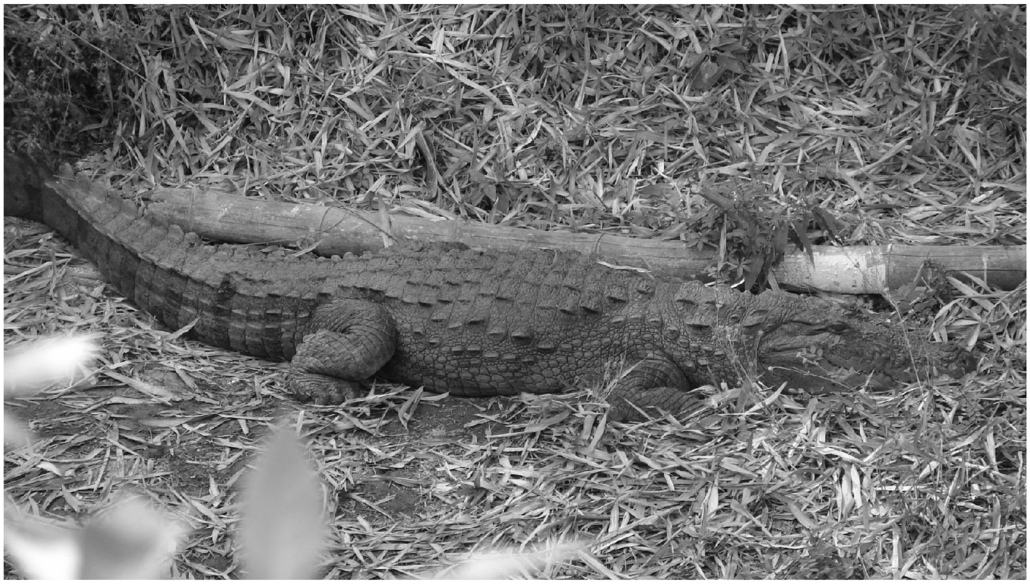


Figure 32: Mugger crocodile (*Crocodylus palustris*) in Kervada, Paper Mill effluent confluence point in Kali River Basin.

Sand Mining: Sand mining is one of the common problems observed in lower reaches of all the river basins (Figure 33). Sand mining is predominant in brackish water region of Kali and Sharavathi River Basins, where mechanized sand mining is in practice for a while. Sand mining cause severe threat to the benthic organisms. Most of the marine and esturine benthic organisms breed in brackish regions faces severe threat due to the mechanized sand mining. Mangrove regions in Kali estuary is also threatened by sand mining due to loss or alteration of habitat.

Figure 33 Mechanized sand mining in Kali River Basin

Table 9 lists the river basin wise threats with the appropriate mitigation measures to enhance the functional aspects of aquatic ecosystems.

Table 9: Threats and Mitigation Measures

River Basin	Region	Problem	Remedial Measures
Kali	Dandeli	Paper mill effluent	Enforce effluent treatment by the industry (implementation of the control of water pollution, Polluter pays principle)
Kali	Ramnagar	Non-point source pollution in streams and rivers from Agriculture fields	Avoiding intense use of chemical fertilizers and pesticides
Kali	Honkon (Brackish)	Mechanized sand mining	Stopping of sand mining in certain ecologically sensitive region and regulated sand mining in selected localities
Bedthi	Sangdevarkoppa	Non-point source pollution	Avoiding intense use of chemical fertilizers and pesticides
Bedthi	Kalghatghi	Urban domestic sewage, non-point source pollution	Implementation of sewage treatment plant in Hubli town. Sewage should be treated before letting in to the river.
Bedthi	Kalghatghi	Solid Waste Disposal in River	Setting up Solid waste disposal facility in outskirts of Hubli town.
	Manchikeri	Urban domestic sewage, non-point source pollution	Implementation of sewage treatment plant in Hubli town. Sewage should be treated before letting in to the river.
Sharavathi	Gerusoppa and downstream	Mechanized sand mining	Stopping of sand mining in certain ecologically sensitive region and regulated sand mining in selected localities

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Annexure 1:

Checklist of Epilithic diatoms of Rivers of Uttara Kannada, Karnataka

TAXA	KALI	BEDTHI	AGHAN ASHINI	SHARA VATHI	VENKAT APURA
ACHNANTHES sp J.B.M. Bory de St. Vincent		+			
Achnanthes minutissima Kützing *v.minutissima* Kützing *(Achnanthidium)*	+	+	+	+	+
Achnanthes sp.		+			
Achnanthidium sp.	+	+	+	+	+
Actinocyclus sp.	+				
Amphora montana Krasske	+				
Amphora pediculus (Kützing) Grunow	+				+
Amphora species		+			
Aulacoseira ambigua (Grunow) Simonsen	+	+		+	
*Aulacoseira granulata (*Ehr.*)* Simonsen		+			
*Aulacoseira granulata (*Ehr.*)* Simonsen morphotype *curvata*		+			
Bacillaria paradoxa Gmelin	+				
Brachysira neoexilis Lange-Bertalot	+	+	+	+	+
Brachysira sp.	+	+	+	+	+
Brachysira wygaschii Lange-Bertalot	+		+	+	+
BRASSIEREA sp Hein & Winsborough		+			
*Caloneis bacillum (*Grunow*)* Cleve	+	+		+	
Caloneis hyalina Hustedt	+				
*Caloneis silicula (Ehr.)*Cleve	+	+			+
Caloneis species		+			
Cocconeis placentula Ehrenberg *var.euglypta (*Ehr.*)* Grunow	+	+	+		+
CRATICULA sp A. Grunow		+			
Craticula accomodiformis Lange-Bertalot		+			
Craticula molestiformis (Hustedt) Lange-Bertalot		+			
Craticula submolesta (Hust.) Lange-Bertalot	+	+			+
Craticula vixnegligenda Lange-Bertalot		+			
CYCLOSTEPHANOS sp F.E. Round		+			

Cyclostephanos species	+	+			+
CYCLOTELLA sp F.T. Kützing ex A de Brébisson		+			
Cyclotella meneghiniana Kützing	+	+			
Cyclotella ocellata Pantocsek		+			
Cyclotella species		+			
Cymbella kolbei Hustedt *var.* kolbei	+	+		+	+
Cymbella species	+	+	+	+	+
*Cymbella tumida (*Brebisson*)*Van Heurck	+	+			
CYMBOPLEURA (Krammer) Krammer					+
Cymbopleura sp.	+			+	+
Diadesmis contenta (Grunow ex V. Heurck) Mann	+	+			+
*Diploneis elliptica (*Kützing) Cleve		+			
*Diploneis oblongella (*Naegeli) Cleve-Euler		+			
Diploneis ovalis (Hilse) Cleve		+			
Diploneis subovalis Cleve	+	+			+
Encyonema mesianum (Cholnoky) D.G. Mann	+				+
*Encyonema minutum (*Hilse in Rabh.) D.G. Mann	+	+			+
Encyonema species	+				+
Entomoneis alata Ehrenberg		+			
Eolimna subminuscula (Manguin) Moser Lange-Bertalot & Metzeltin	+	+			
EUNOTIA sp. C.G. Ehrenberg		+			
Eunotia bilunaris (Ehr.) Mills var. *bilunaris*					+
Eunotia incisa Gregory var.*incisa*	+	+			
*Eunotia minor (*Kützing*)* Grunow	+	+	+	+	+
Eunotia rhomboidea Hustedt	+		+	+	+
Eunotia sp.	+	+		+	
Fallacia insociabilis (Krasske) D.G. Mann		+			
Fallacia pygmaea (Kützing) Stickle & Mann *ssp.pygmaea* Lange-Bertalot	+	+			
Fallacia tenera (Hustedt) Mann in Round		+			
Fragilaria biceps (Kützing) Lange-Bertalot	+	+	+	+	+
Fragilaria species		+			
Fragilaria ulna (Nitzsch.) Lange-	+	+	+	+	+

Bertalot var. *ulna*					
Fragilaria ungeriana Grunow	+				
Frustulia saxonica Rabenhorst				+	
Frustulia species	+			+	+
Geissleria decussis(Ostrup) Lange-Bertalot & Metzeltin		+			
Gomphonema acuminatum Ehrenberg	+				
Gomphonema difformum Karthick and Kociolek		+	+	+	
Gomphonema diminutum Karthick and Kociolek	+	+	+		
Gomphonema gandhii Karthick and Kociolek	+	+	+	+	+
Gomphonema parvulum (Kützing) Kützing var. *parvulum f. parvulum*	+	+	+	+	+
Gomphonema pseudoaugur Lange-Bertalot		+			
Gomphonema species	+	+	+	+	+
*Gyrosigma acuminatum (*Kützing)Rabenhorst	+	+			
Gyrosigma scalproides (Rabenhorst)Cleve	+				
Gyrosigma species		+			
Hantzschia distinctepunctata Hustedt in Schmidt & al.				+	
Hippodonta avittata (Cholnoky) Lange-Bert.Metzeltin & Witkowski	+				+
Luticola species	+	+			
Luticola species (aff. mutica)	+				
Navicula species		+			
Navicula antonii Lange-Bertalot		+		+	
Navicula cincta (Ehr.) Ralfs in Pritchard	+				
Navicula cryptocephala Kützing	+	+	+	+	+
Navicula cryptotenella Lange-Bertalot	+				
Navicula elginensis (Gregory) Ralfs in Pritchard					+
Navicula erifuga Lange-Bertalot	+	+			
Navicula gracilis Ehrenberg	+			+	
Navicula hustedtii Krasske					
Navicula hustedtii Krasske var.*obtusa* Hustedt	+			+	
Navicula leptostriata Jorgensen	+	+	+	+	+
*Navicula peregrina (*Ehr.) Kützing	+				
Navicula reinhardtii (Grunow) Grunow				+	

in Cl. & Möller					
Navicula riediana Lange-Bertalot & Rumrich	+			+	+
Navicula rostellata Kützing	+	+		+	+
Navicula sp.	+	+	+	+	+
Navicula symmetrica Patrick	+	+	+	+	+
Navicula viridula (Kützing) Ehrenberg	+				
Navigiolum species.					
Neidium affine(Ehrenberg)Pfitzer	+				+
NITZSCHIA sp. A.H. Hassall		+			
Nitzschia amphibia Grunow f.*amphibia*	+	+			+
Nitzschia clausii Hantzsch	+	+		+	+
Nitzschia compressa (J.W.Bailey) Boyer		+			
*Nitzschia dissipata(*Kützing*)Grunow var.media (*Hantzsch*.)* Grunow				+	
Nitzschia fonticola Grunow in Cleve et Möller	+	+			
Nitzschia frustulum(Kützing)Grunow var.frustulum	+	+			
Nitzschia gracilis Hantzsch				+	
Nitzschia linearis(Agardh) W.M.Smith var.*linearis*					
Nitzschia nana Grunow in Van Heurck	+				
Nitzschia obtusa W.M.Smith *var. kurzii* (Rabenhorst) Grunow	+	+		+	+
Nitzschia palea (Kützing) W.Smith	+	+		+	+
Nitzschia reversa W.Smith	+	+		+	+
Nitzschia sigma(Kützing)W.M.Smith		+		+	+
Nitzschia species	+	+			+
*Nitzschia umbonata(*Ehrenberg*)*Lange-Bertalot		+			
Pinnularia acrospheria W. Smith var. *acrospheria*		+			+
Pinnularia brebissonii (Kütz.) Rabenhorst *var.* brebissonii	+	+		+	
Pinnularia divergens W.M.Sm. var.*undulata* (M.Perag. & Herib.) Hustedt				+	
Pinnularia gibba Ehrenberg				+	
Pinnularia species		+		+	+
Placoneis sp.	+	+		+	
Planothidium frequentissimum(Lange-Bertalot)Lange-Bertalot	+	+	+	+	+

Planothidium rostratum (Oestrup) Round & Bukhtiyarova	+	+			+
PLANOTHIDIUM sp. Round & Bukhtiyarova		+	+	+	
Pleurosigma salinarum (Grunow) Cleve & Grunow	+				
Pseudostaurosira brevistriata (Grun.in Van Heurck) Williams & Round		+			
Rhopalodia gibba (Ehr.) O.Muller var.gibba					+
*Rhopalodia operculata (*Agardh) Hakansson	+				+
Sellaphora species	+	+			
Sellaphora americana (Ehrenberg) D.G. Mann	+			+	+
Sellaphora laevissima (Kützing) D.G. Mann				+	
Sellaphora nyassensis (O.Muller) D.G. Mann	+	+			
*Sellaphora pupula (*Kützing) Mereschkowksy	+	+		+	+
SEMINAVIS sp. D.G. Mann		+			
Seminavis species		+			
Skeletonema species					
Stauroneis species	+	+			+
Surirella angusta Kützing	+	+		+	+
Surirella species	+	+		+	+
Synedra sp.		+			
Tryblionella calida (grunow in Cl. & Grun.) D.G. Mann	+	+			
Tryblionella levidensis Wm. Smith		+			
TOTAL	**83**	**95**	**22**	**51**	**55**
TOTAL NUMBER OF TAXA REPORTED FROM ALL RIVER BASINS	**140**				

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The diatom genus *Gomphonema* Ehrenberg in India: Checklist and description of three new species

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With 51 figures and 2 tables

Karthick, B., J.P. Kociolek, M.K. Mahesh & T.V. Ramachandra (2011): The diatom genus *Gomphonema* Ehrenberg in India: Checklist and description of three new species. – Nova Hedwigia 93: 211–236.

Abstract: We have compiled a checklist of *Gomphonema* Ehrenberg taxa reported previously from India. From forty-nine references, over 100 *Gomphonema* taxa have been reported, including 39 new taxon descriptions. In addition to these previous reports of *Gomphonema* taxa, we describe three new species, *G. gandhii* Karthick & Kociolek, sp. nov., *G. difformum* Karthick & Kociolek, sp. nov. and *G. diminutum* Karthick & Kociolek, sp. nov., all from hill streams of Western Ghats, India. Frustule morphology, as studied in light and scanning electron microscopy, is compared with that of other recently described *Gomphonema* species from Africa and Asia. All three Indian species have distinctly dilated proximal raphe ends, in addition to differentiated apical pore fields, septa, pseudosepta and a round external stigmal opening. *Gomphonema gandhii* is linear-lanceolate-clavate, has a wide axial area, and is 19–51 µm long, 3–7 µm broad. *Gomphonema difformum* is smaller than *G. gandhii*, and has a hyaline area around the headpole. *Gomphonema diminuta* is much smaller and narrower than the other two species. These species are distinct from their closest congeners by their sizes, shape and structure of the head pole, and striae densities. All these species were described from low nutrient, neutral, low ionic content streams of Western Ghats. As most other species described from tropical region these three species appear to be endemic to India. Moreover, within India they have hitherto only been found in Western Ghats, one of the twelve biodiversity hotspots of the World.

Key words: Bacillariophyceae, diatoms, Gomphonema, India, new species, taxonomy, valve ultrastructure.

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Introduction

The diatom genus *Gomphonema* Ehrenberg is large, including over 500 taxa worldwide (Fourtanier & Kociolek 2009). While its members are almost exclusively freshwater in terms of habitats, and many species are associated with impacted trophic levels (e.g. Patrick in Patrick & Reimer 1966), the genus is quite diverse morphologically. Variation in valve ultrastructure includes presence or absence of stigmata, areolar structure, structure and position of the apical pore fields, and presence/absence of spines to name a few (Kociolek & Stoermer 1993, but also see Metzeltin & Lange-Bertalot 1998, Reichardt 1999). While some species of *Gomphonema* appear to be cosmopolitan in their distribution (for example, it appears that *G. parvulum* (Kützing) Kützing has been reported from all continents on earth), there are many reports of endemic species of *Gomphonema* from South America (Fricke 1904; Metzeltin & Lange-Bertalot 2007), Africa (Compère 1995, Hustedt 1949, Kociolek & Stoermer 1991), Madagascar (Spaulding & Kociolek 1998), North America (Kociolek & Kingston 1999, Thomas et al. 2009), Europe (Hustedt 1945, Reichardt 1999, 2005), Asia (Lange-Bertalot & Genkal 1999, Li et al. 2006) and Australia and environs (Hustedt 1942, Kociolek et al. 2004).

India is a large, geographically complex country with ten different biogeographic zones covering over 3 million sq. km, about a third the size of all of Europe, but with nearly 50% greater human population (World Population Prospects, 2008). The country shares borders with Bangladesh, Bhutan, Myanmar, China, Nepal and Pakistan. The complexity of India's freshwater environments includes three major, complex watersheds (Himalayas and the Karakoram ranges; Vindhya, Satpura ranges and the Chota Nagpur Plateau; and the Western Ghats) that cut across the country, related to their sources in the mountains. Freshwater environments range in elevation from sea level at the coast to over 8000 m above sea level.

The diatom genus *Gomphonema* in India has been documented for over 160 years. First report of the genus in India was by Ehrenberg (1845), who reported *G. clavatum*, *G. gracile* and *G. turris* from "Kolkatta" (then Calcutta) and River Ganges. Since then, 49 separate papers have identified 130 taxa of *Gomphonema* from India, mostly from lowland habitats. Of these, about 30% have been newly described taxa. In the region around India, gomphonemoid diatoms have been considered by Hustedt (1922), Jüttner et al. (2004) from Nepal, and Mereschkowsky (1906), Kociolek (1992), and Li et al. (2006, in press) from China. Though many species of *Gomphonema* have been described from India, there are extensive parts of the country that have not been investigated. The Western Ghats mountain range in Southern India, one of the Gondwanaland breakup landmasses, is amongst the most important hotspots of biodiversity. Western Ghats is a chain of mountains that runs parallel with the west coast of India for over 1600 km from 8°15'N to 21°00'N. Due to its distinct physiographic, edaphic and climatic gradients, this region harbors a wide array of habitats with unique geographic position and that support unique sets of flora and fauna. The Western Ghats harbors approximately 5000 species of vascular plants belonging to nearly 2200 genera; about 1700 species (34%) are endemic. There are also 58 endemic plant genera, while nearly three-quarters of the endemic genera

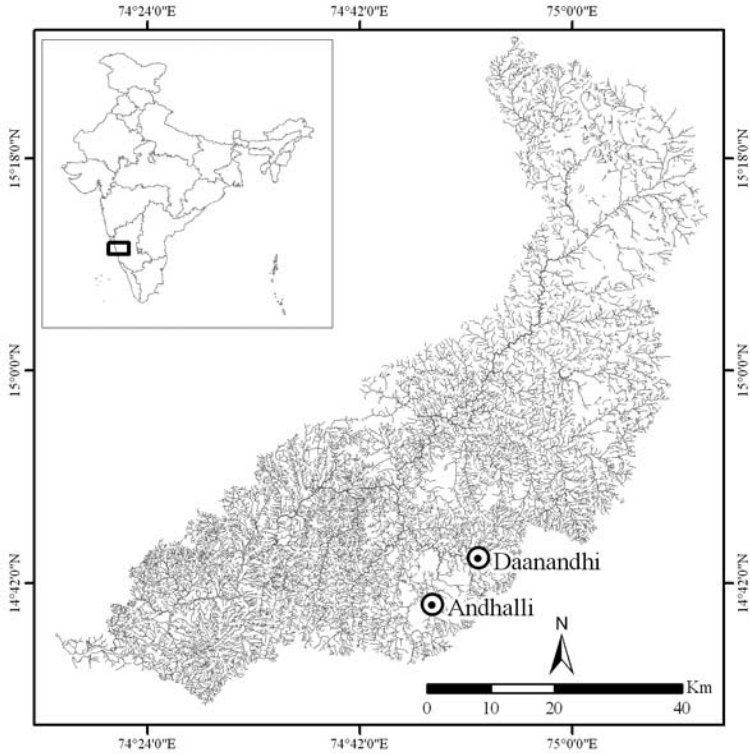


Fig 1. Map showing the area of investigation (inset India with Bedthi River basin highlighted).

have only a single species (Conservation International, 2008). The fauna and flora of this region has attracted attention of systematic and evolutionary biologists because of the mixture of high-level endemism (Inger, 1999; Myers et al. 2000) and various affinities with other biogeographic regions (Bossuyt & Milinkovitch, 2001).

In the present report we have compiled a checklist of the *Gomphonema* taxa previously reported and described from India (Table 1). We also document and describe with light and scanning electron microscopy three new species of *Gomphonema* from Central Western Ghats, Karnataka State, India. We also present information about each species' autecology, with particular attention paid to water chemistry and seasonality.

Materials and methods

Ten first to fourth order streams were surveyed for diatoms and water quality assessment in the Bedthi River Basin, Central Western Ghats, Karnataka (Fig. 1) from January to December, 2006. Diatom samples were collected by vigorously scrubbing 3–5 stones from the substratum with a toothbrush and the resultant suspension was preserved in ethanol. A portion of sample was oxidized by the hot HCl and $KMnO_4$ method (Taylor et al. 2007). Cleaned material was mounted onto glass slides with

Table 1. Listing of *Gomphonema* taxa for India and references that have reported each taxon. (Note: * denotes the species described from Indian administrative boundary; † indicates the studies on fossil material)

	Species name	Reference
1	*Gomphonema abbreviatum* Kütz.	Abdul-Majeed 1935; Srinivasan 1965; Suxena and Venkateshwarlu 1970
2	*Gomphonema abbreviatum* Kütz. f. *minor*? Krishnamurthy*	Krishnamurthy 1954; Kumawat et al. 2008
3	*Gomphonema abbreviatum* Kütz. v. *pulneyensis*? Krishnamurthy*	Krishnamurthy 1954
4	*Gomphonema acuminatum* Ehr.	Carter 1926; Biswas 1936; Krishnamurthy 1954
5	*Gomphonema acuminatum* Ehr. v. *elongata* (Rabh.) W.Sm.	Biswas 1936
6	*Gomphonema acuminatum* Ehr. v. *directum* A.Cl.	Gandhi 1959b
7	*Gomphonema acuminatum* Ehr. v. *turris* (Ehr.) Cl.	Krishnamurthy 1954; Gandhi 1960a; Sarode and Kamat 1980; Sarode and Kamat 1983; Sarode and Kamat 1984; Prasad and Srivastava 1992; Kumawat et al. 2008
8	*Gomphonema aequatoriale* Hust.	Gandhi 1960a; Gandhi 1964; Sarode and Kamat 1980; Sarode and Kamat 1983; Sarode and Kamat 1984; Kumawat et al. 2008
9	*Gomphonema angustatum* (Kütz.) Rabh.	Krishnamurthy 1954; Srinivasan 1965; Kumawat et al. 2008
10	*Gomphonema angustatum* (Kütz.) Rabh. v. *producta* Grun	Krishnamurthy 1954; Kumawat et al. 2008
11	*Gomphonema angustatum* (Kütz.) Rabh. v. *producta* Grun. f. indica Gandhi*	Gandhi 1960a; Sarode and Kamat 1984
12	*Gomphonema apicatum* Ehr.	Singh 1963
13	*Gomphonema augur* Ehr.	West and West 1907; Gandhi 1959a; Gandhi 1960a; Singh 1961; Gandhi 1962a; Gandhi 1966; Gandhi 1983a†; Sarode and Kamat 1984; Kumawat et al. 2008
14	*Gomphonema augur* Ehr. v. *gautieri* V.H	Gandhi 1983a†
15	*Gomphonema augur* Ehr. v. *genuinum* May.	Gandhi 1956; Singh 1961; Singh 1963; Prasad and Srivastava 1992; Kumawat et al. 2008
16	*Gomphonema balatonis* Pant.	Gandhi 1960a; Srinivasan 1965; Sarode and Kamat 1984; Kumawat et al. 2008
17	*Gomphonema balatonis* Pant. v. *lanceolata* Gandhi	Gandhi 1960a; Sarode and Kamat 1984;
18	*Gomphonema brasiliense* Grun.	deToni 1891–94; Srinivasan 1965
19	*Gomphonema bengalensis* Grun*	deToni 1891-94;
20	*Gomphonema bohemicum* Reichelt et Fricke	Gandhi 1983a†
21	*Gomphonema capitatum* Ehr.	Abdul-Majeed 1935
22	*Gomphonema clavatoides* Gandhi*	Gandhi 1960a; Gandhi 1964; Srinivasan 1965; Gandhi 1966; Sarode and Kamat 1984; Prasad and Srivastava 1992; Gandhi 1998; Kumawat et al. 2008
23	*Gomphonema clavatoides* Gandhi v. *valida* Gandhi*	Gandhi 1960a; Sarode and Kamat 1984
24	*Gomphonema clavatoides* v. *rostrata* Gandhi*	Gandhi 1998
25	*Gomphonema clavatum* Ehr.	Ehrenberg 1845
26	*Gomphonema clevei* f. *acuta* Gandhi*	Gandhi 1966
27	*Gomphonema clevei* Fricke	Gandhi 1959b; Srinivasan 1965; Gandhi 1966; Prasad and Srivastava 1992

28	*Gomphonema clevei* v. *bipunctata* Gandhi*	Gandhi 1959b; Gandhi 1966
29	*Gomphonema clevei* v. *javanica* Hust.	Gandhi 1966
30	*Gomphonema clevei* v. *undulata* Gandhi*	Gandhi 1966
31	*Gomphonema constrictum* Ehr.	Abdul-Majeed 1935; Biswas 1936; Srinivasan 1965; Gandhi 1983a†; Kumawat et al. 2008
32	*Gomphonema constrictum* Ehr. v *capitata* (Ehr.) Cl.	Gandhi 1960a; Gandhi 1983a†; Sarode and Kamat 1984; Kumawat et al. 2008
33	*Gomphonema constrictum* Ehr. v. *indica* Gandhi*	Gandhi 1960a; Sarode and Kamat 1984; Kumawat et al. 2008
34	*Gomphonema constrictum* Ehr. v. *capitatum* Cleve. f. *italica* Kuetz.	Kumawat et al. 2008
35	*Gomphonema constrictum* Ehr. v. *capitatum* Cleve. f. *turgida* Mayer	Kumawat et al. 2008
36	*Gomphonema dharwarensis* Gandhi*	Gandhi 1956; Srinivasan 1965
37	*Gomphonema dichotomum* Kütz.	Ehrenberg 1845; Grunow 1865;
38	*Gomphonema dubia* Meister	Meister 1932
39	*Gomphonema dubravicense* Pant.	Gandhi 1998
40	*Gomphonema geminatum* Ag. v. *hybrida* Grun.	Gandhi 1983a†
41	*Gomphonema ghosea* Abdul-Majeed*	Abdul-Majeed 1935
42	*Gomphonema gracile* Ehr.	Ehrenberg 1845; Carter 1926; Krishnamurthy 1954; Gandhi 1955; Gandhi 1957a; Gandhi 1959c; Gandhi 1960a; Gandhi 1962a; Singh 1962; Singh 1963; Gandhi 1966; Srinivasan 1965; Sarode and Kamat 1984; Gandhi 1998; Kumawat et al. 2008
43	*Gomphonema gracile* Ehr. f. *turris* (Ehr.) Hust.	Sarode and Kamat 1984
44	*Gomphonema gracile* Ehr. v. *auritum* A.Br.	Gandhi 1960a; Gandhi 1966; Sarode and Kamat 1983; Sarode and Kamat 1984; Prasad and Srivastava 1992
45	*Gomphonema gracile* Ehr. v. *dichotomum* (W.Smith) Cleve	Thomas and Gonzalves 1965d
46	*Gomphonema gracile* Ehr. v. *frickei* Gandhi*	Gandhi 1960a; Sarode and Kamat 1984
47	*Gomphonema gracile* Ehr. v. *hybridum* A.Cl.	Sarode and Kamat 1984
48	*Gomphonema gracile* Ehr. v. *intricatiforme* May.	Sarode and Kamat 1983; Sarode and Kamat 1984
49	*Gomphonema gracile* Ehr. v. *lanceolata* (Kütz.) Cl.	Krishnamurthy 1954; Gandhi 1960a; Sarode and Kamat 1984; Kumawat et al. 2008
50	*Gomphonema gracile* Ehr. v. *major* Grun.	Thomas and Gonzalves 1965b; Sarode and Kamat 1984; Kumawat et al. 2008
51	*Gomphonema gracile* Ehr. v. *naviculoides* (W.Sm.) Grun.	Gandhi 1960a; Gandhi 1962b; Sarode and Kamat 1983; Sarode and Kamat 1984; Kumawat et al. 2008
52	*Gomphonema gracile* Ehr. v. *subcapitata* Gandhi*	Sarode and Kamat 1984; Gandhi 1960a; Kumawat et al. 2008
53	*Gomphonema grovei* M.S	Gandhi 1983a†; Gandhi 1998†
54	*Gomphonema grovei* M.S v. *conspicua* Gandhi et al.*	Gandhi 1983a†; Gandhi 1998†
55	*Gomphonema grovei* M.S v. *lanceolata* Gandhi et al.*	Gandhi 1983a†; Gandhi 1998†
56	*Gomphonema grovei* M.S v. *rhomboidea* Gandhi et al.*	Gandhi 1983a†; Gandhi 1998†
57	*Gomphonema hebridense* Ehr.	Gandhi 1970; Sarode and Kamat 1980; Sarode and Kamat 1983 ; Sarode and Kamat 1984; Prasad and Srivastava 1992; Kumawat et al. 2008

Table 1 continued.

	Species name	Reference
58	*Gomphonema intermedium* Hust.	Prasad and Srivastava 1992
59	*Gomphonema intricatum* Kütz.	West and West 1907; Abdul-Majeed 1935; Krishnamurthy 1954; Gandhi 1958a; Gandhi 1960a; Gandhi 1983a†; Gandhi 1985†; Sarode and Kamat 1984; Gandhi 1998†
60	*Gomphonema intricatum* Kütz. v. *dichotoma* (Kütz.) Grun.	Gandhi 1983a†; Gandhi 1985†; Gandhi 1998†
61	*Gomphonema intricatum* Kütz. v *vibrio* Cl. f. *subventricosa* Gandhi*	Gandhi 1962b
62	*Gomphonema intricatum* Kütz. v. *bohemicum* (Reich. et Fricke) A.Cl.	Gandhi 1958a; Sarode and Kamat 1984
63	*Gomphonema intricatum* Kütz. v. *fossile* Pant.	Sarode and Kamat 1980; Sarode and Kamat 1983; Sarode and Kamat 1984
64	*Gomphonema intricatum* Kütz. v. *pumila* Grun.	Singh 1962; Sarode and Kamat 1984
65	*Gomphonema intricatum* Kütz. v. *pusillum* May.	Sarode and Kamat 1983; Gandhi 1970; Prasad and Srivastava 1992
66	*Gomphonema intricatum* Kütz. v. *vibrio* (Ehr.) Cl.	Venkataraman 1939; Gandhi 1959b; Gandhi 1960a; Sarode and Kamat 1980; Sarode and Kamat 1984; Kumawat et al. 2008
67	*Gomphonema lacus-rankala* Gandhi*	Gandhi 1958a; Gandhi 1964; Srinivasan 1965; Sarode and Kamat 1984; Gandhi 1998
68	*Gomphonema lacus-rankala* Gandhi v. *gracilis* Gandhi*	Gandhi 1962b; Gandhi 1964; Gandhi 1967; Gandhi 1970; Sarode and Kamat 1980; Sarode and Kamat 1984; Gandhi 1998; Kumawat et al. 2008
69	*Gomphonema lacus-rankala* v. *chandolensis* Gandhi*	Gandhi 1964; Gandhi 1998; Kumawat et al. 2008
70	*Gomphonema lacus-rankala* Gandhi v. *robusta* Gandhi*	Gandhi 1958a; Sarode and Kamat 1980; Sarode and Kamat 1983; Sarode and Kamat 1984; Gandhi 1998; Kumawat et al. 2008
71	*Gomphonema lapponicum* A.Cleve	Kumawat et al. 2008
72	*Gomphonema lanceolatum* Ehr.	Grunow 1865; Carter 1926; Venkataraman 1939; Gandhi 1958a; Gandhi 1959c; Gandhi 1960a; Gandhi 1960b; Gandhi 1962a; Gandhi 1962b; Gandhi 1964; Gandhi 1966; Gandhi 1967; Gandhi 1983a†; Sarode and Kamat 1983; Sarode and Kamat 1984; Prasad and Srivastava 1992; Kumawat et al. 2008
73	*Gomphonema lanceolatum* Ehr. v. *insingis* (Greg.) Cl.	Venkataraman 1939; Gandhi 1955; Gandhi 1960a; Gandhi 1966; Sarode and Kamat 1983; Sarode and Kamat 1984; Prasad and Srivastava 1992
74	*Gomphonema lanceolatum* Ehr. f. *turris* (Ehr.) Hust.	Gandhi 1959b
75	*Gomphonema lanceolatum* Ehr. v. *affine* (Kütz.) A.Cl.	Gandhi 1957b; Gandhi 1960b; Sarode and Kamat 1984
76	*Gomphonema lingulatum* Hust.	Gandhi 1960a; Sarode and Kamat 1984
77	*Gomphonema longiceps* Ehr.	Krishnamurthy 1954
78	*Gomphonema longiceps* Ehr. v. *subclavata* Grun.	Krishnamurthy 1954; Sarode and Kamat 1983
79	*Gomphonema longiceps* Ehr. v. *subclavata* Grun. f. *gracilis* Venkataraman*	Venkataraman 1956
80	*Gomphonema macropunctatum* Krishnamurthy*	Krishnamurthy 1954; Srinivasan 1965
81	*Gomphonema magnifica* Gandhi*	Gandhi 1960a; Srinivasan 1965; Sarode and Kamat 1984; Kumawat et al. 2008

82	*Gomphonema magnifica* Gandhi v. *rhomboida* Gandhi*	Gandhi 1960a; Sarode and Kamat 1984
83	*Gomphonema major* A.Cl.F. *unipuncta* A.Cl.	Thomas and Gonzalves 1965c
84	*Gomphonema martini* Fricke	Sarode and Kamat 1984; Gandhi 1960a
85	*Gomphonema moniliforme* Gandhi*	Gandhi 1960a; Srinivasan K.S. 1965; Sarode and Kamat 1984
86	*Gomphonema montanum* Schum	Gandhi 1960a; Gandhi 1964; Sarode and Kamat 1984
87	*Gomphonema montanum* Schum v. *acuminatum* May.	Gandhi 1956; Gandhi 1960a; Gandhi 1960b; Gandhi 1964; Gandhi 1967; Sarode and Kamat 1980; Sarode and Kamat 1983; Sarode and Kamat 1984; Gandhi 1998; Kumawat et al. 2008
88	*Gomphonema montanum* Schum v. *acuminatum* May. f. *indicum* Sarode et Kamat*	Sarode and Kamat 1984; Kumawat et al. 2008
89	*Gomphonema montanum* Schum v. *acuminatum* May. f. *maharashtrensis* Sarode et Kamat*	Sarode and Kamat 1980; Sarode and Kamat 1984
90	*Gomphonema nagpurense* Sarode et Kamat*	Sarode and Kamat 1984
91	*Gomphonema olivaceoides* Hust.	Sarode and Kamat 1984
92	*Gomphonema olivaceum* (Lung.) Kütz.	Biswas 1936; Krishnamurthy 1954; Gandhi 1958a; Gandhi 1960a; Singh 1962; Singh 1963 Sarode and Kamat 1980; Gandhi 1985†; Sarode and Kamat 1984; Prasad and Srivastava 1992
93	*Gomphonema olivaceum* (Lyng.) Kütz. v. *calcarea*	Krishnamurthy 1954;
94	*Gomphonema olivaceum* (Lyng.) Kütz. v. *balticum* Cl.	Krishnamurthy 1954; Gandhi 1956
95	*Gomphonema olivaceum* (Lyng.) Kütz. v. *genuinum* Mayer. f. *minutula* Mayer	Kumawat et al. 2008
96	*Gomphonema oregonicum* Ehr.	Grunow 1865
97	*Gomphonema parvulum* (Kütz.) Grun.	Grunow 1865; Skvortzow 1935; Venkataraman 1939; Gandhi 1955; Gandhi 1957a; Gandhi 1958b; Gandhi 1959a; Gandhi 1959c; Gandhi 1960a; Gandhi 1960b; Singh 1961; Gandhi 1962a; Gandhi 1966; Gandhi 1967; Sarode and Kamat 1980; Sarode and Kamat 1983; Sarode and Kamat 1984; Prasad and Srivastava 1992; Gandhi 1998; Kumawat et al. 2008
98	*Gomphonema parvulum* (Kütz.) Grun. v. *lagenula* (Grun.) Hust.	Gandhi 1960a; Gandhi 1962b; Gandhi 1966; Sarode and Kamat 1983; Sarode and Kamat 1984; Kumawat et al. 2008
99	*Gomphonema parvulum* (Kütz.) Grun. v. *micropus* (Kütz.) Cl.	Gandhi 1960a; Gandhi 1960b; Gandhi 1962b; Gandhi 1966; Sarode and Kamat 1983; Sarode and Kamat 1984; Prasad and Srivastava 1992
100	*Gomphonema parvulum* (Kütz.) Grun. v. *subellipticum* Cl.	Gandhi 1956; Gandhi 1957a; Gandhi 1958b; Gandhi 1960a; Gandhi 1960b; Gandhi 1966; Sarode and Kamat 1983; Sarode and Kamat 1984; Kumawat et al. 2008
101	*Gomphonema parvulum* (Kütz.) Grun. v. *subcapitata* V.H.	Venkataraman 1957
102	*Gomphonema parvulum* (Kütz.) v. *exlissma* Grun.	Gandhi 1959c; Gandhi 1962b; Gandhi 1964; Gandhi 1967; Sarode and Kamat 1983; Sarode and Kamat 1984; Prasad and Srivastava 1992; Gandhi 1998; Kumawat et al. 2008;
103	*Gomphonema parvulum* (Kütz.) V.H. v. *genuinium* May.	Gandhi 1956

Table 1 continued.

	Species name	Reference
104	*Gomphonema punctatum* Krasske	Kumawat et al. 2008
105	*Gomphonema saravanthense* Gandhi*	Gandhi 1970
106	*Gomphonema sphaerophorum* Ehr.	Krishnamurthy 1954; Gandhi 1957a; Gandhi 1958b; Gandhi 1959c; Gandhi 1960a; Gandhi 1964; Srinivasan 1965; Gandhi 1966; Sarode and Kamat 1980; Sarode and Kamat 1983; Sarode and Kamat 1984; Prasad and Srivastava 1992; Kumawat et al. 2008
107	*Gomphonema sphaerophorum* Ehr. v. *kolhapurense* Sarode et Kamat*	Sarode and Kamat 1984; Kumawat et al. 2008
108	*Gomphonema sphaerophorum* Ehr. v. *subcapitata* Venkatraman*	Venkataraman 1939; Thomas and Gonzalves 1965a
109	*Gomphonema sphaerophorum* f. *jogensis* Gandhi*	Gandhi 1966
110	*Gomphonema spiculoides* Gandhi*	Srinivasan 1965; Gandhi 1960a; Sarode and Kamat 1984
111	*Gomphonema spiculoides* Gandhi v. *major* Gandhi*	Gandhi 1960a; Sarode and Kamat 1984
112	*Gomphonema subapicatum* Fiitsch et Rich v. *okamurae* (Skv) Gandhi	Gandhi 1960a; Sarode and Kamat 1984
113	*Gomphonema subapicatum* Fritsch et Rich	Abdul-Majeed 1935; Gandhi 1956; Gandhi 1958a; Gandhi 1960a; Gandhi 1960b; Gandhi 1962b; Gandhi 1964; Gandhi 1966; Gandhi 1967; Sarode and Kamat 1984; Gandhi 1998
114	*Gomphonema subcapitatum* v. *curta* Fritsch et Rich	Abdul-Majeed 1935
115	*Gomphonema subclavatum* Grun.	Carter 1926; Abdul-Majeed 1935
116	*Gomphonema submalayense* Gandhi*	Gandhi 1970
117	*Gomphonema substicature* Fritsch v. *stipitata*	Abdul-Majeed 1935
118	*Gomphonema subtile* Ehr.	Gandhi 1958b; Gandhi 1962a; Gandhi 1966; Sarode and Kamat 1984
119	*Gomphonema subtile* Ehr. v. *malayensis* Hust.	Gandhi 1960a; Gandhi 1966; Gandhi 1970; Sarode and Kamat 1984; Prasad and Srivastava 1992
120	*Gomphonema subventricosum* Hust.	Gandhi 1962a; Gandhi 1966; Sarode and Kamat 1984; Prasad and Srivastava 1992
121	*Gomphonema sumatrense* Fricke	Gandhi 1960a; Sarode and Kamat 1984
122	*Gomphonema tenellum* W.Sm.	Dickie G 1882; West and West 1907; Gandhi 1998
123	*Gomphonema tenuis* Gandhi*	Gandhi 1960a; Srinivasan 1965; Sarode and Kamat 1984
124	*Gomphonema tergestinum* (Grun.) Frickie	Krishnamurthy 1954
125	*Gomphonema tropicale* Brun	Gandhi 1959b
126	*Gomphonema turris* Ehr.	Ehrenberg 1845; Grunow 1865
127	*Gomphonema undulatum* Hust.	Gandhi 1960a; Sarode and Kamat 1984
128	*Gomphonema varanasis* Singh*	Singh 1961
129	*Gomphonema vastum* Hust *v elongata Skv.*	Gandhi 1958b
130	*Gomphonema vidarbhense* Sarode et Kamat*	Sarode and Kamat 1984

Naphrax mounting medium and observed with Olympus BX-51 light microscopes equipped with DIC and 1.4NA objectives. Digital images were taken with an Olympus DP-71 digital camera. Scanning electron microscopy was done with cleaned specimens air dried onto cover glasses, attached to aluminum stubs, sputter-coated with 10 nm of Au-Pd, and examined in high vacuum mode with a JSM-6480LV (LVSEM) at 15 kV, with a spot size of 15, and a working distance of 8 mm. SEM work was performed at the University of Colorado's Nanomaterials Characterization Facility. In India, SEM work was accomplished with cleaned material air-dried onto cover glasses and sputter coated with ca. 10 nm of Au-Pd. Coated material was viewed in a FEI Quanta 200 ESEM at Indian Institute of Science Nanoscience Initiative Facility. Terminology on the diatom valves follows Ross et al. (1979). For features found in the gomphonemoid diatoms, we follow the terminology and character descriptions of Kociolek & Stoermer (1993). Water chemistry analysis were carried out as per the Standard methods for water and waste water analysis by American Public Health Association (APHA, 2005)

Results

Gomphonema gandhii Karthick & Kociolek, **sp. nov.** Figs 2–19

Descriptio: Valvae lineares ad lineares-lanceolatae clavatae apicibus rotundatis ad anguste-rotundatis ad fere acuminatae capitolo-polo. Area apicalis porellorum distincta ad baso-polo. Frustula aspectu cincturae cuneata. Striae continuae circa capitulum-polum. Longitudo 19–51 µm. Latitudo 3–7 µm. Area axialis lata linearis-lanceolata. Area centralis indistincta. Raphe lateralis undulata. Extrema proximales externi raphis dilatatae. Externum orificium stigmatis rotundatis. Striae punctatae leviter radiatae ad parallelae, 9–11/10 µm. Septa et pseudosepta prasentia ad polos.

Description: Valves linear- to linear-lanceolate-clavate, with apices rounded to narrowly-rounded to nearly acuminate at the headpole. Apical pore field distinct at the footpole. Frustules cuneate, striae are continuous around the headpole. Length 19–51 µm, breadth 3–7 µm. Axial area broad, linear-lanceolate. No distinct central area. Raphe lateral, undulate. External proximal raphe ends dilated. Stigmal opening is round. Striae are punctate, slightly radiate to parallel, 9–11/10 µm. Septa and pseudosepta are present at the poles.

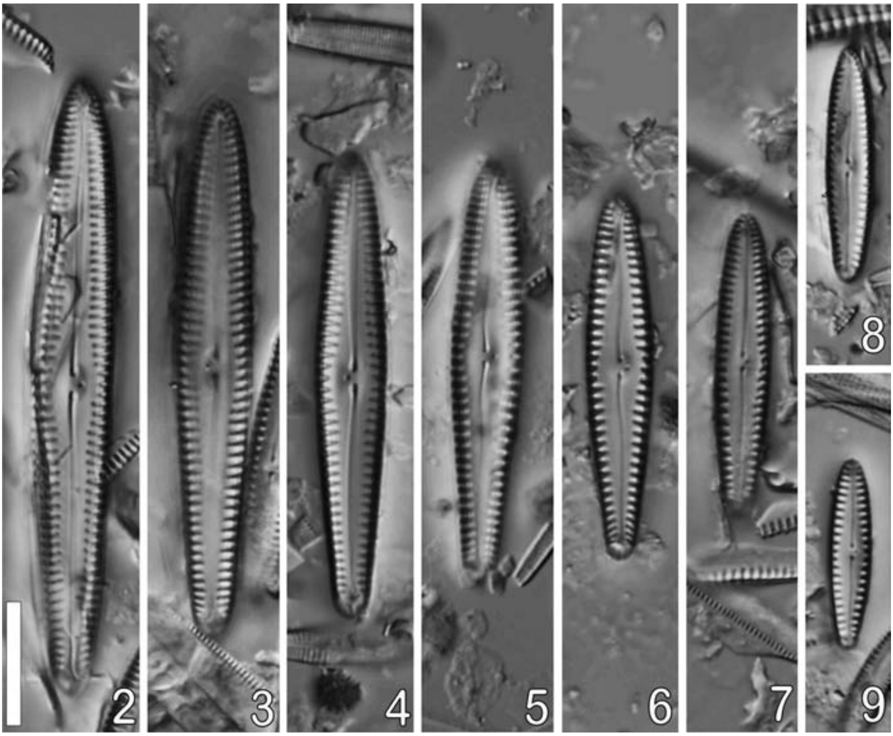
Holotype: CESH-5-1869, Centre for Ecological Science Herbarium Diatom Collection, Indian Institute of Science, Bangalore, INDIA.

Isotypes: BM 101392. The Natural History Museum, Department of Botany, London, UK and Diatom Collection, University of Colorado, Boulder, USA

Type Locality: A Stream at Kammani (14°42' 47.52"N–74°35' 44.988"E); Altitude 109 m asl (meters above sea level), a tributary Bedthi River. Uttara Kannada District, Karnataka, India. (leg. Karthick, B. and D.M.Vishnu, January 2006)

Etymology: Named in honor of H.P.Gandhi, for his outstanding contributions to diatom research in India.

In the SEM, the exterior of the valve is dominated by areolae with flaps that form c-shaped openings (Figs 10–13). The undulate raphe has dilated proximal ends, while the external ends are deflected onto the mantle in the same direction (opposite the side bearing the stigma) (Figs 10, 13). The external stigmal opening is small and round (Figs 10, 12). The apical pore field is separated from the striae, and composed of rounded porelli (Figs 10, 13, 15). Internally, a small central nodule, relatively large helictoglossae, pseudosepta and the raphe slit are visible (Figs 16, 17, 18, and 19). The central nodule has highly recurved raphe ends that terminate as tight loops. A flap extends from each side of the central nodule, obscuring part of the curvature

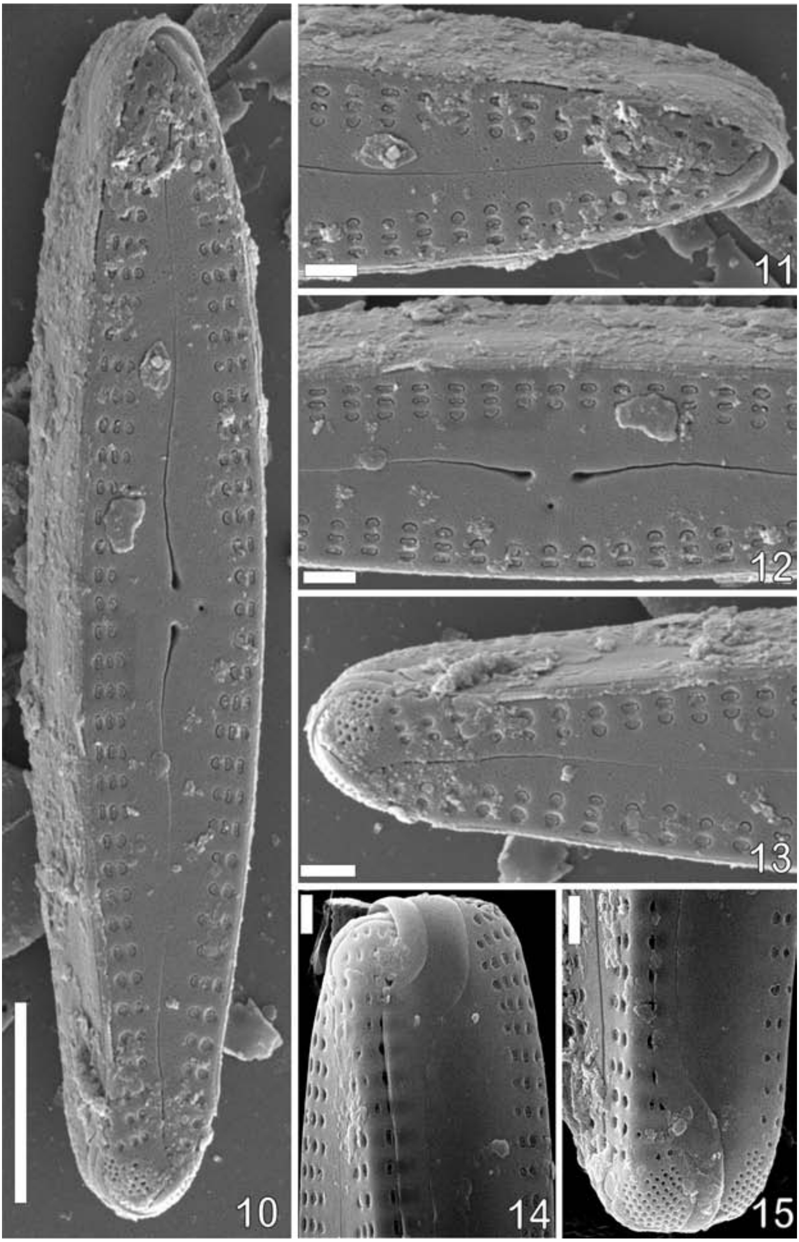


Figs 2–9. LM of *Gomphonema gandhii,* from the type population; valve views showing the size diminution series. Scale bar represents 10 µm.

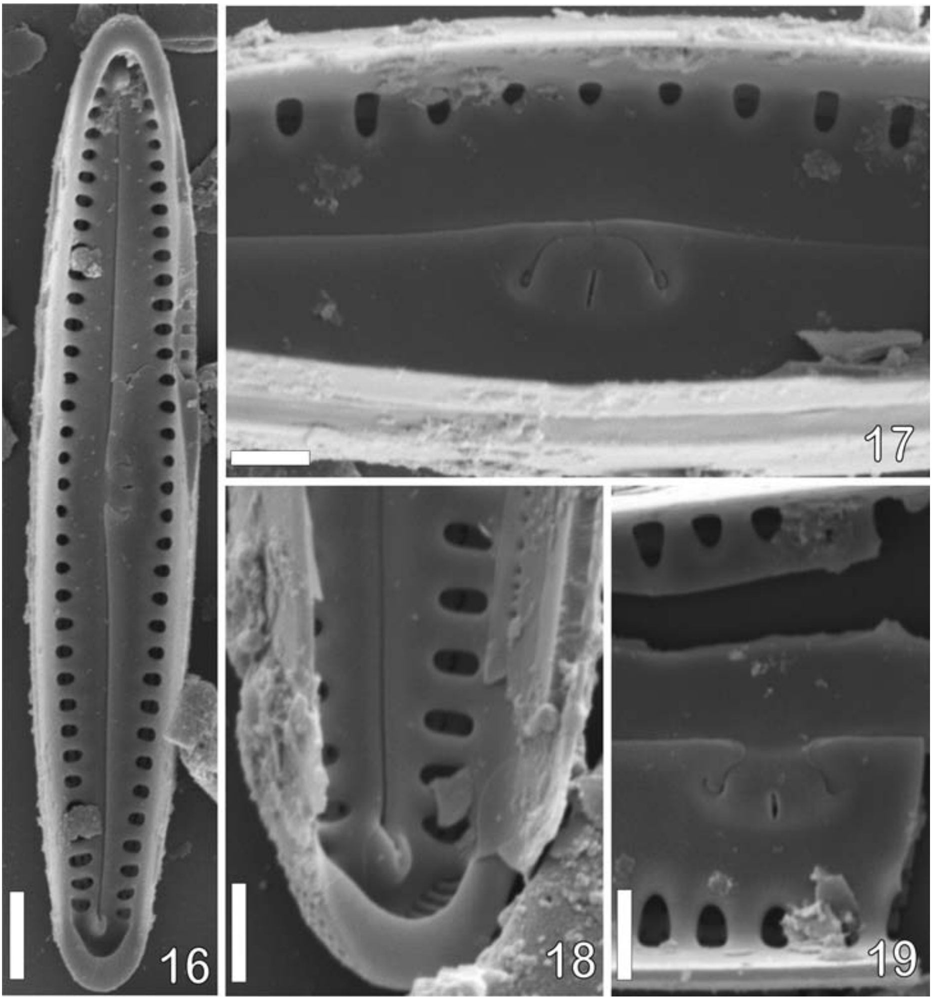
of the raphe (Figs 16, 17, 19). A slit-like stigmal opening is present on the small central nodule (Figs 16, 17, 19). On either side of the valve interior, marginal laminae are present (Figs 16). Helictoglossae appear to be in line with each raphe branch (Figs 16, 18).

In girdle view, the apical pore field porelli are round, extending from the edge of the valve face and to the end of the mantle (Fig. 15). Bands are of the open type, and narrow; they follow the contour of the valve in girdle view. At the headpole the distal raphe end can be seen extending onto the mantle (Fig. 14). Areolae appear sunken into ellipsoidal depressions, in each of which is a flap (Figs 14, 15).

This species resembles both *G. pararhombicum* Reichardt, Jüttner & Cox and *G. incognitum* Reichard, Jüttner & Cox (Jüttner et al. 2004, p. 238). All three taxa have a similar valve outline and wide axial area. *Gomphonema gandhii* is more slender, has a narrower headpole and coarser striae than either of the species described from Nepal. The expanded concept of *G. incognitum* suggested by Reichardt (2005) is difficult to embrace, since specimens with very different valve shapes, sizes and striae densities have been considered conspecific. Coarser striae and more slender valves also distinguish *G. gandhi* from *G. siamense* Reichardt, and valve shape



Figs 10–15. SEM. External view of *Gomphonema gandhii.* Fig. 10. Exterior view of whole valve. Fig. 11. Exterior of valve, headpole, with the external distal raphe end curving onto the valve mantle. Fig. 12. Exterior of valve center showing the stigma, dilated proximal raphe end and striae. Fig. 13. Exterior of valve showing the deflected apical end of raphe and rounded porelli. Fig. 14. Girdle view of the head pole showing the distal raphe end extending on to the mantle. Fig. 15 Girdle view of the foot pole with round apical pore field porelli. Scale bar represents 5µm (Fig. 10); 1 µm (Figs 11, 12, 13, 14, 15).



Figs 16–19. SEM. Internal view of *Gomphonema gandhii*. Fig. 16. Interior view of the whole valve showing the central nodule, large helictoglossae, pseudosepta and raphe slit. Fig. 17. Interior view of the center showing the central nodule, curvature of raphe and slit like stigmal opening. Fig. 18. Internal view showing the helictoglossae, pseudosepta and raphe slit. Fig. 19. Internal view of center showing the curvature of the raphe and slit-like stigmal opening. Scale bar represents 2 μm (Fig. 16); 1 μm (Figs 17, 18, 19).

(lacking the cuneate headpole) and coarser striae separate the Indian species from *G. uniserhombicum* Reichardt (2005).

ECOLOGY: *Gomphonema gandhii* is found throughout the central Western Ghats rivers. This species is present throughout the year, reaching maximum relative abundance (60%) in September. The population of this species increases in winter season (Oct–Jan). This species occurs in abundance in many hill streams of central Western

Table 2. Water Chemistry Characteristics (Mean ± Standard Deviation) for the type localities measured from January to December 2006.

Water Chemistry Characters (Units)	**Kammani**	**Andhalli**
pH	7.08±0.17	7.16±0.27
Water Temperature (°C)	26.66±2.20	24.96±1.90
Electrical Conductivity (μScm^{-1})	89.86±26.18	79.71±11.12
Total Dissolved Solids (mgl^{-1})	44.62±13.09	39.63±5.78
Air Temperature (°C)	30.54±2.94	26.25±2.97
Free Carbon di oxide (mgl^{-1})	8.53±3.02	9.83±3.55
Alkalinity (mgl^{-1})	33.27±16.29	47.00±42.67
Chlorides (mgl^{-1})	13.00±3.17	14.82±3.19
Hardness (mgl^{-1})	33.78±14.38	28.87±4.16
Calcium (mgl^{-1})	7.32±3.34	6.63±1.37
Magnesium (mgl^{-1})	6.46±2.75	5.43±1.04
Dissolved Oxygen (mgl^{-1})	7.88±1.40	6.83±2.54
Phosphates (mgl^{-1})	0.04±0.02	0.08±0.08
Nitrates (mgl^{-1})	0.29±0.37	1.12±1.87
Sulphates (mgl^{-1})	8.58±3.00	21.09±26.94
Sodium (mgl^{-1})	7.62±2.26	13.59±1.85
Potassium (mgl^{-1})	1.64±0.60	3.15±1.17

Ghats region. This species occurs in circumneutral streams (pH: 7.08 ± 0.17) with poor nutrients (Phosphate: 0.04 ± 0.02 mgl^{-1}; Nitrates: 0.29 ± 0.37 mgl^{-1}) and conductivity between 89.86 ± 26.18 μScm^{-1} (see Table 2). The land cover in the catchment is characterized with wet evergreen to semi-evergreen forest type, and with least agricultural activities.

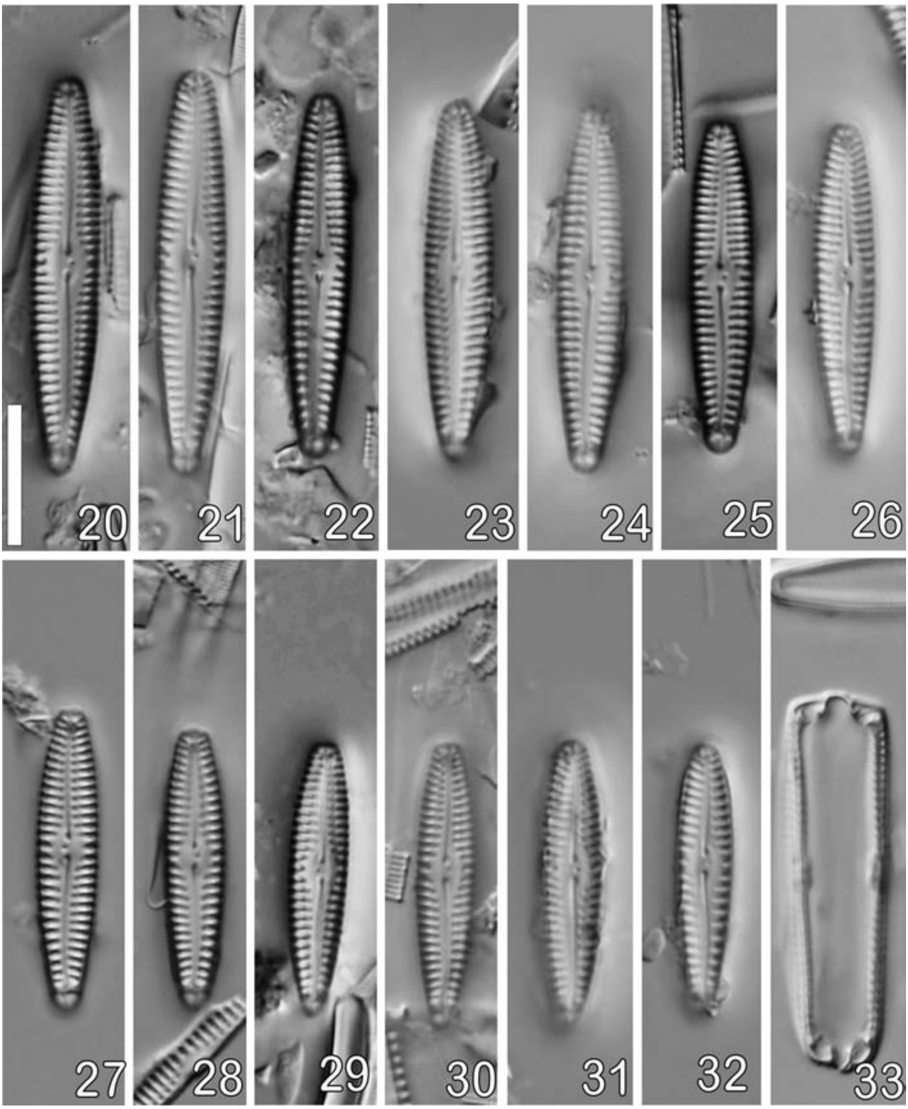
Gomphonema difformum Karthick & Kociolek, **sp. nov.** Figs 20–40

DESCRIPTIO: Valvae linearers-clavatae apicibus late rotundatibus ad quadratis ad capitolo-polo. Area apicalis porellorum distincta ad bsao-polo. Frustula cuneatum. Striae non-continuae circa capitulum-polum. Longitudo 19–32 µm. Latitudo 4–6 µm. Area axialis angusta dilatatescens dilute, faciens aream centralem linearem-ellipticalem. Raphe lateralis, dilute undulata. Extrema proximales externi raphis distincte dilatata. Striae aspectu costae, parallelae ad dilute radiatae 12–14/10 µm. Externum orificium stigmatis parvum rotundatis praesens in aream centralem. Area bilobata unornata ad capitolo-polo. Septa et pseudosepta prasentia ad polos.

DESCRIPTION: Valves linear-clavate, apices broadly rounded to quadrate at the headpole. Apical pore field distinct at the footpole. Frustules cuneate. Striae do not appear continuous around headpole. Length 19–32 µm, breadth 4–6 µm. Axial area narrow, expanded slightly to form a linear-elliptical central area. Raphe lateral, weakly undulate. External proximal raphe ends distinctly dilated. Striae appear costate, parallel to weakly radiate, 12–14/10 µm. A small round stigmal opening is present in the central area. A bilobed unornamented area is present at the headpole. Septa and pseudosepta are present at both poles.

HOLOTYPE: CESH-5-1870, Centre for Ecological Science Herbarium Diatom Collection, Indian Institute of Science, Bangalore, INDIA

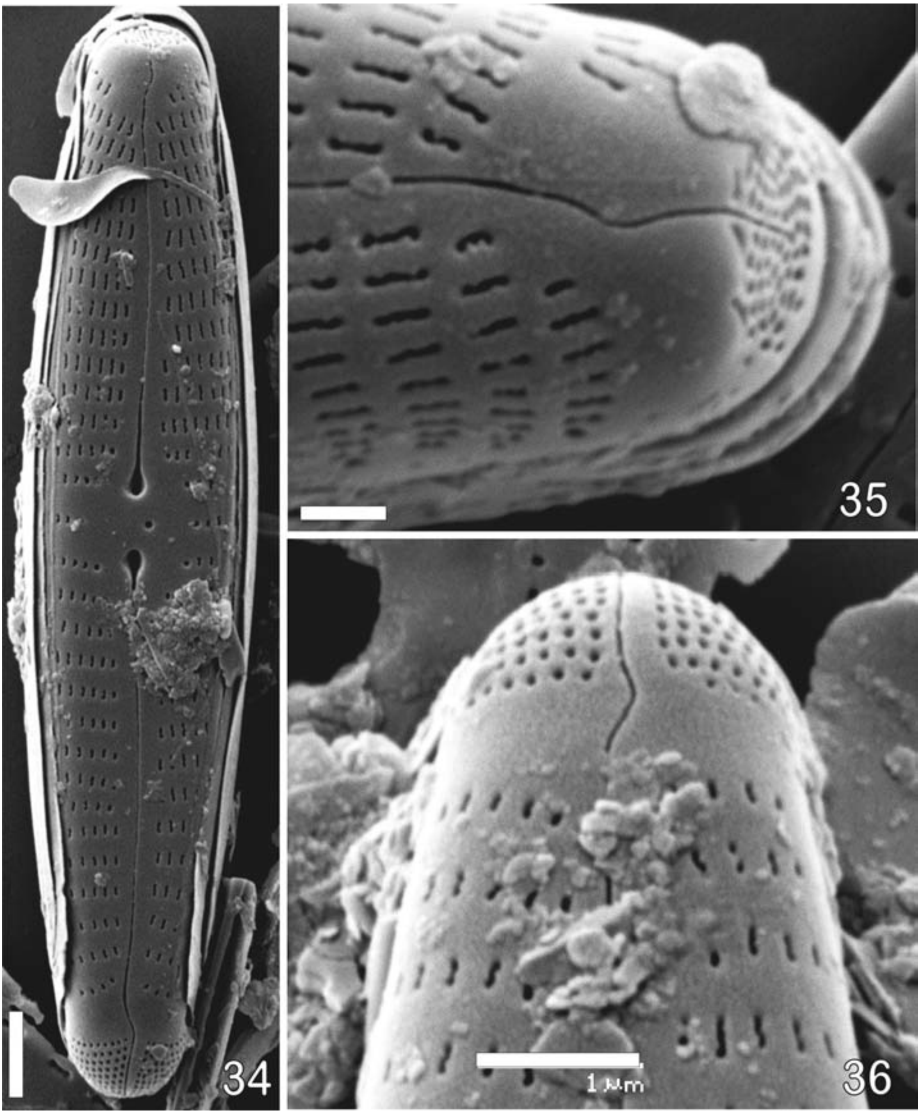
ISOTYPES: BM 101393, The Natural History Museum, Department of Botany, London, UK. And Diatom Collection, University of Colorado, Boulder, USA.



Figs 20 –32. LM of *Gomphonema difformum,* from the type population; valve view showing the size diminution series. Figure 33. Girdle view showing apical pore field like structures at both apices. Scale bar represents 10 µm.

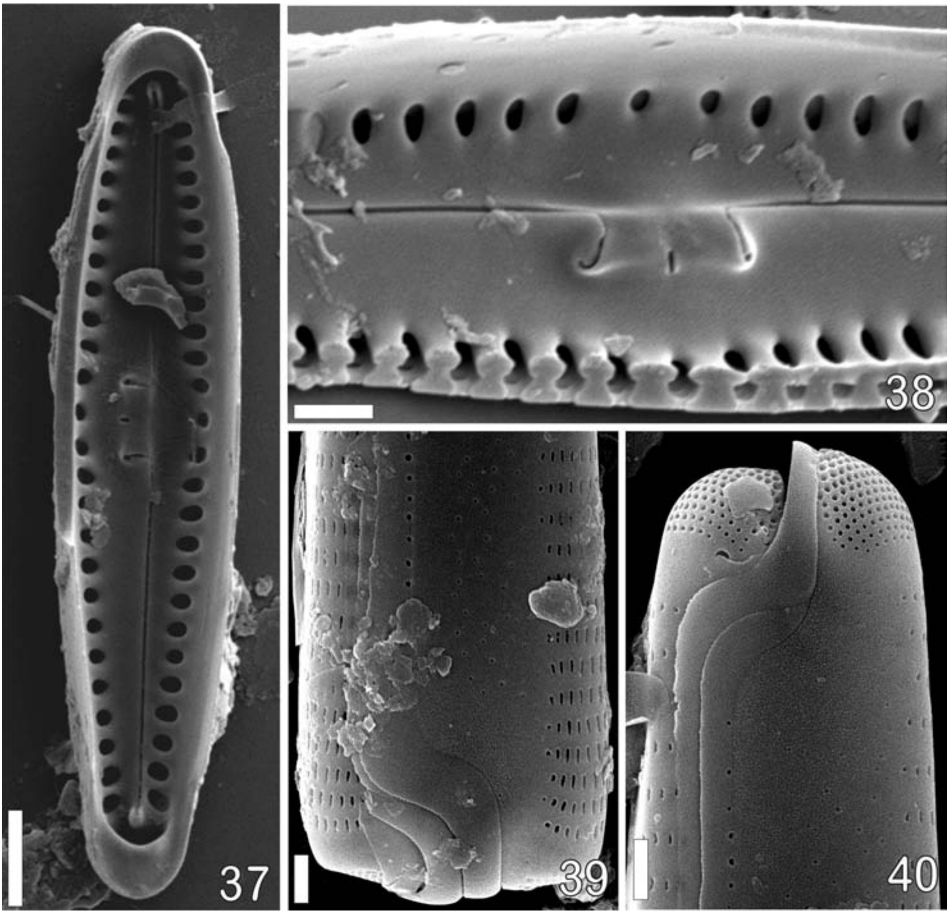
TYPE LOCALITY: A Stream at Andhalli (14°40'12.1794"N–74°48'5.904"E; Altitude 483 mtrs above MSL), a tributary Bedthi River. Uttara Kannada District, Karnataka, India. (leg. Karthick, B. and D.M.Vishnu -12th, January, 2006)

ETYMOLOGY: The species epithet indicates the very different structure of this diatom relative to other members of the genus.



Figs 34–36. SEM. External view of *Gomphonema difformum.* Fig. 34. Exterior view of whole valve showing slit-like areolae, round stigma opening and undulate raphe with dilated proximal ends. Fig 35. Exterior view of the valve showing blunt headpole. Fig 36. Exterior view of the valve showing raphe bends onto the mantle, porelli and hyaline area which separates porelli from areolae. Scale bar represents 2 µm (Fig. 34); 1 µm (Fig. 36); 0.5 µm (Fig. 35)

In the SEM, the valve exterior is dominated by slit-like areolae, a slightly undulate raphe with dilated proximal ends and a bilobed apical pore field (Figs 34–36). The central area has large, tear-dropped shaped proximal raphe ends and a small, round



Figs 37–40. SEM. Interior and girdle view of *Gomphonema difformum.* Fig. 37. Interior view of the whole valve showing pseudosepta at both ends and large helictoglossae. Fig. 38. Interior view showing the central nodule with broadly recurved proximal raphe ends, rounded stigmal opening and marginal lamina. Fig. 39. Girdle view showing randomly distributed porelli on the mantle Fig. 40. Girdle view showing the open type bands with septa. Scale bar represents 2 μm (Fig. 37); 1 μm (Figs 38, 39, 40).

stigmal opening (Fig. 34). The apical pore field is composed of round porelli that are both physically separated and morphological distinct from the areolae (Figs 34, 36). The headpole looks blunt, where the interface between the valve face and mantle is abrupt (Figs 34, 35). The raphe bends onto the mantle, and bisects a group of porelli-like pores that are both physically separate and morphologically differentiated from the areolae (Figs 34, 36). Porelli extend from the valve face onto the mantle (Figs 34, 36, 40). Internally, the proximal raphe ends are broadly recurved on a central nodule that appears composed of two internally-elevated sections. Between the sections is situated a rounded stigmal opening (Figs 37, 38). Along the mantle on each side is a marginal lamina (Fig. 38). Helictoglossae are relatively large, and the one positioned at the headpole is usually offset from the raphe branch (Fig. 37). Pseudosepta are visible at each pole (Fig. 37).

In girdle view the mantle has round porelli randomly distributed across it. Bands are of the open type, with the closed ends also bearing septa (Figs 39, 40). The bands follow the valve outline in girdle view.

This taxon resembles *Gomphonema kaznakowi* Meresch. in that the headpole looks similar in structure to the footpole. In both *G. kaznakowi* and G. *difformum*, the headpole striae are physically separated from the striae. In *G. difformum*, the headpole has porelli-like openings, very similar to the porelli of the apical pore field at the footpole; this condition is not seen in *G. kaznakowi* (Kociolek 1996; Li et al. 2006).

Ecology: *Gomphonema difformum* is known only from the type locality. This species is present throughout the year with relative abundance of 20% and less. This species occurred in a stream with neutral pH (7.16 ± 0.27), poor nutrients (Phosphate: 0.04 ± 0.02 mgl^{-1}; Nitrates: 0.29 ± 0.37 mgl^{-1}) and conductivity between 79.71 ± 11.12 μScm^{-1} (see Table 2). The land cover in the catchment is characterized with wet evergreen to semi-evergreen forest type with moderate agricultural activities.

Gomphonema diminutum Karthick & Kociolek, **sp. nov.** Figs 41–51

Descriptio: Valvae anguste lineares-clavatae apicibus rotundatibus. Longitudo 21–27 µm. Latitudo 3–4 µm. Area axialis angusta linearis. Area centralis indistinctis. Raphe lateralis undulata. Externum orificium stigmatis rotundatis. Area apicalis porellorum distincta bilobata. Septa et pseudosepta praesentia ad polos.

Description: Valves narrowly linear-clavate with apices rounded. Length 21–27 µm, breadth 3–4 µm. Axial area narrow, linear. Central area indistinct. Raphe lateral, undulate. External proximal raphe ends dilated. A round stigmal opening is present. Striae are parallel to radiate, 16–17/10 µm. Apical pore field evident, bilobed. Septa and pseudosepta are present at the poles.

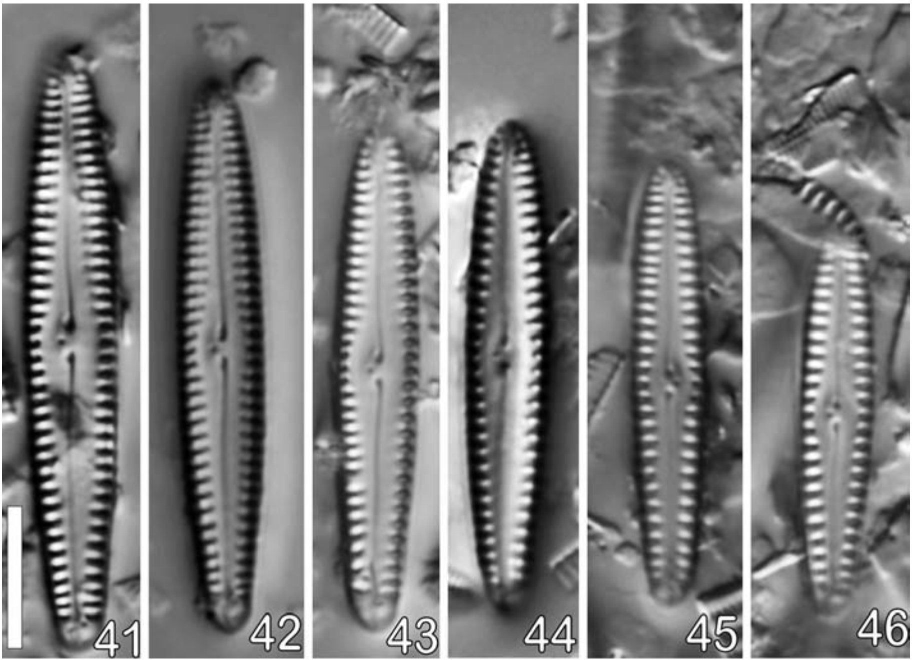
Holotype: CESH-5-1871, Centre for Ecological Science Herbarium Diatom Collection, Indian Institute of Science, Bangalore, INDIA

Isotypes: BM 101394, The Natural History Museum, Department of Botany, London, UK. Diatom Collection, University of Colorado, Bolder, USA

Type Locality: A Stream at Kammani (14°42'47.52"N–74°35'44.988"E); Altitude 109 m asl, a tributary Bedthi River. Uttara Kannada District, Karnataka, India. (leg. Karthick, B. and D.M.Vishnu, January, 2006).

Etymology: The species is named for its small size.

In the SEM, the valve exterior has areolae that are slit- or c-shaped on the valve face, but on the mantle striae are composed of two rows of rounded areolae (Figs 47, 48). The raphe appears slightly undulate with enlarged proximal raphe ends. A small, round external stigmal opening is present in the central area (Figs 47, 48). At the footpole, the apical pore field is physically offset from the areolae by a hyaline border. Porelli are round, sembling in size and shape the last stria near the hyaline area. At the headpole areolae are rounded and in double rows, like those on the mantle (Figs 47 and 49). Internally, the central nodule is bilobed, hosting the broadly recurved proximal raphe ends. In the middle of the central nodule is placed an



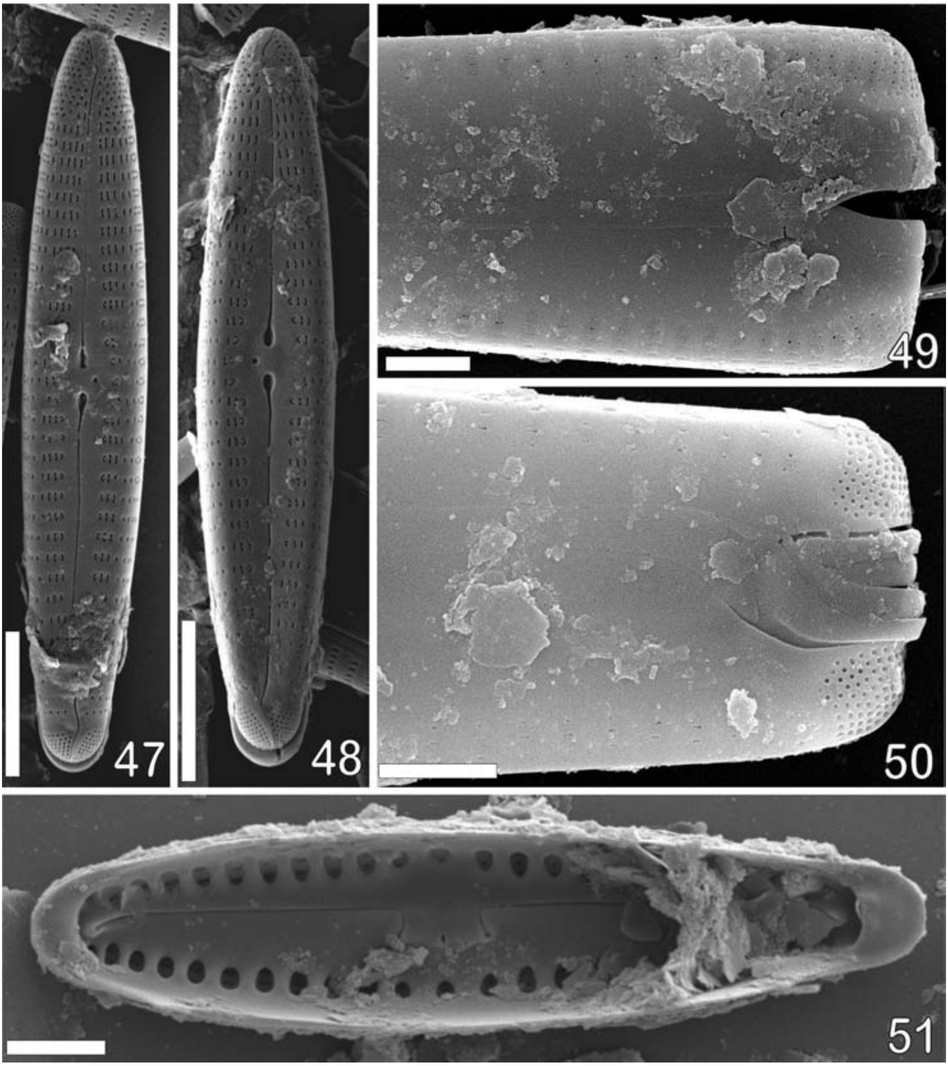
Figs 41–46. LM of *Gomphonema diminutum,* from the type population; valve view showing the size diminution series. Scale bar represents 10 μm.

ellipsoidal stigmal opening (Fig. 51). Marginal laminae are present on each side of the valve (Fig. 51). Helictoglossae at the headpole and footpole are offset from the raphe branches. Pseudosepta are present at the poles (Fig. 51).

In girdle view the mantle of the valve has striae with areolae that terminate as slits or in double rows of punctate striae. Striae have round areolae at the headpole (Fig. 49). At the footpole the round apical pore field porelli extend onto to the end of the mantle (Fig. 50). Girdle bands are of the open type, following the contour of the valve. Closed ends of the bands possess septa.

Gomphonema diminutum resembles *G. incognitum* Reichardt, Jüttner & Cox in Jüttner et al. (2004, p. 245) in size range and having a wide axial area. The species from India is linear in shape, is narrower and has finer striae than the species described from Nepal. Superficial resemblance in terms of having a broad axial area exists between *G. diminutum* and *G. schweickerdtii* Cholnoky (which was, in part, recently suggested to be conspecific with *G. clevei* Fricke, Reichardt 2005), but the Indian species is longer but narrower than the South African taxon (Cholnoky 1953).

ECOLOGY: *Gomphonema diminutum* was found in many central Western Ghats Rivers. This species was present throughout the year with relative abundance ranging from 20–40%. This species occurred in a stream with circumneutral pH (7.08 ± 0.17), poor nutrients (Phosphate: 0.04 ± 0.02 mgl^{-1}; Nitrates: 0.29 ± 0.37 mgl^{-1}) and



Figs 47–51. SEM. Exterior, Interior, Girdle view of whole valve of *Gomphonema diminutum.* Figs 47–48. Exterior view of whole valve showing slit or c-shaped areolae, mantle striae with two rows of rounded areolae, hyaline border, a stigmal opening and proximal raphe ends. Fig. 49. Girdle view of the valve showing doubly punctate striae with rounded areolae at headpole. Fig. 50. Girdle view of the valve showing open type girdle bands and closed ends of bands with septa. Fig 51. Internal view of the valve showing central nodule with stigmal opening, marginal laminae, pseudosepta and helictoglossae at both the poles. Scale bar represents 5 µm (Figs 47, 48); 2 µm (Fig. 51); 1 µm (Figs 49, 50).

conductivity between 89.86 ± 26.18 μScm^{-1} (see Table 2). The land cover in the catchment is characterized with wet evergreen to semi-evergreen forest type with the least agricultural disturbance.

Discussion

Our work on the present group of species contributes to a growing opinion that endemism in freshwater diatoms, particularly those based in Southern Hemisphere locations, may be much more common than was previously thought (e.g., Mann & Droop 1996, Mann 1999, Kociolek & Spaulding 2000, Kociolek & Stoermer 2001, Kilroy et al. 2003, Vanormelingen et al. 2008). However, recent taxonomic work on selected diatom taxa from Himalayas (Jüttner et al. 2004) and the current study has led to the recognition of an increasing number of endemic taxa in the freshwater diatom flora of the Indian subcontinent, particularly biodiversity hotspots like Western Ghats and Eastern Himalayas. Based on unpublished work by Karthick (Ph.D. Dissertation on Ecology of Stream Diatom Community in Central Western Ghats, to be submitted to Mysore University), some of the *Gomphonema* species found in the Western Ghats are widespread on other continents, but a few others, particularly those in streams of Western Ghats, seem to have limited geographical distributions. India has a diverse flora, but there is still a lot to do to document and create a more substantial understanding of this large and complex country. The three new species presented here occur in several environments, and are the dominants or represent a large proportion of the diatoms present in the collections. While there have been many (over 100) *Gomphonema* taxa reported from India, it still does not approach the number recorded from the intensely studied continent of Europe (e.g. Krammer & Lange-Bertalot 1986, e.g. Reichardt 1999) or the little studied country of the USA (Kociolek 2005, lists 237 *Gomphonema* taxa reported in the literature).

Of the three new species, *G. difformum* is quite different from almost all other *Gomphonema* species. Of particular note is the presence of what appears to be apical pore fields at both the headpole and footpole. Our observations illustrate at the headpole, groups of pores on the mantle at either side of the external distal raphe end that are separate from and quite dissimilar to the areolae. Their oblong to rounded appearance is more similar to the porelli of the apical pore fields at the footpole than the slit-like areolae found in *G. difformum*. Structures similar to apical pore fields at the headpole are also seen in *G. kaznakowi*, described from high mountain sites from China (Mereschkowsky 1906). Kociolek (1992) showed with electron microscopy that hyaline areas at the headpole of this species were composed of densely arranged areolae, that were physically separate from valve face areoale, but not structurally differentiated from nor more compact (at least in terms of the porelli found at the footpole) than the valve areolae. *Gomphonema difformum* differs from *G. kaznakowi* by a number of features, most notably by possessing a stigma and having external proximal raphe ends that are quite dilated. *Gomphonema gandhii* has a unique feature, namely the presence of a hood or siliceous fold over the central nodule, the edge of which is suggestive of the internal proximal raphe ends. In this feature it looks very similar to *Gomphocymbella* species from the East African Rift Valley lakes (Kociolek & Stoermer 1993); the feature is found in no other freshwater gomphonemoid diatoms. *Gomphonema diminutum* seems to be closely allied with species described from the Himalayas, though more work is necessary to affirm their relationships. For example, though not described nor illustrated in the original work, it appears that the Himalayan species do have both septa and pseudosepta. These features have been overlooked by many students of the genus *Gomphonema* (e.g. Patrick in Patrick & Reimer 1966, Reichardt 2005, 2007). These similarities with species from a variety of areas support the idea of biogeographic distributions that have a phylogenetic basis. Williams & Reid (2006) have addressed this issue amongst the Eunotioid diatoms. These three new species occur in oligotrophic, low conductivity, pH neutral water, whereas the commonly reported *Gomphonema* species in Southern India, such as *G. parvulum, G. gracile, G.affine, and G. pseudoaugur,* occur in eutrophic, alkaline and high conductivity, waters. The distribution ranges of all three species were restricted to Western Ghats streams; hence these three species appear to be endemic to Western Ghats. However studies on diatoms in peninsular India are meager and it is too early to comment on the distribution of these species.

A phylogenetic analysis based on morphological data is necessary to further confirm the relationships of these three taxa with African and Himalayan taxa. The data from fossil and contemporary faunas indicate that, throughout the late Cretaceous, India maintained biological exchanges with adjacent lands (Briggs 2003). This could be a reason for these species connection with the African and Himalayan species. The biotic components of Africa, Madagascar and Western Ghats have inspired centuries of speculation relating to the mechanisms by which these biotas came to reside in these regions, and regarding their commonalities. Most of the authors claim that the most probable causal factors are Gondwanan vicariance and/or Cenozoic dispersal (Yoder & Nowak 2006). It would be interesting to study further on diatom flora of Western Ghats in detail and compare them with Indian Ocean islands and African species to elucidate their biogeographic history.

While recent researches on diatom taxonomy from tropical regions are challenging the ubiquity hypothesis for diatoms, they also seem to confirm that diatom communities are controlled by the same processes affecting macro-organisms in a different scale (Vanormelingen et al. 2008). These studies therefore also highlight the need for conservation and the protection of unique and isolated areas, such as Western Ghats, against habitat alterations and introduction of exotic species. Thus, it is important for future studies of diatom biodiversity to include the mechanisms generating diatom species diversity and distributions. Previous reports of *Gomphonema* taxa from Western Ghats are from light microscope observations and therefore are subject to further verification. The current report improves our knowledge of status, and phylogentic relation of *Gomphonema* and the biodiversity of freshwater diatoms of Western Ghats. These current results underscore the pressing need to continue research into diatom taxonomy and ecology in least explored geographical zone on earth particularly southern hemisphere.

Acknowledgements

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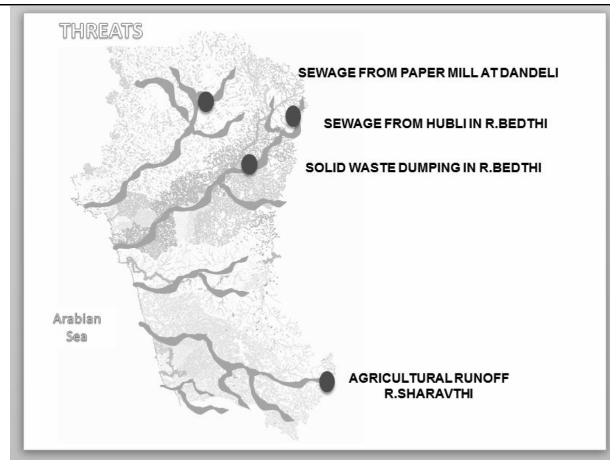
THREATS
SEWAGE FROM PAPER MILL AT DANDELI
SEWAGE FROM HUBLI IN R.BEDTHI
SOLID WASTE DUMPING IN R.BEDTHI
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