The health of benthic diatom assemblages in lower stretch of a lesser Himalayan glacier-fed river, Mandakini

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This study examines the ecological state of epilithic diatom assemblages along the lower stretch of Mandakini, a glacier-fed Himalayan river. The diatoms were sampled at four stations during winter and summer, only once in each season. Valve counts were obtained from Naphrax mounts prepared from each sample. Assemblages were recorded for each location. The software OMNIDIA Ver. 5.3 was used for computing the ecological values from the sample counts. Normally *Achnanthidium* spp. dominated the assemblages, except *Nitzschia fonticola* (Grunow) at S1 (Kund) and *Encyonema minutum* (Hilse in Rabh) at S4 (Rudraprayag), only during summer. The ecological values revealed that the assemblages were in β-mesosaprobic and mésotraphentic states. However, at S4, trophic state was observed to be eutraphentic. Louis Leclercq index indicated that organic pollution was nonexistent, while the anthropogenic eutrophication was low except at S2 (Tilwara) and S3 (Medanpur) in summer and was moderate at S4 in winter characterized by a lean flow. The most abundant indicator taxa for anthropogenic eutrophication are varied; *Cymbella tumida* (Brebisson-Van Heurck) at S1, *Encyonema minutum* at S2, S4 while *Surirella aungusta* (Kutzing) at S3. Ordination showed that the taxa indicating degradation and anthropogenic eutrophication figured as characteristic taxa at respective locations.

1. Introduction

Diatoms are effective biological indicators for monitoring the changes in water quality because they respond and integrate the effects of changes in their environment and, for this reason, they need not be sampled as often as chemical parameters (Dixit *et al.* 1992). Diatom indices have been developed to monitor eutrophication (Descy and Coste 1990; Van Dam *et al.* 1994; Kelly and Whitton 1995), organic pollution (Watanabe *et al.* 1986) and human disturbance (Fore and Grafe 2002), and recently, they have been widely applied for biomonitoring of the river/streams, assess ecological conditions and monitor environmental changes during the routine water quality surveys in Europe, North America, Australia, New Zealand, Japan, India and Brazil (Prygiel *et al.* 1999; Stevenson and Pan 1999; Hill *et al.* 2000; Potapova and Charles 2002; Chessman and Townsend 2010; Rimet 2012; Alakananda *et al.* 2013; Moresco and Rodrigues 2014). In view of the above studies, it has been found that diatoms are one of the suitable biological components determining the ecological condition of river/streams. However, the paucity of studies on the health of diatom assemblages in the south-Asian Himalayan countries has hindered their use as indicators in this region. This study

Keywords. *Achnanthidium* spp.; anthropogenic eutrophication; degradation; ecosystem health; mésotraphentic; PCA; spatial distribution.

was meant to record the health of diatom assemblages and hence, the ecological state of the river Mandakini. This river is impacted by agriculture, small rural habitations and mushrooming infrastructure for pilgrims (mostly hotels, restaurants of all dimensions) and hydropower development along the Rudraprayag–Kedarnath NH-109 (route to the Kedarnath shrine), alongside the river. The flood fury on 16–17 June, 2013 in the Mandakini river eroded the banks and devastated the human habitations and supporting infrastructure in the lower stretch. Since some hydroelectric projects are under construction on the river and few others are proposed in the Mandakini basin, river health will be a future issue. This study will provide basic information on the river ecosystem health for future comparisons.

2. Study area

The river Mandakini is a glacier-fed tributary of the river Alaknanda (figure 1). River Mandakini originates from the Mandakini glacier (a part of Chaurabari glacier) and flows down to 630 m within 100 km to form confluence with the Alaknanda at Rudraprayag. The river course has very high gradient (82.6 m km^{-1}) from source to Gaurikund at 1999 m (ca. 20 km apart), moderate (24.8 m km^{-1}) till Kund at 1008 m (ca. 40 km

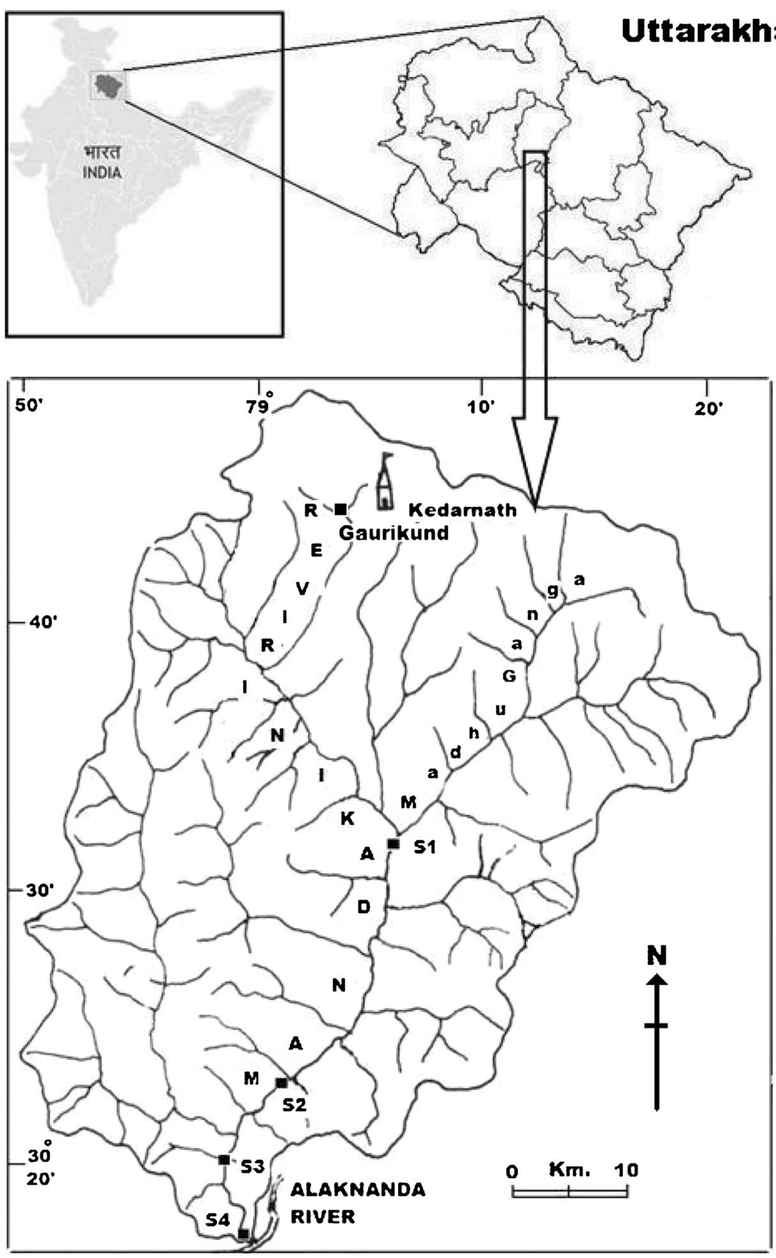

Figure 1. Location of the study area in India. The sampling stations S1–S4 are indicated on the river Mandakini.

Table 1. *Geographical co-ordinates of the river Mandakini at different stations. The range of physico-chemical characteristics at different stations during winter and summer seasons.*

Parameters	Kund (S1)	Tilwara (S2)	Medanpur (S3)	Rudraprayag (S4)
Landuse type	Type I	Type II	Type III	Type IV
Riparian vegetation	Forest	Agriculture	–	–
Latitude (N)	30°30′	30°20′	30°18′	30°17′
Longitude (E)	79°01′	78°38′	78°58′	78°57′
Altitude (m)	1008	707	640	630
Depth range (m)	0.20–50	0.20–70	0.35–0.75	0.40–1.2
Seasonal variation in water temperature June –December (°C)	16–9.5	18.5–10	21–10	22–11.5
Substratum	R>B	B>C>P	C>B>P	C>P>B

Type I: open forest; Type II: small town in forested landscape; Type III: village with adjacent agriculture and forested slopes; Type IV: larger town on forested slopes; SF: slow flow; FF: fast flow; R: rock; B: boulder; C: cobble; P: pebble.

apart) and low (10.8 m km^{-1}) till Rudraprayag (ca. 35 km apart). Several semi-urban habitations along the NH-109 occur at regular frequency from Gaurikund to Kund. Urbanized villages and towns occur from Kund to Rudraprayag as the river valley widens and mountain slopes become gentle. The present study was performed in the lower stretch of the Mandakini at four stations from Kund to Rudraprayag. The selected locations lie between latitudes of 30°30′–30°17′N and longitudes of 79°01′48″–78°57′E at an elevation range of 1008–630 m above msl (mean sea level). Sampling locations and other physical and chemical characteristics are summarized in table 1. The land use comprises forest at S1, forest-small town at S2, forest-agriculture at S3 and forest-large town at S4 (figure 1).

3. Materials and methods

Each sampling station was sampled once in summer (4–5 June 2007) and in winter (10–11 December 2007), representing a major dry period (9 months – October to June) and with relatively stable composition of flora and fauna in contrast to disturbed period during the monsoon months (July–September; Ormerod *et al.* 1994; Jüttner *et al.* 2003).

The sampling was restricted to shallow waters (<30 cm). The epilithic diatom samples were obtained by scraping a 3 cm^2 area of the cobble surface from two different current velocities (flow conditions: FF, SF) at different points in the stream at each station as diatom communities were expected to differ. The range of fast and slow flows (current velocities) varied from 30 to 50 and 10 to 30 cm sec^{-1}, respectively. The flows were measured with the help of EMCON current velocity meter. Two replicates of the samples were taken from each substrate and integrated for further analysis. The volume of the sample varied from 3 to 5 ml. Samples were preserved in 4% formaldehyde solution. The acid–peroxide treated samples were used to prepare permanent diatom mounts in Naphrax that were later examined under bright-field using a BX-40 Trinocular Olympus microscope (×10 and ×15 wide field eyepiece) fitted with a PLANAPO ×100 oil immersion objective used to enumerate diatom valves using standard literatures (Hustedt 1931–59; Krammer and Lange-Bertalot 1986–1991, 1999; Lange-Bertalot 2001; Krammer 2002, 2003). The slides are kept at the Aquatic Biodiversity Unit, Department of Zoology and Biotechnology.

The relative abundance (in %) was determined on the basis of 300 valves from each sample at each station. Variations in the taxon with >10% relative abundance were recorded to determine the assemblages. The water temperature (WT) was analyzed using a digital probe (Mextech, multimeter), pH by digital pocket meter (Hanna) and current velocity (CV) by EMCON water current meter. Dissolved oxygen (DO) was measured by Winkler's methods while, total alkalinity (TA; Kit No. HANHI 3811), total hardness (TH; Kit No. HANHI 3812), chloride (Kit No. HANHI 3815) and silicates (Kit No. HANHI 38076) were determined with the help of various Hanna kits. Nitrate and phosphate were measured by photocolorimeter ESICO model No. 1313.

3.1 *Data analysis for characteristic taxa, saprobic and trophic state*

The data analysis was based on the number of diatom taxa present in the assemblages. Principal component analysis (PCA; CANOCO Ver. 4.5) was performed to determine the characteristic taxa in respective sampling location, season and flow conditions. The OMNIDIA software Ver. 5.3 output provides various metrics of water quality through the indices and ecologic characteristics. The ecological information given by diatoms is usually summed up through one or more diatom-based indices, which indicates the trophic level with just one number, suitable for biomonitoring lakes and rivers. However, the purpose of this study is to know the ecological state of the river and not just the water quality. The ecologic values of Van Dam *et al.* (1994) assess the pH, salinity (S), nitrogen uptake (NU), oxygen requirements (OR), saprobity (SP), trophic state (TS) and moisture (M) conditions of the diatom community. The water quality is indicated by the saprobic and trophic states. The Lange-Bertalot's and Hofmann's values confirmed the findings of Van Dam. Each parameter is measured on a scale of 1–7. Barring pH which scales acidic to alkaline conditions, other parameters in this index indicate increase in degradation with an increase in numeric index value. Lange-Bertalot's tolerance, Hofmann's trophic state and saprobic conditions, Hakansson et Denys values for pH, habitat and tolerance characteristics were also determined. OMNIDIA was also used to compute degradation (D) using IDSE/5 and Louis Leclercq indications for organic pollution (OP) and anthropogenic eutrophication (AE) that were expressed as NE – nonexistent; L – low; M – moderate; H – high. OMNIDIA is considered suitable because the diatoms have wide distribution and thus same species exist wherever the ecological conditions are similar. Further, there is established role of the proximate factors (water chemistry, substrate, current velocity) though a high proportion of geographically restricted diatoms also exist (Kociolek and Spaulding 2000; Potapova and Charles 2002).

4. Results

4.1 *Physico-chemical characteristics*

The minimum water temperature was same at all stations while maximum value increased downstream of S1 but for slight decrease at S4 due to sampling in morning hours compared to early to late noon at other locations. A general increase was observed in the current velocities from S1 to S4. A decreasing trend was observed for dissolved oxygen from S1 to S4, while there was an increasing trend for transparency. The chemical characteristics like pH, conductivity, total hardness and total alkalinity were almost similar from S1 to S4 (figure 2).

4.2 *Diatom assemblages*

The diatom assemblages varied with respect to season and flows (table 2). During winter, FF was characterized by co-dominance of *Achnanthidium biasolettianum* (Grunow) and *Achnanthidium minutissimum* (Kützing) in the assemblages from S1 to S3. These two taxa also formed assemblage at S4, with *Achnanthidium biasolettianum* being dominant and *Achnanthidium minutissimum* subdominant. Therefore, the assemblages were identical at S1 and S3 but differed at S2 due to additional co-dominants and at S4 where a subdominant was also present (table 2). The SF during winter were highly variable; *Achnanthidium biasolettianum* and *Achnanthidium minutissimum* figured as dominant–subdominant at S1, *Achnanthidium subhudsonis* (Hustedt) at S2, no dominance at S3 and only *A. biasolettianum* at S4.

During summer, each station was characterized by different assemblages in both fast and slow flow conditions. Notably, *Achnanthidium biasolettianum* and *Achnanthidium minutissimum* were part of all the assemblages *albeit* as subdominants except at S3 where *Achnanthidium biasolettianum* and *Achnanthidium minutissimum* were dominant and subdominant, respectively with *Achnanthidium subhudsonis* in both fast and slow flows (table 2). Further, *Achnanthidium minutissimum* dominated the assemblage in slow flow at S1 and fast flow at S2.

If the assemblages are viewed across the spectrum of seasons and flows, then winter assemblages were dominated by *Achnanthidium biasolettianum–Achnanthidium minutissimum* in both FF and SF, while during summer, *Nitzschia fonticola* (Grunow) dominated assemblage in FF but *Achnanthidium minutissimum* in SF. The assemblages at S2 differed across the season and flow spectrum while at S3 *Achnanthidium biasolettianum–Achnanthidium minutissimum* dominated assemblages were peculiar to both flows and seasons. At S4, *Achnanthidium biasolettianum* continued to dominate the assemblage during winter in both flows in contrast to *Encyonema minutum* (Hilse in Rabh), which dominated assemblage during summer in FF. No dominance was observed in SF at S4.

4.3 *Taxa associated with locations*

PCA indicated that axes 1 and 2 accounted 28.9% (eigenvalue 0.289) and 16.6% (eigenvalue 0.166) variance. The characteristic taxa differed with season, flow conditions and locations. *Synedra ulna* var. *dorsiventralis* (Otto Müller) was characteristic to SF during winter season at S1, while *Rhoicosphenia abbreviata* (C. Agardh) Lange-Bertalot was characteristic to SF during summer. Further, *Nitzschia fonticola* was also characteristic to FF during summer. At S2, *Gomphonema minutum* (Agardh) was characteristic to FF during summer, while *Encyonema minutum* was characteristic to FF during winter. At S3, *Adlafia miniscula* (Grunow) and *Achnanthidium subhudsonis* were characteristic to FF and SF conditions during

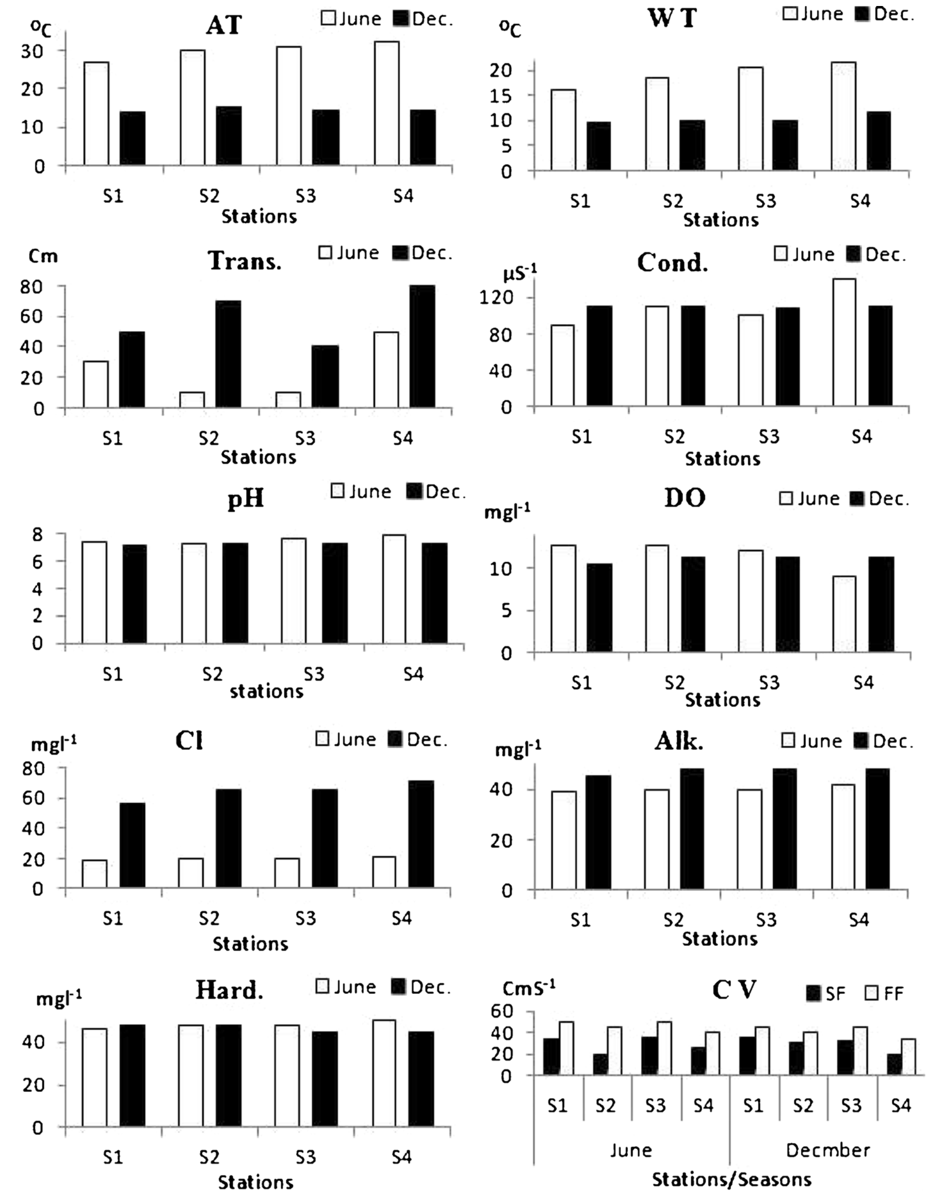

Figure 2. Seasonal variations in physico-chemical characteristics in the Mandakini river at different stations. (Alk.: alkalinity; AT: air temperature; Cl: chloride; Cond.: conductivity; CV: current velocity; DO: dissolved oxygen; Hard.: hardness, WT: water temperature; Trans.: transparency.)

Table 2. *Assemblages forming taxa along with their percentage composition at different stations in the river Mandakini.*

	Stations			
Flow condition	S1	S2	S3	S4
Winter				
FF	ABIA-AMIN: 17-17	ABIA-AMIN-ASHU-ENMI: 13-13-13-13	ABIA-AMIN: 13-13	ABIA-AMIN-SULN: 30-15-12
SF	ABIA-AMIN-DMES: 19-16-11	ASHU-ENMI-AMIN-ABIA: 17-15.5-14.6-12		ABIA: 28
Summer				
FF	NFON-ABIA-AMIN-ASHU: 22-13-13-11	AMIN-ASHU-ABIA: 17-15-13	ABIA-AMIN-ASHU: 19-17-14	ENMI-CTGL-ABIA-AMIN-ASHU: 20-15-14-12-10
SF	AMIN-ABIA-ESLE: 29-17-10	ABIA-ASHU-AMIN: 18-17-16	ABIA-AMIN-ASHU-CTGL: 18-17-15-15	

ABIA: *Achnanthidium biasolettianum*; AMIN: *Achnanthidium minutissimum*; ASHU: *Achnanthes subhudsonis*; CTGL: *Cymbella turgidula*; DMES: *Diatoma mesodon*; ENMI: *Encyonema minutum*; ELSE: *Encyonema silesiacum*; NFON: *Nitzschia fonticola*; SULN: *Synedra ulna*; SF: slow flow; FF: fast flow.

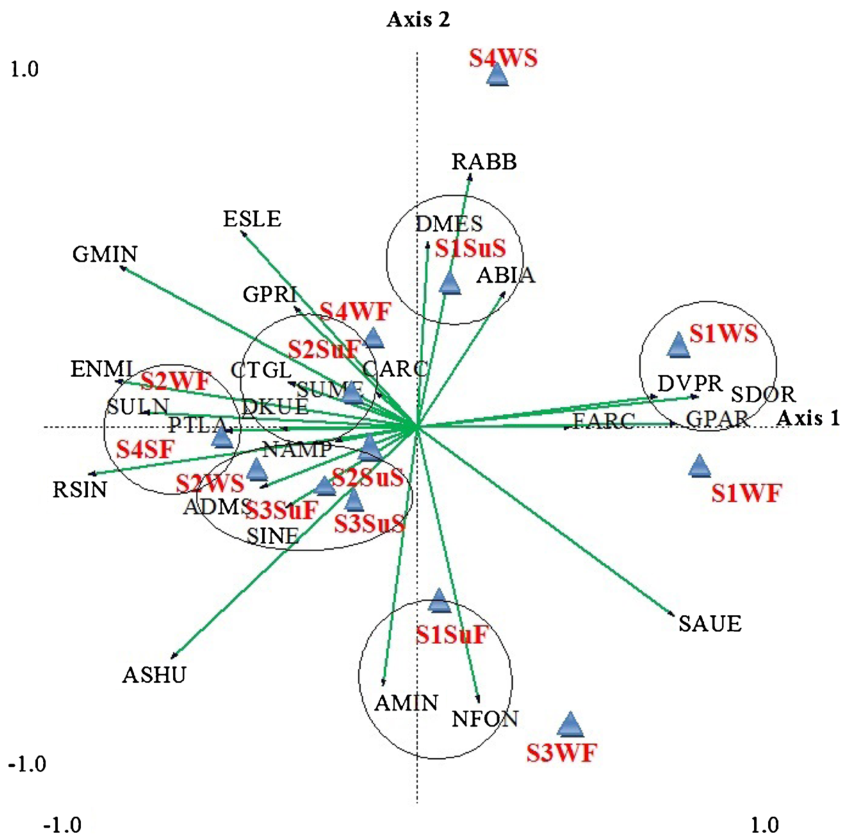

Figure 3. Principal component analyses to determine the characteristic taxa in the Mandakini river of Uttarakhand. The most characteristic taxon is indicated by long arrows closely associated with their respective landuse. (ABIA – *Achnanthidium biasolettiana*; ADMS – *Adlafia miniscula*; AMIN – *Achnanthes minutissima*; ASHU – *Achnanthes subhudsonis*; FARC – *Ceratoneis arcus* var. *recta*; CARC – *Ceratoneis arcus*; CTGL – *Cymbella turgidulla*; DKUE – *Denticula kuetzingii*; DMES – *Diatoma mesodon*; DVPR – *Diatoma vulgare* var. *producta*; ENMI – *Encyonema minutum*; ESLE – *Encyonema silesiacum*; GMIN – *Gomphonema minutum*; GPAR – *Gomphonema parvulum*; GPRI – *Gomphonema pumilum* var. *rigidum*; NAMP – *Nitzschia amphibia*; NFON – *Nitzschia fonticola*; PTLA – *Planathodium lanceolata* var. *lanceolata*; RABB – *Rhoecosphenia abbreviate*; RSIN – *Reimeria sinuate*; SINE – *Synedra inaequalis*; *Sus* – SSUE – *Synedra subequails;* SULN – *Synedra ulna*; SDOR – *Synedra ulna dorsiventralis*; SUME – *Synedra ulna* forma*mediocontracta*. W – winter, Su – summer, S – slow flow, F – fast flow. Landuse type details are given in table 1.)

summer. *Reimeria sinuata* (Gregory) Kociolek and Stoermer was also characteristic to S4 in FF during summer (figure 3).

4.4 *River health: Ecological state of the assemblages*

Diatom assemblages of the Mandakini river show the presence of alkaliphilous (pH), fresh-brackish conditions (salinity), nitrogen autotrophic taxa mostly tolerating the elevated concentration of organically bound nitrogen (nitrogen uptake), high O_2 supply (O_2 requirement, 100% saturation), β-mesosaprobous (saprobity; BOD 2–4 mg l^{-1}), and taxa mainly occurring in water bodies, also rather regularly on wet and moist places (table 3). The trophic status of the river is mainly meso-traphentic except at S1 (oligo to eutraphentic in FF during winter and SF during summer) and S4 (eutraphentic in SF during winter). Minor variations were recorded for some of the parameters (table 3). The Lange-Bertalot values accorded α-mesosaprobic status to assemblages at all stations and resembled the Hofmann's category of oligo-β-mesosaprob at most locations and flows except at S1 and S2 (mesosaprob/β-α-mesosaprob). Deny's values portray them as epontic life forms indifferent to the current.

Organic pollution (OP) was nonexistent (NE) all along the river. Degradation (D) was low at all stations but was NE at S1 and S2 during summer in SF (table 4). The AE was NE at S1 in both flows during winter and only in FF during summer but was low (L) in SF during summer at S1. At other three locations, the AE was low (L) irrespective of seasons and flows, except at S2 where AE increased and was observed to be moderate (M) even in the FF condition (table 4). During winter and SF condition, indicator taxa for organic pollution were same having variable abundance while indicator taxa for AE varied at all four stations (table 5).

Table 3. *Van Dam and other values depicting the ecological state of the river Mandakini at different stations with respect to flow conditions and seasons.*

	Winter							Summer						
	S1 F	S1 S	S2 F	S2S	S3F	S4 F	S4 S	S1 F	S1S	S2F	S2S	S3F	S3S	S4 F
Van Dam *et al.* (1994)														
pH	4	4	3	4	4	4	4	4	3	4	4	4	4	4
S	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Nu	2	1	2	2	2	2	2	2	2	2	2	2	2	2
Or	1	1	1	1	1	1	2	2	1	1	1	1	1	1
Sp	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Ts	**7**	3	3	3	3	3	**5**	3	**7**	3	3	3	3	3
M	3	3	3	3	3	3	2	3	3	3	2	3	3	2
Lange-Bertalot (1979)	5	5	5	5	5	5	5	5	5	5	5	5	5	6
Hofmann (1994)														
Ts	6	6	6	6	6	6	6	6	6	6	6	6	6	6
Sp	2	2	2	2	5	2	2	4	5	5	2	2	2	2
Håkansson (1993)														
pH	7	7	5	5	5	5	5	5	5	5	5	5	5	5
Denys (1991)														
LH	3	3	3	3	3	3	3	3	5	3	3	3	3	3
C	4	4	4	4	4	4	4	4	4	4	4	4	4	4

F: fast flow; S: slow flow. The abbreviations for the numbers are given in the description table.

Interpretation of the numeral values given in table 3.

pH	3/4	Circumneutral (mainly occurring at pH value 7)/alkaliphilous (mainly occurring at pH 7)
Salinity (S)	2	Fresh-brackish (chloride <500 mg l^{-1})
Nitrogen uptake (NU)	1/2	Nitrogen autotrophic taxa tolerating very small concentrations of organically bound nitrogen/nitrogen autotrophic taxa tolerating elevated concentrations of organically bound nitrogen
Oxygen requirements (OR)	1/2/3	O_2 continuously high (100% saturation)/fairly high (75% saturation)/moderate (50% saturation)
Saprobity (Sp)	1/2/3	Oligosaprobous (BOD < 2 mg l^{-1})/β-mesosaprobous (BOD: 2–4 mg l^{-1})/ α-mesosaprobous (BOD: 4–13 mg l^{-1})
Trophic state (TS)	2/3/4/5/7	Oligo-mésotraphentic/mésotraphentic/mésoeutraphentic/eutraphentic/ oligo–eutraphentic
Moisture (M)	1/2/3	Never or rarely occurring outside water bodies/mainly occurring in water bodies sometimes on wet places/mainly occurring in water bodies, also rather regularly on wet and moist places
Lange-Bertalot (1979)	1/2/5/6	Most pollution tolerant/α-mesosaprobic/more sensible (less frequent)
Hofmann (1994)		
Trophic state	5/6	Eutraphent/tolerant
Saprobity	2/3/5	Oligo-β-mesosaprob/mesosaprob/β-α-mesosaprob
Håkansson (1993)		
pH	3/5/6/7	Acidophilous/neutral circumstance/alkaliphilous to indifferent/alkaliphilous
Denys (1991)		
Lifeform habitat (LH)	3/4	Tychoplanktonic, epontic origin/tychoplanktonic, epontic origin
Current	4	Indifferent

5. Discussion

A variety of diatom indices were used for monitoring eutrophication, organic pollution and influence of land use on water quality of freshwater ecosystems (Watanabe *et al.* 1986; Whitton *et al.* 1991; Ormerod *et al.* 1994; Lobo *et al.* 1995; Whitton and Kelly 1995; Jüttner *et al.* 1996, 2003; Walsh and Wepener 2009; Bere and Tundisi 2011; Nautiyal and Mishra 2013). The present study focuses on the Van Dam criterion for assessing the ecological state of assemblages *vis-à-vis* river

Table 4. *OP, D and AE at various stations in the Mandakini river.*

Stations	Months	Flow	OP %	OP S	D C	A E %	A E State
S1	January	S	5.06	NE	L	6.96	NE
S1	January	F	3.74	NE	L	6.83	NE
S1	June	S	4.10	NE	NE	10.24	L
S1	June	F	8.82	NE	L	7.72	NE
S2	January	F	1.04	NE	L	14.84	L
S2	June	S	1.63	NE	NE	10.20	L
S2	June	F	1.66	NE	L	8.97	NE
S3	June	S	2.21	NE	L	8.46	NE
S3	January	S	5.85	NE	L	10.82	L
S3	June	F	1.38	NE	L	12.41	L
S4	January	S	7.59	NE	L	15.52	L
S4	January	F	2.40	NE	L	20.96	M

Note. D: degradation; OP: organic pollution; AE: anthropogenic eutrophication; NE: nonexistent; M: moderate, L: low; S: slow, F: fast.

Table 5. *Indicator taxa showing abundance for OP and AE at all four stations during winter season (January) and SF condition in the river Mandakini.*

Stations	OP Taxa	OP Abundance	AE Taxa	AE Abundance
S1	*GPAR-DVUL	9–8	*CTUM-FCAV-PLFR	13-11-7
S2	*GPAR	4	**ENMI-SULN	50-7
S3	*GPAR-DVUL	21–14	**SANG-CTUM-ENMI-FCVA	23-16-14-12
S4	NA		†ENMI- SULN -CTUM-NAAN	125-21-4-3

Note. *: NE; **: L; †: M. moderate. CTUM: *Cymbella tumida*; DVUL: *Diatoma vulgare*; ENMI: *Encyonema minutum*; FCVA: *Fragilaria capucina* var. *vauchariea*; GPAR: *Gomphonema parvulum*; NAAN: *Navicula aungusta*; PLFR: *Planathodium lanceolata* var. *fregnentissima*; SANG: *Surirella angusta*; SULN: *Synedra ulna.*

and Louis Leclercq indications for determining pollution, degradation and eutrophication caused by anthropogenic sources. The Van Dam ecologic values though developed for the European waters, can be suitably applied only in the Indian conditions, especially the Himalaya where the diatom flora of cold water glacier-fed rivers resemble temperate conditions. Though many new indices have been developed, the wide array of ecologic information generated by Van Dam criterion is valuable compared to the single values of other indices. However, the indices alone do not determine the water quality and water quality is not the only factor that determines the ecological status. Other factors such as the structure of the community or hydrodynamics of the ecosystem must also be taken into account.

The physical and chemical characteristics are governed by longitudinal gradient typical of a mountain river. Thus, the water temperature, transparency and current velocity increase while the solar radiation and dissolved oxygen decrease longitudinally from S1 to S4. Similarly, conductivity and total alkalinity (TA) vary slightly. There is notable increase in chloride ions from S1 to S4 attributed to the increase in frequency of human habitations along with agriculture in the rivers of Nepal Himalaya and across the rivers of whole Himalaya (Manel *et al.* 2000).

5.1 *Diatom assemblages*

The diatom assemblages are similar only in FF but differed in SF during winter from S1 to S4. During summer, the assemblages vary, both in FF and SF. Examination of the assemblages across the spectrum of seasons shows the influence of not only seasons but also flows, to some extent at S1 and S4 and to a greater extent at S2, while least at S3. Seasons had a greater influence on the assemblages, as they were similar in winter for both FF and SF (except at S2) but differed during summer in both flows. Lamb and Lowe (1987) observed that the diatom-dominated periphyton communities growing under different current velocities were compositionally very similar but differed in their physical structure. Soininen (2003) observed that current velocity (10–125 cm s^{-1}) did not have any particular effect on diatom distribution patterns.

It is notable that despite high variability of assemblages at S2 and none at S3 and low variation at S1 and S4, *A. biasolettianum* and *A. minutissimum* figured either as dominant, codominant and subdominant in all assemblages irrespective of the seasons and flows. *A. biasolettianum* and *A. minutissimum* dominance from S1 to S4 during winter indicates relative stability compared with summer when assemblages go on changing implying increased variability of environmental conditions. The reasons are not very apparent but may be weakly connected to pilgrim activity that begins in summer and reaches peak during June. Summer is also a period of floods due to snow melt that brings allocthonous materials into the river that may lead to variation in assemblages.

Jüttner *et al.* (1996) reported that *Achnanthidium minutissimum* (Kützing), *Fragilaria ulna* (Nitzsch) and *Navicula* sp. were the most dominant taxa in the streams draining through natural reference conditions [forest land use] of Arun Valley, Nepal, while *Cocconeis placentula* (Ehrenberg) is the most common taxon in agricultural streams. Cantonati *et al.* (2001) and Torrisi and Dell'Uomo (2001) have observed that the most common taxa in Middle Hill streams outside the Kathmandu Valley were characteristic for unpolluted streams in the Himalaya and the Alps, such as *A. biasolettianum*, *F. arcus* var. *recta* (Cleve) and *Diatoma mesodon* (Ehrenberg) Kutzing. Only in the Mandakini River, *A. biasolettianum* and/or *A. minutissimum* were the mostly dominant or subdominant taxon and hence resemble the streams draining through natural reference conditions of Arun Valley, Nepal. There is no resemblance with agriculture or settlement-impacted streams of Nepal that have very different community comprising *Navicula minima* (Grunow), *Navicula rostellata* (Kutzing) and *Navicula atomus* var. *permitis* (Lange-Bertalot), and *N. atomus* var. *alcimonica* (Reichardt), *Sellaphora seminulum* (Grunow) D G Mann and *Nitzschia palea* (Kutzing). These have been figured as the characteristic taxa in ordination analysis in semi-natural and modified land uses, though not due to sewage enrichment.

The ecological preferences of some taxa figuring in assemblages are given below.

Taxa	Stations	Ecological preferences	Sources
A. biasolettianum	S1–S4	Medium electrolyte rich in calcium content and also in or poor nutrition	Krammer and Lange-Bertalot (1986–1991)
A. minutissimum and *N. fonticola*	S1–S4, S1	Aqueous corrosion and less electrolyte water	Krammer and Lange-Bertalot (1986–1991)
Diatoma mesodon	S1	High flow	Kobayashi (1995)
		Abundant in mesotrophic waters	Patrick and Reimer (1966)
Synedra ulna (Ulnaria ulna)	S1, S2, S4	Epiphytic species of aqueous ambiguity, eurythermy, alkalophilic, eutrophic nature, rot or poor aqueous corrosion	Kobayashi (1995)
		Nutrient rich places	Patrick and Reimer (1966)
Gomphonema parvulum (Kützing)	S1–S3	Indicator for phenol wastewater pollution	Palmer (1977)
		Large spring fountain, waterway, the river of the mountains	Krammer and Lange-Bertalot (1986–1991)

5.2 *Ecological state of the assemblages vis-à-vis river*

In the Van Dam's scale of 1–7, value of 2 was recorded for both salinity and saprobity, irrespective of seasons and flows, indicating that most of the forms in assemblage depict fresh-brackish (chloride <500 mg l^{-1}) and oligosaprobous condition (BOD <2 mg l^{-1}). The ecologic values for pH (3/4), NU (1/2), OR (1/2), TS (3/5/7) and M (2/3) in general, indicate near pristine conditions that appear to diminish at some locations (table 3). The role of current velocities (FF or SF) do not depict any specific trend in the Van Dam ecologic values because the assemblages and hence, the floral components do not differ substantially from S1 to S4. Despite, lack of a trend in this study certainly hints that some sections of the river can deteriorate, as the flows vary horizontally across a river depending on the bottom sediments.

The Håkansson (1993) values also categorise pH as circumneutral and alkaliphilous, while Hofmann (1994) indicated tolerant trophic state and oligo-β-mesosaprobous (saprobity) condition as evidenced from the Van Dam values. Nautiyal *et al.* (2007) observed similar ecological state in the snow-fed streams of Kakra sub-basin of the Mandakini basin. Nautiyal and Mishra (2013) reported alkaliphilic, fresh-brackish, β-mesosaprobic (saprobity) and eutraphentic condition (trophic state) in a spring fed Khanda Gad that is under anthropogenic influence.

Ordination analysis indicated that the characteristic taxa differed among the stations. *Synedra ulna* var. *dorsiventralis* and *Gomphonema parvulum* were mostly characteristic to S1 during winter, while *Rhoicosphenia abbreviata* and *Nitzschia fonticola* were characteristic to S1 in SF and FF conditions, respectively in summer. *Encyonema minutum* was the most characteristic taxa in winter (FF) while *Gomphonema minutum* during summer in FF condition at S2. *Adlafia miniscula* was characteristic to S3 in summer. *Reimeria sinuta* (Gregory) was the characteristic taxa in summer and FF condition at S4. In the Nepal Himalayan rivers, Jüttner *et al.* (2003) observed that *Achnanthes siamlinearis* (Lange-Bertalot), *A. subhudsonis, Achnanthes undata* (Meister) were the characteristic taxa in base-poor forested catchments, while unidentified *Gomphonema* spp., *Cocconeis placentula* and *Navicula minima* were in agricultural catchments and *Mayamaea atomus* var. *alcimonica* (Reichardt), *M. atomus* var. *permitis* (Lange-Bertalot), and *Nitzschia palea* at polluted sites near settlements.

Louis Leclercq values clearly demonstrate that the river is free of organic pollution. However, the degradation index indicates low degradation in the river. Low anthropogenic eutrophication was recorded in slow flows during summer at S1. In other three locations, the AE is low (L) irrespective of seasons and flows, being moderate at S4.

The present study, hence, demonstrates that the pristine Himalayan rivers such as Mandakini are under anthropogenic stress, though physically they appear to be free-flowing clean rivers. The rapidly growing pilgrimage-related infrastructure and hydropower activity are the source of degradation in the ecological state in the Mandakini basin. This emphasizes the need to assess the ecological state of the Himalayan rivers stressed by various anthropogenic activities. The determination of ecological values in conjunction with other diatom indices can be implemented for routine water assessment programs. The diatoms are the right tools for such programs since all Himalayan and peninsular rivers have stony or rocky beds, the substrates densely colonized by the bottom dwelling diatoms. They also form a sizeable part of the plankton community in the rivers of Indo-Gangetic plains and thus, prevail in the whole country (India). The indicator value of diatoms is well accepted and highly used across the continents. However, to enable their use in India, capacity building must be initiated which would facilitate its inclusion in the routine water assessment programs. This could lead to development of condition specific indices, though OMNIDIA has found wide applicability in Europe (www.intechopen.com).

6. Conclusions

Mandakini is a river with semi-urbanised human settlements at regular intervals all along its course due to NH-109 that leads to the Kedarnath shrine. The flow condition did not impact the diatom assemblages, but seasonal variations caused slight changes in the assemblages especially at S1 and S4. Few variations were observed in characteristic taxa for each location with respect to seasons and flow conditions. The urbanization accounts for the β-mesosaprobic and mésotraphentic states of the river which turns eutraphentic at S1 and S4, implying deterioration with increasing anthropogenic stress. If the river was pristine, the diatom community would have been in the oligotrophic condition and should have consisted of nitrogen autotrophic taxa tolerating very small concentrations instead of elevated concentrations of organically bound nitrogen. The O_2 requirement conditions are best since the flow is pristine (unhindered). Minor variations were recorded for some of the parameters. Organic pollution was nonexistent but degradation with minor exceptions was low along the river, especially at the lower half of the river. Further, no impact of flow and season was observed on ecological state of the river. In view of the semi-urban localities that occur with regular frequency along the NH-109, the Van Dam index appropriately reflects the ecological state of the Mandakini though visually the river appears to be oligotrophic.

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