



Geochemistry, spatial distribution and environmental risk assessment of the surface sediments: Anchar Lake, Kashmir Valley, India

Aasif Mohmad Lone¹ · Rayees Ahmad Shah¹ · Hema Achyuthan¹ · A. A. Fousiya¹

Received: 27 February 2017 / Accepted: 6 January 2018 / Published online: 24 January 2018
© Springer-Verlag GmbH Germany, part of Springer Nature 2018

Abstract

Anchar Lake, a mono-basined freshwater lake in Kashmir Valley, has experienced major sediment deterioration due to changes in the local catchment and anthropogenic inputs during the recent past. The present study was conducted to evaluate the major, trace element concentrations and environment risk assessment in the surface sediments of Anchar Lake. Spatial distribution of organic matter (OM), CaCO₃, TOC, sand–silt–clay and C/N ratio was studied to understand their source and accumulation in recent surface sediments. Textural studies indicate that most of the sediment samples are clayey silt to silty clay except one sample being of sandy–clay–silt nature. OM, CaCO₃ content and C/N ratio results reveal that the sediments are organically rich and the source of OM is controlled by both; autochthonous and terrestrial sources. The major oxide geochemistry reflects higher concentrations of CaO, MgO and TiO₂ compared to the UCC values and the possible dilution effect of CaO on other major oxides. Environmental risk assessment indices (Igeo and EF) reveal that the lake surface sediments are low to moderately enriched with Cu, Ni, Zn and Pb and thus are a direct threat to aquatic life. Pollution load index indicates higher contamination of the sediment samples collected along the agricultural and urban land-cover sites. In the absence of industries and metal mines in the catchment area, the agricultural inputs, domestic effluents and untreated sewage discharges are the probable source for the moderate increase in trace metals in the lake sediments. Based on geochemical and environmental parameters, an assessment of sediment contamination results revealed potential risks ranging from moderate to strong for the lake environment, particularly towards areas proximal to agricultural and land-use sites. The above results from this study thus add to the fundamental knowledge of the present lake processes occurring within the lake and its interactions with the surrounding catchment areas.

Keywords Anchar Lake · Geochemistry · Environmental risk assessment · Organic matter · C/N ratio

Introduction

The valley of Kashmir is home to innumerable and pristine freshwater lakes situated at different altitudes with varied depths, sizes and shapes (Kaul et al. 1980; Zutshi et al. 1980). The water from these lakes is widely used for

various purposes including drinking, agriculture and horticulture, and tourism purposes by the local settlers (Sarah et al. 2011; Yousuf et al. 2015). As a result of these direct influences, most of the Himalayan lakes exhibit eutrophication and thus are under greater threat due to high sedimentation rates, sediment and water pollution, especially due to human interferences (Sheikh et al. 2014; Rashid et al. 2013, 2014; Sarkar et al. 2016; Lone et al. 2017). The human impact on the lakes has not only declined the water quality, but have also made a significant impact on the sediment chemistry and lake flora and fauna. In addition, during the recent years, sewage and domestic effluent inputs and proliferation of local population, runoff from agricultural land and the residual insecticides and pesticides from the paddy fields and orchard plantations have also accelerated the process of eutrophication in these lakes. This has led to excessive growth of unwanted vegetation within the lake waters,

✉ Hema Achyuthan
hachyuthan@yahoo.com

Aasif Mohmad Lone
geoaasif@gmail.com

Rayees Ahmad Shah
shahrayees04@gmail.com

A. A. Fousiya
fousevs@gmail.com

¹ Department of Geology, Anna University, Chennai 600 025, India

which is the case for most of the Himalayan lakes (Rashid et al. 2013).

The natural and anthropogenic processes occurring along the lake catchments primarily govern both the water and sediment chemistry of the lake basins (Tarras-Wahlberg et al. 2002). Further, the sediment chemistry of the lakes is governed by a complex combination of biological, physical and chemical processes that take place within the lake waters and this is also in response to the sediment–water chemistry (McManus et al. 2015). Weathering of rocks both by physical and chemical processes release sediment detritus and soil particles that are later transported and deposited through the catchment watershed into the lake basins (Kastratovic et al. 2016). Sediments that are distinctly modified during the transportation and subsequent deposition hold signatures of local catchment inputs with high local representation including natural and anthropogenic influences (Chapman 1992; Blumberg and Schutt 2004).

The major source of organic and inorganic nutrients in lake sediments is often controlled by the deposition of particulate detritus from natural and anthropogenic sources (Meyers and Ishiwatari 1993; Holmer and Storkholm 2001). However, limited studies have been carried out on the relative contribution of OM from the catchment areas, its distribution pattern and origin and source of organic carbon in the lake systems (Hilton 1985). Thus the geochemistry of lake sediments is a collective function of catchment lithology, weathering type and intensity and erosional and depositional processes occurring within the lake basins (Minyuk et al. 2007; Khan et al. 2012). Currently, geochemical survey of the lake surface sediments is being increasingly applied to assess the environmental impact, sediment provenance and weathering intensity, etc., in the lake systems (Tarras-Wahlberg et al. 2002; Meyers 2003; Boyle et al. 2004; Yao and Xue 2015). Detailed study on the physico-chemical parameters of lake surface sediments helps us to understand the controlling factors responsible for the distribution pattern and geochemistry of the eroded detritus sediments deposited within the lakes (Zhang et al. 2014; Chandrajith et al. 2008).

Anchar Lake is one of the important freshwater urban lakes, located in the Kashmir Valley, and the lake serves as a vital resource of freshwater for the local population. In recent decades, this aquatic ecosystem has altered significantly in size and come under tremendous pressure due to anthropogenic loading, ingressing mainly from the catchment areas in the form of domestic and agricultural waste (Ahanger et al. 2012a, b). The lake waters and its sediment chemistry have deteriorated considerably, thereby affecting the aquatic life and the health of the lake (Bhat et al. 2013). This has also increased the rate and speed of eutrophication process around the lake margins. The lake is now under stress both in terms of its hydrology and sediment load and

its chemistry (Kango et al. 1987). This is also owing to its close proximity to the main Srinagar city (Farooq and Muslim 2014), that contributes anthropogenic inputs in the form different point and non-point sources.

A comprehensive study regarding the assessment of sediment geochemistry, trace metal pollution, spatial distribution of OM and sources of anthropogenic influences into the Anchar Lake is lacking up to date. Hence, it is important to assess the spatial distribution of various physico-chemical parameters combined with surface sediment geochemistry and environmental risk assessment to improve our understanding of the present-day sedimentation pattern in the Anchar Lake. The primary goals of this study were to: (1) provide information concerning the geochemistry and OM sources controlled by climate-driven lake–catchment interactions and (2) examine the potential environmental risk using pollution indices such as enrichment factor (EF), geo-accumulation index (Igeo), contamination factor (CF) and pollution load index (PLI). These findings will improve our understanding of fundamental lake processes and thus form an important base for the interpretation of the past sedimentary record for this region by analysing sedimentary lake core profiles.

Study area

The Kashmir Valley, an intermontane basin, is bounded by the Pir-Panjal thrust on the southwest and the Zaskar thrust on the northeast forming a Nappe zone. The valley is oriented NW to SE, running parallel to both the thrust blocks on either side (Ahmad and Chandra 2013; Alam et al. 2015). The valley is abound with numerous deep, freshwater lakes with fluvial, glacio-fluvial and lacustrine nature of origin (Babeesh et al. 2017a, b).

Anchar Lake is located nearly 25 km northwest of the main Srinagar city (Fig. 1) and lies between 34°20'N latitude and 74°82'E longitude with an average elevation of ~ 1583 mts amsl. The mean depth of lake is ~ 4 metres. The catchment of the lake spatially covers an area of about 5.8 km² with an open drainage type fed by a network of channels including the local catchment watersheds, open springs and the Sindh River (Fig. 2). The Sindh River constituting one of the largest basins in the Kashmir Himalayas drains major part of its water into the lake. Further, a number of channels from the agricultural fields, sewage from human settlements and surface runoff directly drain into the lake throughout the year. The excess water of the Anchar Lake drains into the Jhelum River through the Shalabaugh wetland (Ganaie et al. 2015; Khanday et al. 2016).

The lake catchment is surrounded by diverse lithological formations, which mainly include the Panjal traps, the Triassic limestones, the Karewa deposits and the recent alluvium

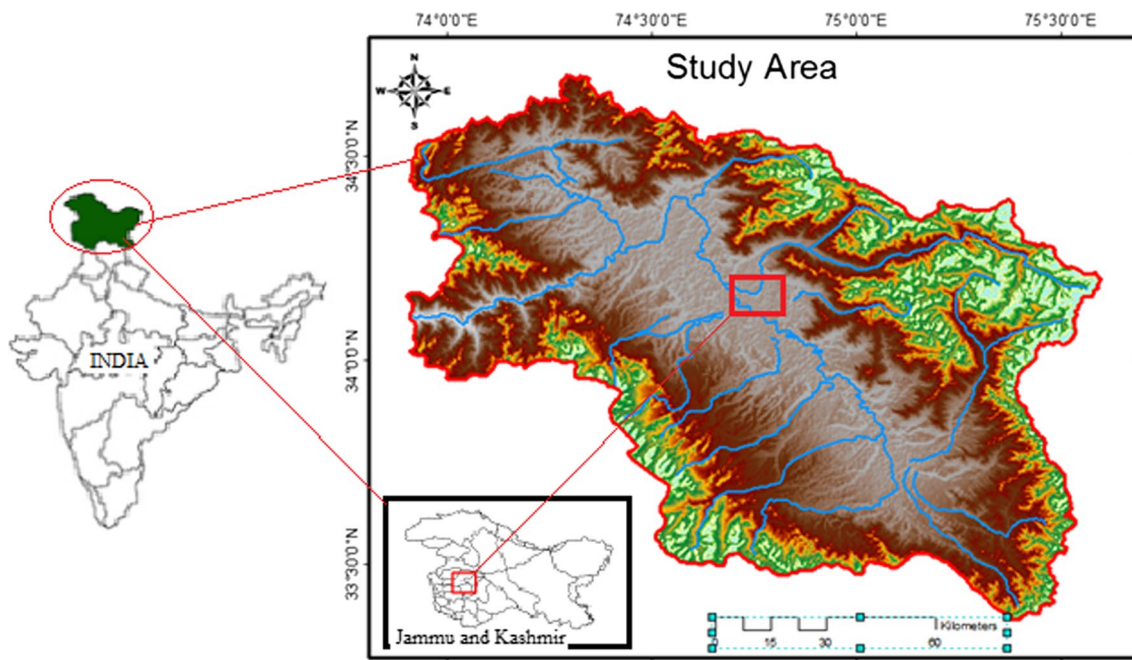
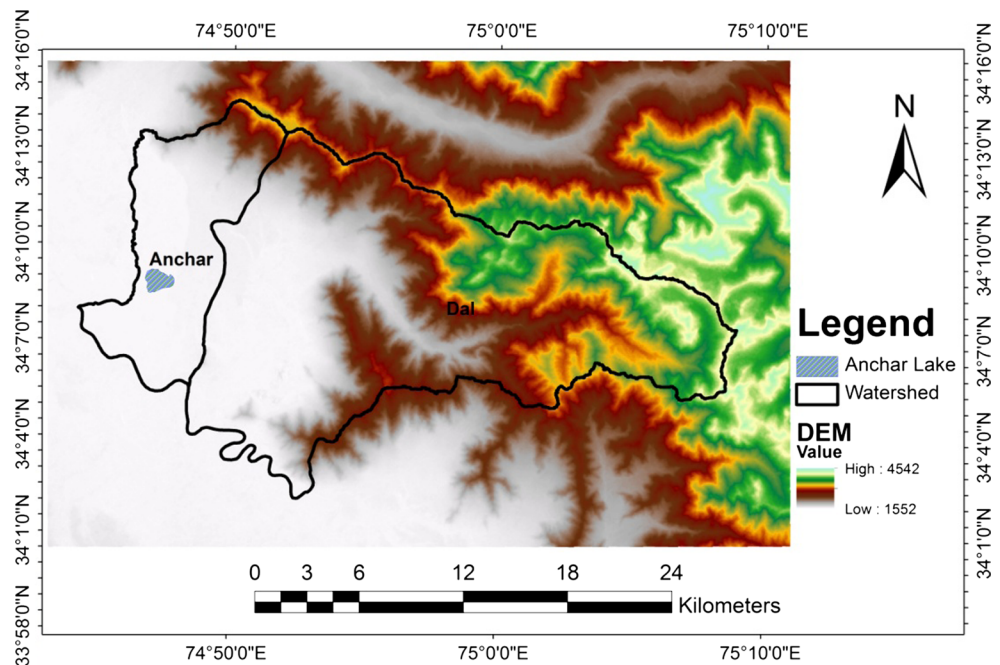


Fig. 1 DEM map of study area showing location of Anchar Lake

Fig. 2 Watershed map of the study area with Anchar Lake



(Fig. 3). Panjal traps (volcanic rocks) are of Permian age dominated by the basalts. The Triassic limestones consist of the carbonates and dolomites. The 2000-m thick Plio-Pleistocene Karewa sediments are glacial-fluvio-lacustrine deposits composed of gravels, silt, marls, lignite and glacial moraines associated with varved clays. (Agrawal et al. 1985, 1989; Singh 1982). The catchment of the lake is

also surrounded by various land-use land-cover patterns, including built-up, parks, orchards and agricultural fields (Fig. 4). A major portion of the lake is presently under the floating garden cover including the aquatic vegetation and macrophytes and this is due to high anthropogenic influences. The area experiences a temperate climate with warm summers and intense cold winters characterised by four

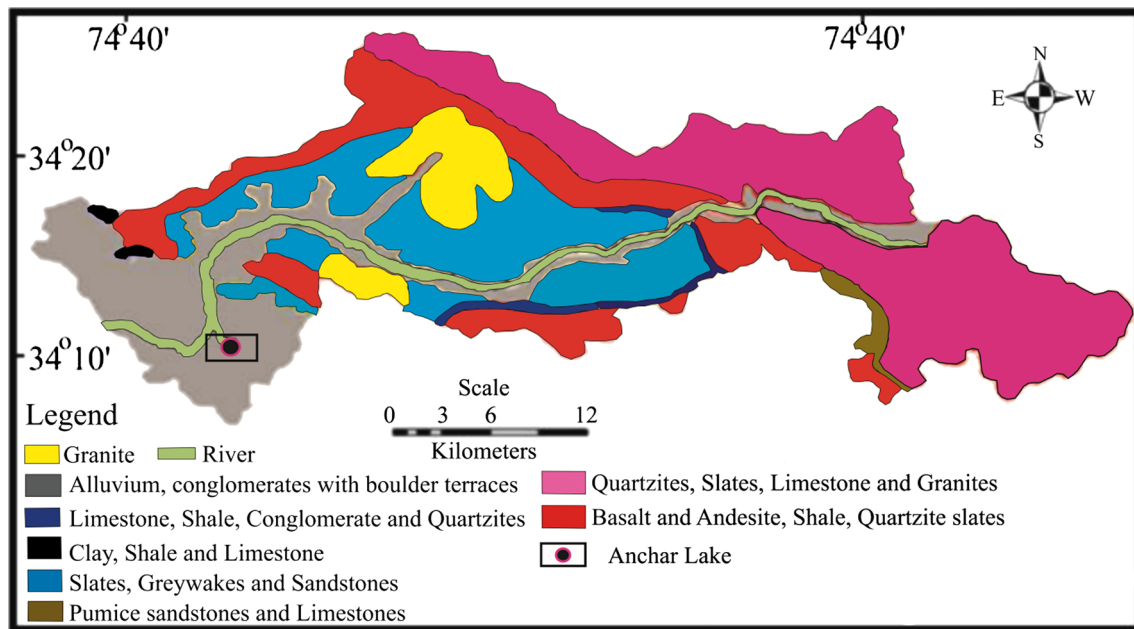


Fig. 3 Lithology map of the Anchar Lake catchment

seasons, spring, summer, autumn and winter. Most of the precipitation falling around the area is due to the western disturbances (WD) (80%) mainly during the winter season and owing to local topography. The average annual rainfall is 650–710 mm with an average annual temperature of 13 °C (Dar et al. 2014).

Materials and methods

In this study, lake surface sediments (upper 0–10 cm) were collected in July 2015 at regular intervals under a water column of 2–6-m depths. Twenty-four (24) lake sediment samples were collected with the help of a Van Veen grab sampler (Fig. 5). Further, the samples were tightly packed in polyethylene zip lock covers, dried in open air and later in the oven at the 35 °C. For further laboratory analyses, the samples were homogenised using an agate mortar.

The sediment textural analysis of the lake surface sediment samples was carried out to understand the sand, silt and clay content and its spatial distribution (Ingram 1970). Before obtaining the grain size measurement, the sediment samples were pre-treated with H_2O_2 and HCl to decrease the influence of OM and carbonates. A small pinch of sodium hexametaphosphate ($NaPO_3$)₆ was also added in order to fully disperse the finer-size particles.

For the geochemical analyses, all the representative samples were analysed for the major oxides and trace elements using VP-320 X-ray fluorescence (XRF)

spectrometry at the Department of Geology, Savitribai Phule Pune University, Pune. For the XRF analyses, the sediment samples were powdered and later allowed to pass through the mesh sieve (ASTM-230) size. The above procedure involved an analytical error of $\pm 0.5\%$ for major oxides and < 1 ppm for the trace elements. Carbon-to-nitrogen (C/N) ratio and total organic carbon (TOC) were analysed to infer the source of OM using (CHNSO-2000) elemental analyser available at the Department of Geology, Anna University, Chennai. For this analyses the samples were powdered using an agate mortar and later sieved through ASTM-230 sieve. Further, 10–12 mg sample was filled in a tin capsule and positioned in the auto-sampler tray for analyses. Blank samples (tin capsules) and standard BBOT (2,5-Bis (5-tert-butyl-2-benzo-oxazol-2-yl) thiophene) with known elemental composition were used for accurate data assurance. The analytical precision of this method, expressed in terms of standard deviation, ranges from 3 to 5%. For calculating TOC, the samples were acidified with a 1 M solution of hydrochloric acid to remove inorganic carbon (IC) (Hedges and Stern 1984). Later, the samples were washed using distilled water and allowed to dry in oven for 40 °C and further analysed using the CHNSO-2000 analyser at combustion temperature of 950 °C. The relative OM content was determined as percent loss during ignition (LOI). Samples were placed in a furnace at temperatures of 550 and 950 °C for over 1 h, and the LOI was calculated from the measured loss in weight following Heiri et al. (2001).

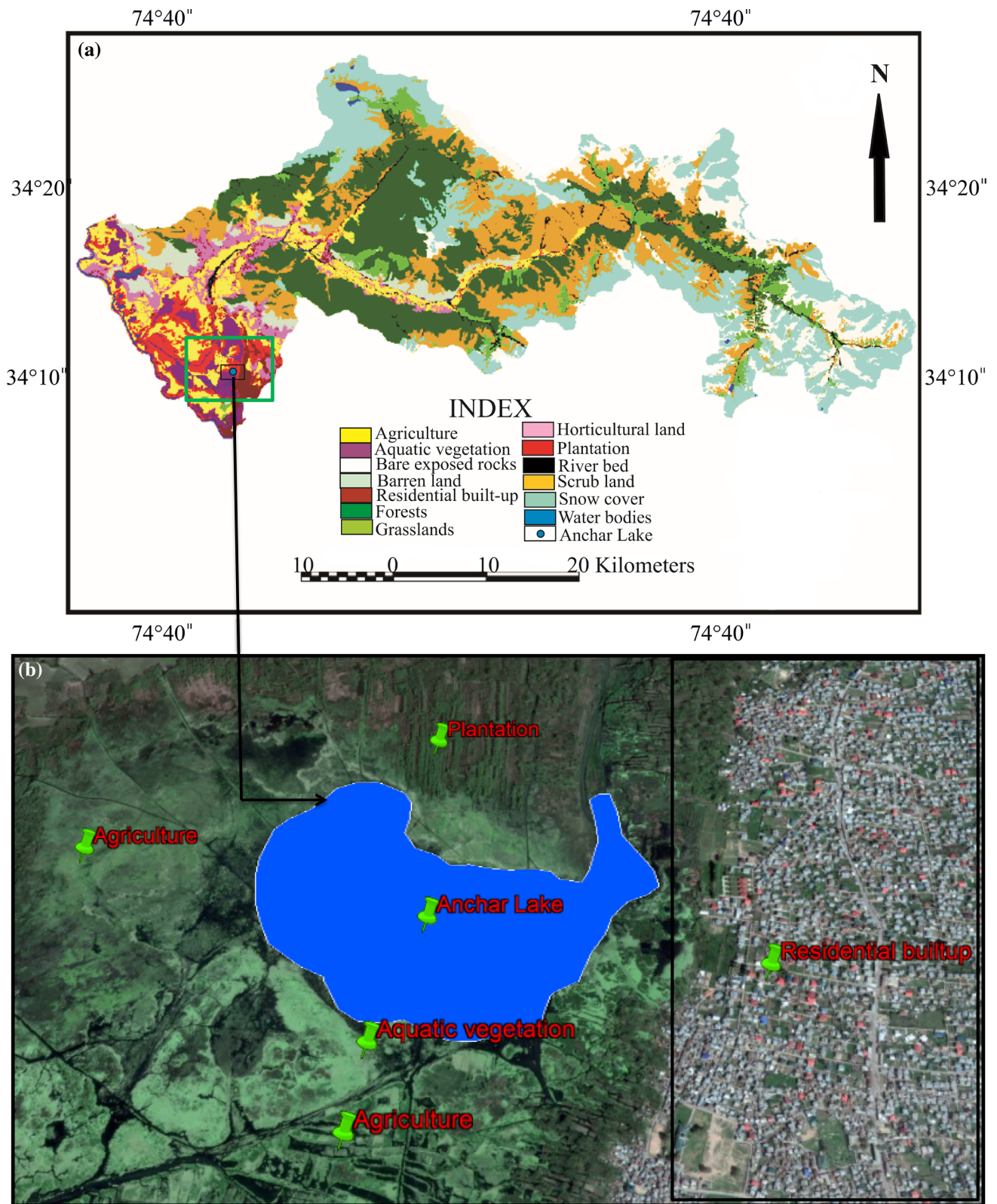
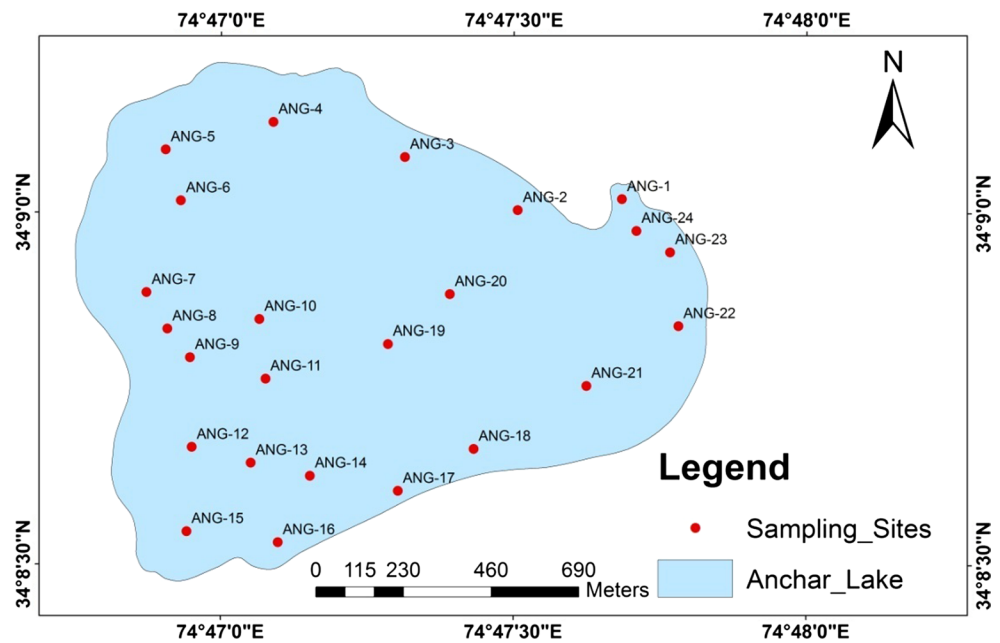


Fig. 4 Land use/land cover (a) and Google earth map (b) of the Anchar Lake catchment

Fig. 5 Map of the study area showing sample stations



Statistical analyses

Multi-variate statistical analysis was carried out using SPSS software version 21 of windows. Principal component analysis (PCA) was performed to assess the continuity and/or overlap of clusters and homogeneity in the studied parameters. Correlation matrix was applied to check the significant relationship (positive and negative) between the studied parameters. The triangular plot was prepared using the triplot software and represents the relative percentage of sand, silt and clay in the sediment samples. The spatial distribution of the physico-chemical parameters was interpolated through inverse distance weighted (IDW) algorithm available in the geo-statistical analytical tool of Arc GIS 10.3. Cluster analytical (CA) results were displayed using the dendrogram, which evaluates the degree of similarity between the different physical and chemical parameters (Cesari 2007).

Results

Sediment grain size and spatial distribution pattern

The relative abundance of sand, silt and clay content inferred for the lake sediments are presented in the trilinear diagram for sediment nomenclature (Fig. 6). The sediment grain size was found to be (silty + clay) mud dominated except one sample that fall under sandy clay domain in the ternary diagram. The sand class was very low, ranging from 0.39% to 30.18%. The grain size content of clay and silt varies from 19.45% to 79.68% and 19.76% to 79.05%, respectively. The clay and silt fraction revealed almost the similar trend in

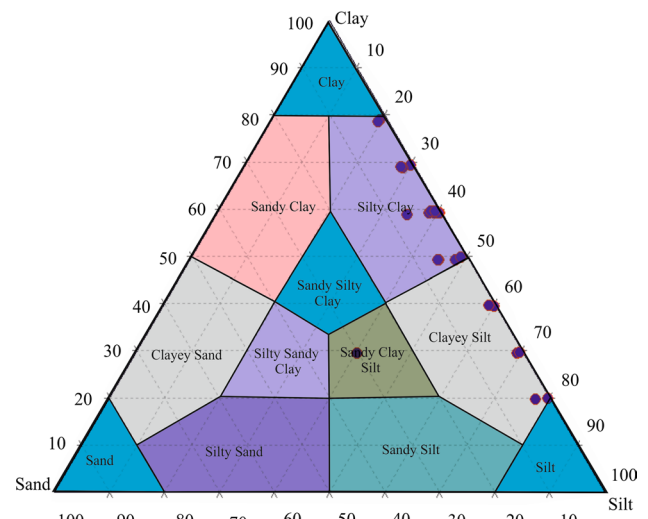


Fig. 6 Ternary plot for sand, silt and clay distribution of lake surface sediments (Shepard 1954)

grain size concentration with a mean value of 51.87% and 44.97%, respectively. However, the sand fraction showed the lowest average value of 3.16%, however one station showed a very high value of sand (ANG-24 = 30.18%).

The lake sediment samples showed a near positive link between the lake water depth (bathymetry) and sediment grain size. The sediment spatial distribution maps (Fig. 7a–c) revealed the highest percentage of fine grain sediments (clay and silt) along the central portions of the lake. The high content of sand is observed along the north-eastern edges of the lake and along catchment stream inlets (Fig. 7a). The spatial distribution of silt

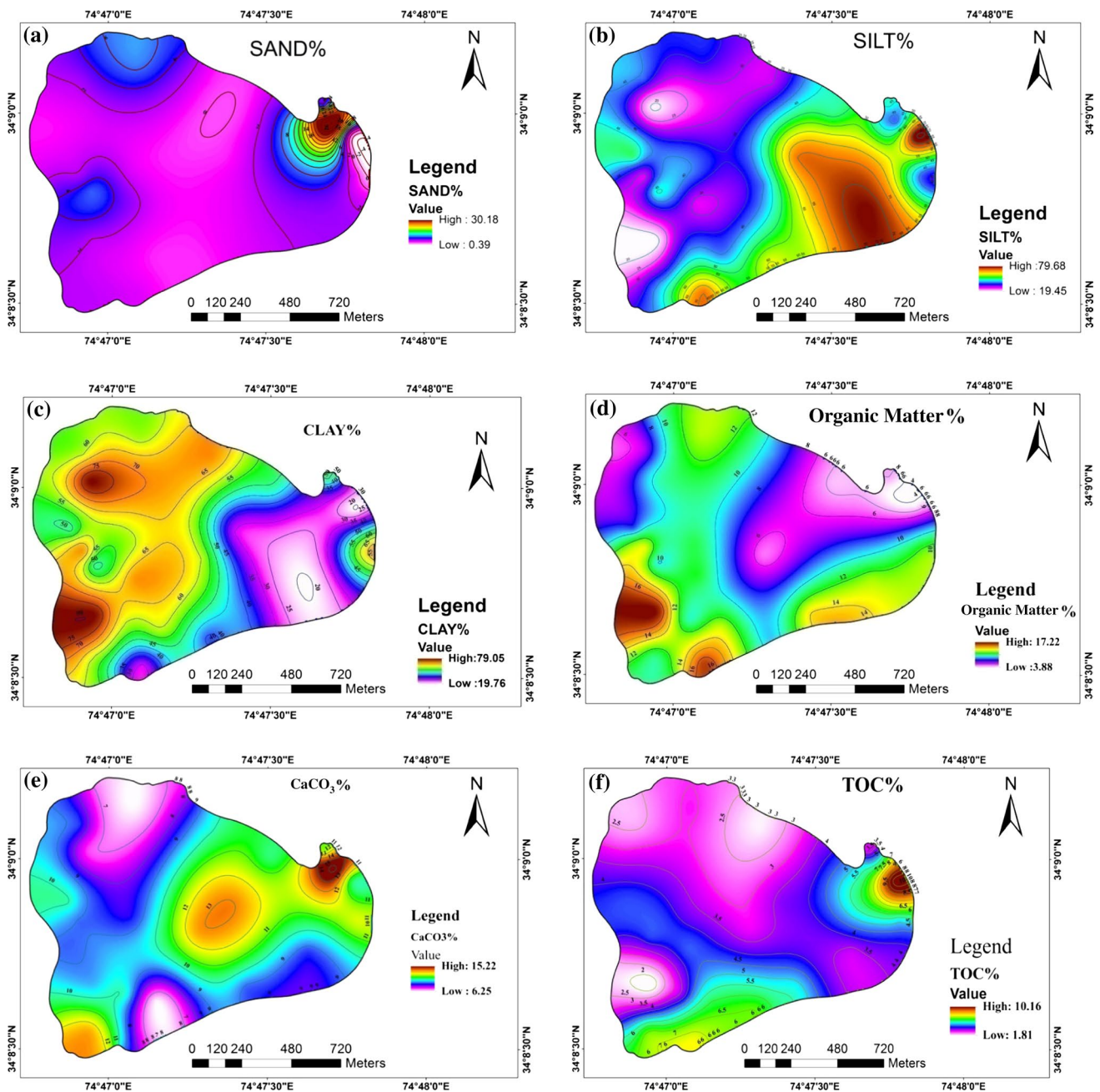


Fig. 7 Spatial distribution map for **a** sand, **b** silt, **c** clay, **d** organic matter, **e** CaCO₃ and **f** TOC in lake sediments

exhibited a high concentration of 79.68% along the south-eastern edges of the lake and lowest content along the north-western portions (Fig. 7b). Elevated clay content with maximum values of 79.05% (Fig. 7c) was observed along the central and south-western flanks of the lake. In general, all the surface samples were considerably low in the coarser sand fraction.

OM and calcium carbonate (CaCO₃) content

The concentration of OM and CaCO₃ is presented in Table 1. Mainly terrestrial runoff contributes OM and CaCO₃ and organisms present in the water column of the basin. The concentration of both OM and CaCO₃ varies largely both between and within the lakes (Dean 2006). This disparity

Table 1 Sand, silt, clay, OM, CaCO₃, C/N and TOC concentration in surface sediments of Anchar Lake

S ID	Sand (%)	Silt (%)	Clay (%)	OM (%)	CaCO ₃ (%)	C/N	TOC%
ANG-1	5.51	45.28	49.21	4.98	11.44	27.27	3.35
ANG-2	2.56	48.13	49.31	4.77	10.33	18.20	3.76
ANG-3	0.60	29.96	69.44	9.16	9.76	10.48	2.05
ANG-4	6.47	34.71	58.82	12.90	6.25	15.99	3.04
ANG-5	2.37	38.46	59.17	6.68	8.67	10.11	2.42
ANG-6	1.38	19.57	79.05	9.92	7.24	16.15	3.15
ANG-7	1.20	48.90	49.90	8.34	10.03	10.15	4.39
ANG-8	2.36	28.74	68.90	13.49	8.93	15.11	4.40
ANG-9	5.72	44.97	49.31	10.12	9.03	16.90	4.34
ANG-10	1.38	39.33	59.29	11.31	8.43	16.15	3.82
ANG-11	2.56	28.40	69.03	11.63	9.44	6.67	4.47
ANG-12	1.96	19.45	78.59	17.22	9.35	6.56	1.81
ANG-13	1.19	39.29	59.52	10.35	9.85	5.49	3.58
ANG-14	0.40	40.32	59.29	13.12	6.26	14.92	5.96
ANG-15	1.79	38.69	59.52	10.91	12.60	8.55	6.43
ANG-16	1.18	69.29	29.53	16.45	7.58	7.36	7.21
ANG-17	0.39	60.16	39.45	9.46	8.76	7.69	6.48
ANG-18	1.19	59.05	39.76	13.82	8.95	7.25	5.24
ANG-19	0.59	40.12	59.29	5.47	12.82	13.68	3.15
ANG-20	0.60	69.64	29.76	6.27	13.03	17.40	3.69
ANG-21	2.77	77.47	19.76	12.64	8.66	8.45	3.34
ANG-22	0.99	39.48	59.52	11.61	11.71	10.49	5.19
ANG-23	0.40	79.68	19.92	4.38	10.48	13.06	10.16
ANG-24	30.18	40.24	29.59	3.88	15.22	11.59	6.14

is due to the differences in water chemistry, which in turn is controlled by the presence and type of bedrock geology in the catchment, climate, lake flora and fauna and anthropogenic influences along the catchments. The overall concentration of OM (Fig. 7d) and CaCO₃ (Fig. 7e) in surface sediments varies along the four transects. The OM varies between 3.88% and 17.22% with mean value of 9.95%. In addition, the CaCO₃ percentage varies between 6.25% and 15.22% having an average value of 9.78%. The spatial distribution diagram showed high percentage of OM along the south and south-western flanks of the lake. However, the concentration of CaCO₃ was predominantly high along the north-eastern fringe and along the central portions of the lake.

C/N ratio and TOC content

The C/N ratio of lake sediments reveals the relative contribution of terrestrial, anthropogenic, phytogenic and phyco-genic carbon and nitrogen supplied to the accumulation of sediments from diverse sources (Kaushal and Binford 1999; Meyers 1994; Meyers and Ishiwatari 1993; Meyers and Teranes 2001; Mahapatra et al. 2011; Sampei and Matsumoto 2001). Lake algae bear a C/N ratio that varies from 4 to 10, whereas for terrestrial vegetation the ratio is always > 20.

The Anchar Lake surface sediments revealed a wide variation in C/N ratio at different sampling stations and also from the margins to deeper and central part of the lake. The C/N ratio exhibited a low value of 5.49 and a higher value of 27.27 with an average of 12.32. The TOC revealed a minimum value of 1.8% (ANG-12) and a higher content of 10.16% (ANG-23) with an average of 4.48% (Fig. 7f).

Sediment chemistry (major and trace element)

The sediment chemistry of the lake is a function of the catchment flux, climate, rock-mineral weathering and physico-chemical characteristics of the detritus material from the watershed (Basavaiah et al. 2014). The amount of in situ organic and inorganic matter incorporated into the sediments also governs this proportion (Lottermoser et al. 1997; Jin et al. 2006a, b). The major oxides in decreasing order of average percentages can be summarised as SiO₂ > CaO > Al₂O₃ > Fe₂O₃ > MgO > K₂O > Na₂O > TiO₂ > P₂O₅ > MnO, respectively. From the geochemistry data, it is observed that the enrichment of SiO₂ varies from 40.14% (ANG-24) to 50.62% (ANG-5), CaO ranges from 10.46% (ANG-05) to 20.04% (ANG-24), Al₂O₃ ranges from 10.66% (ANG-05) to 16.08% (ANG-24), Fe₂O₃ ranges from 5.25% (ANG-24) to 7.87% (ANG-6), MgO ranges from 2.92% (ANG-17)

to 4.12% (ANG-6), K₂O ranges from 1.88% (ANG-24) to 3.67% (ANG-05), Na₂O ranges from 0.62% (ANG-23) to 1.68% (ANG-05). TiO₂ ranges from 0.75% (ANG-23) to 0.93% (ANG-05), P₂O₅ ranges from 0.14% (ANG-06) to 0.42% (ANG-17), and MnO ranges from 0.07% (ANG-19) and were present in minor concentrations.

The chemical variation in the major elements in lake sediments were plotted on variation diagrams against Al₂O₃ and further compared with upper continental crust (UCC values) (Taylor and McLennan 1985). In a plot against Al₂O₃ (Fig. 8), all other major oxides show a positive correlation except CaO and P₂O₅ which showed a negative trend with Al₂O₃. This suggests CaO and P₂O₅ in the lake sediments have caused relative depletion of other elements and are derived primarily from authigenic sources probably in situ vegetation. The geochemistry data of Anchar Lake sediments when compared with UCC values (Fig. 9a) revealed enrichment of CaO, MgO and TiO₂ concentrations and depletion in SiO₂, Na₂O and P₂O₅ data. Further, MnO, K₂O, Al₂O₃ and Fe₂O₃ values

show a similar trend. This suggests that the lake sediment geochemistry is controlled by weathering intensity and the dilution effect of CaO. The relatively high content of CaO and lower concentration of SiO₂ may be due to carbonate fraction and its dilution effect, respectively.

The relative enrichment or depletion of trace elements in sediments has been extensively used to infer source changes in sediments in response to weathering, sedimentation and anthropogenic inputs. Weathering, provenance, diagenesis, anthropogenic inputs, sediment sorting and the aqueous geochemistry of the individual elements mainly control trace element concentrations in sediments (Das and Haake 2003). The distribution of various trace elements showed enrichment of S followed by Cl, Sr, Zn, Rb, V, Cr, Cu, Ni, Pb and Co in the lake surface sediments. When compared with UCC values (Fig. 9b), the trace elements reflect relatively high concentrations of S, Cl, Cr and Cu values, moderately high in Pb and Rb and low in Nb and Ba contents. The high concentration of S and Cl is related to human and anthropogenic interferences.

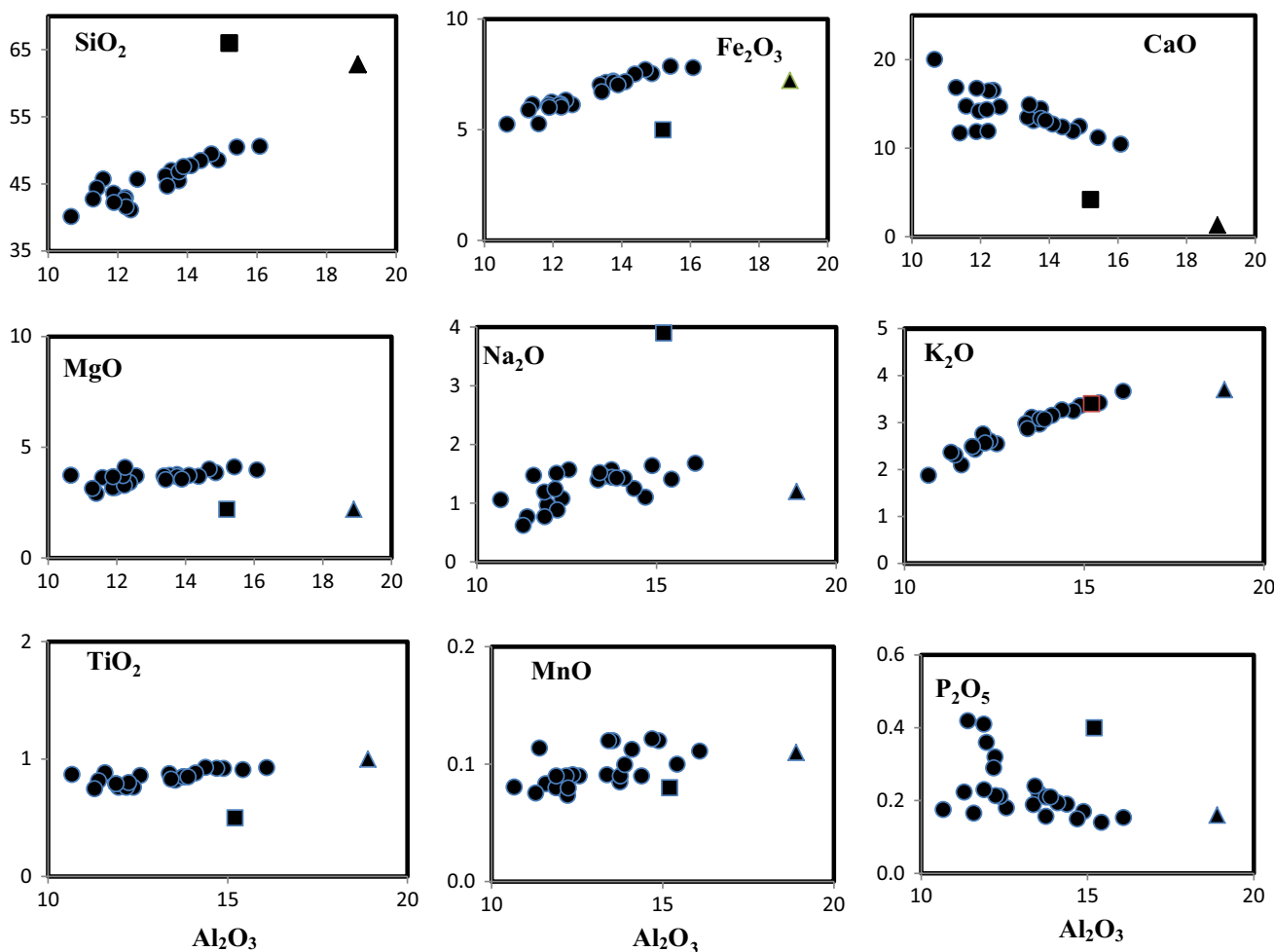


Fig. 8 Variation diagrams of major elements plotted against Al₂O₃ for the Anchar Lake sediments

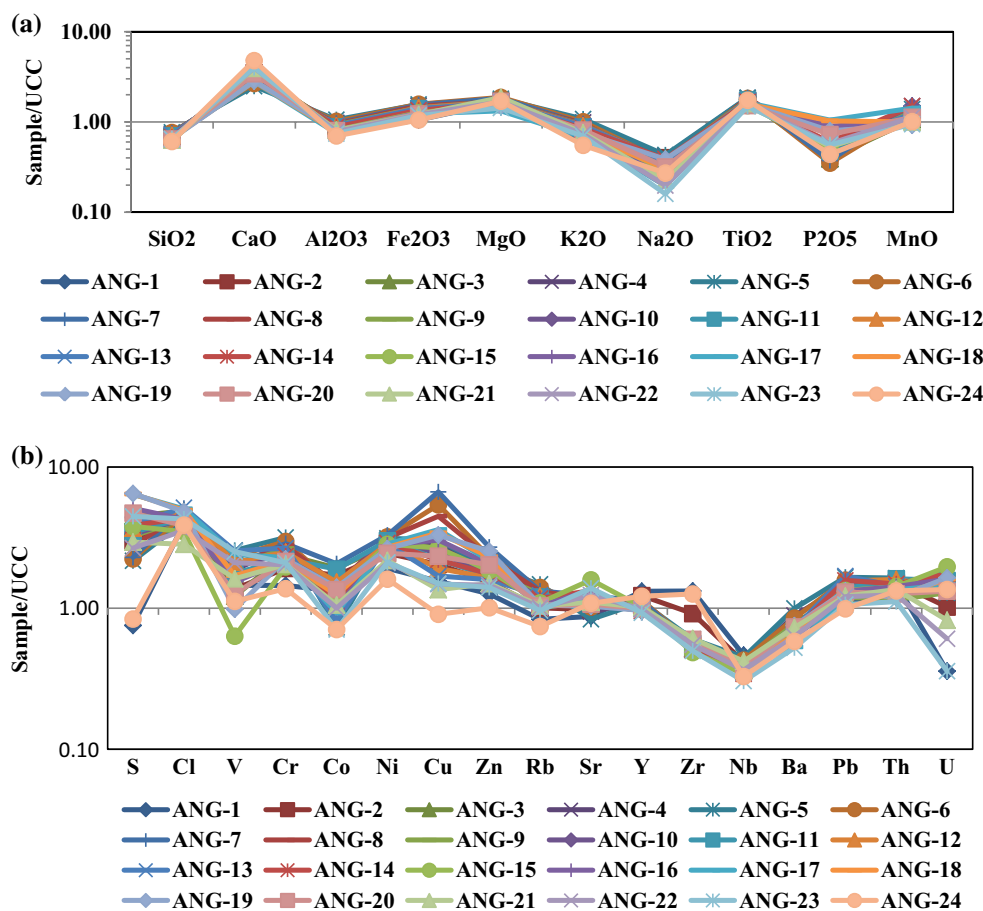


Fig. 9 Sediment normalised diagrams for a major oxides and b trace elements of Anchar Lake sediments

Environmental risk assessment

The geochemical composition of lake sediments is a reliable marker for inferring the anthropogenic pollution, as the geochemistry is mainly controlled by the physico-chemical processes operating near the sediment–water boundary during depositional processes (Sheela et al. 2012). The evaluation of enriched and unsafe anthropogenic inputs in the form of trace metals is vital for extensive lake mitigation and management (Dung et al. 2013). To evaluate the extent of anthropogenic impacts and the level of contamination, numerous environmental indices (e.g. the geo-accumulation index (Igeo), enrichment factor (EF), contamination factor (CF), pollution load index (PLI) and statistical tools are employed globally (Tang et al. 2014; Wang et al. 2014; Li et al. 2013; Iqbal et al. 2016; Yao et al. 2006; Suresh et al. 2012; Xiao et al. 2014; Gopal et al. 2016; Kasilingam et al. 2016). The pollution load index for the studied sediments varies from 1.32 to 3.10 with a mean value of 2.17. The average values for the geo-accumulation index include Cr (0.59), Co (0.25), Ni (0.92), Cu (1.52), Zn (0.70), Pb (0.04), Fe (0.14) and Mn

(− 0.12). In the enrichment factor index, Cu, Ni and Zn showed considerable enrichment in the sediments.

Geo-accumulation index (Igeo) was initially defined by Muller (1979) to assess the lake sediment contamination by comparing the studied heavy metal contents with the background crustal average elemental concentrations. The geo-accumulation index (Igeo) enrichment for the studied metals was quantified using the below formula:

$$I_{geo} = \frac{C_n}{1.5B_n}$$

where (Cn) is the measured concentration of studied element (n) and (Bn) is the geochemical average background value of crustal metal(n) (Wedepohl 1995). The factor 1.5 is introduced to minimise the effect of probable variation in the background values, governed by geogenic or anthropogenic influences. The Igeo index is divided into six classes that represent sediment quality as: 0 (practically no pollution), 0–1 (no pollution to moderately polluted), 1–2 (intermediately polluted), 2–3 (moderately to significantly polluted), 3–4 (strongly polluted), 4–5 (strongly to extremely polluted) and > 5 (extremely polluted). The average Igeo of

the elements in the surface sediment is 1.52 for Cu; 0.92 for Ni; 0.59 for Cr; 0.70 for Zn; 0.25 for Co; 0.14 for Fe; 0.04 for Pb and - 0.12 for Mn. The observed Igeo value for Mn (Fig. 10a) was found lower than 0, indicating practically no pollution. However, Igeo index of Pb, Fe, Co, Cr and Zn showed uncontaminated to moderately contamination. Igeo for Cu ranges from 0.08 to 2.96 with an average of 1.52 indicating moderately to strongly contaminated sediments.

Enrichment factor (EF)

The evaluation of enrichment factor (EF) widely helps us to determine the extent of anthropogenically sourced trace element pollution in diverse environments using a normalised element "r" to minimise the variations governed by the sediments. Various trace metals including Fe, Al, K are applied in the form of normalised elements. The EF was calculated using by the formula:

$$EF = \frac{(Metal/Al)_{sample}}{(Metal/Al)_{background}}$$

The earth crustal average values are drawn from Wedepohl (1995) which correspond to the average composition of the surficial rocks. In this study, the EF enrichment was interpreted following Sakan et al. (2009). EF < 1 indicates rock sources with no enrichment, EF 1–3 slight enrichment, EF = 3–5, intermediate enrichment, EF = 5–10, moderate to severe enrichment, EF = 10–25, significant enrichment, EF = 25–50, very severe enrichment and EF > 50 extremely strong enrichment. The average enrichment of trace metals is 5.27 for Cu; 3.25 for Ni; 2.83 for Zn; 2.58 for Cr; 2.09 for Co; 1.75 for Pb and 1.56 for Mn. The surface sediments reveal higher values of Pb, Cu, Zn, Cr, Co, Ni and Fe. EF technique (Fig. 10b) signified moderate to severe enrichment for Cu; moderate enrichment for Ni and Zn and minor enrichment of Co, Pb and Mn in the sediments.

Contamination factor (CF)

The mechanism and deposition pattern of contaminants in the sediments is strongly governed by the nature of the pollutant, and the in situ physico-chemical conditions that cause dissolution and accumulation (Sheela et al. 2012). The CF acts as a vital indicator of the sediment contamination, to study and evaluate the lake environment pollution using a single parameter. Contamination factor (CF) is computed by dividing the concentration of each studied metal by the earth’s crustal value (Hakanson 1980). The CF was calculated as:

$$CF = \frac{C_{sample}}{C_{crust}}$$

In CF, the concentration levels are differentiated based on their intensity on a scale varying from 1 to 6 as < 1 indicates low contamination, 1–3 moderate contamination, 3–6 strong contamination and > 6 significantly strong contamination. The trace element contamination concentration (Table 2) for Anchar Lake reveals that the sediments are low to moderately contaminated by trace metals.

Pollution load index

The PLI was initially proposed by Tomlinson et al. (1980) to evaluate pollution intensity in sediments. PLI allows a comparison of pollution level between the various stations and over a temporal scale. In this study, the PLI was calculated as suggested by Tomlinson et al. (1980). According to Singh et al. (2003), PLI values vary from 0 to 10. The PLI level of 0 indicates background concentration, PLI 1–4

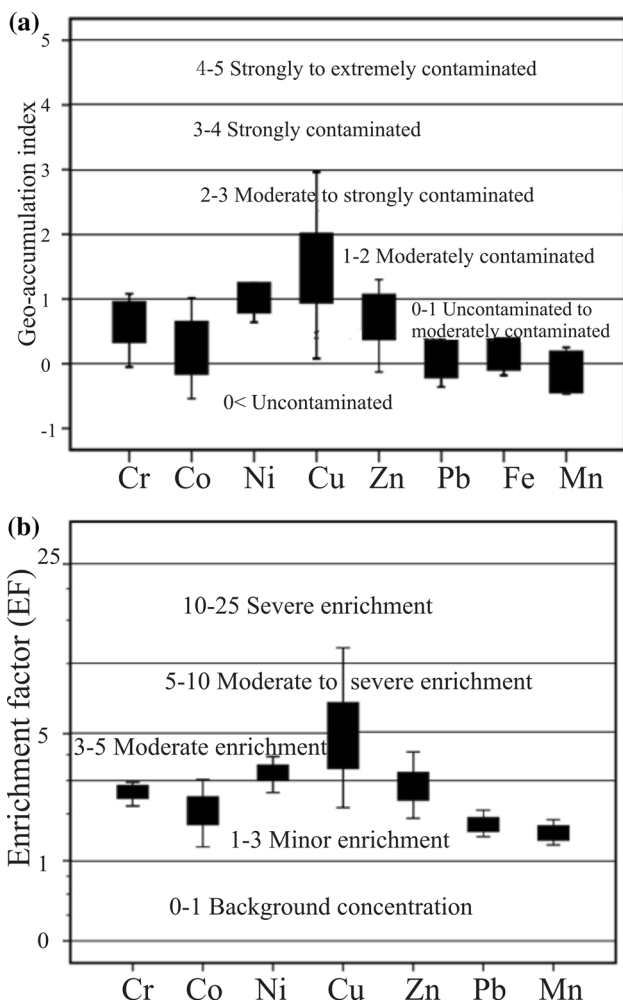


Fig. 10 Stock plot for **a** geo-accumulation index and **b** enrichment factor for Anchar Lake sediments

Table 2 Metal contamination factors (CFs) and pollution load index (PLI) for selected metals at various sampling sites

	Cr	Co	Ni	Cu	Zn	Pb	Fe	Mn	PLI
ANGB-1	1.45	1.93	2.06	2.71	1.73	1.20	1.32	1.22	1.64
ANGB-2	1.91	2.50	2.63	3.57	2.10	1.34	1.57	1.24	1.99
ANGB-3	2.39	2.82	3.00	4.67	2.44	1.49	1.81	1.25	2.30
ANGB-4	2.74	2.07	3.28	5.00	2.60	1.70	1.89	1.44	2.40
ANGB-5	3.17	1.07	3.36	5.31	2.65	1.95	1.96	1.63	2.37
ANGB-6	2.97	2.07	3.44	9.44	3.15	1.86	1.95	1.71	2.81
ANGB-7	2.87	3.03	3.54	11.66	3.69	1.87	1.94	1.79	3.10
ANGB-8	2.77	2.16	3.39	7.83	3.10	1.58	1.87	1.72	2.66
ANGB-9	2.64	1.53	3.20	4.61	2.48	1.41	1.80	1.65	2.23
ANGB-10	2.46	2.16	3.25	4.29	2.42	1.52	1.79	1.50	2.28
ANGB-11	2.23	2.77	3.23	3.87	2.30	1.62	1.77	1.34	2.26
ANGB-12	2.49	2.24	3.06	3.34	2.24	1.84	1.77	1.40	2.21
ANGB-13	2.67	1.19	3.09	2.95	2.17	1.99	1.77	1.46	2.05
ANGB-14	2.34	1.64	3.12	3.85	2.38	1.85	1.68	1.40	2.16
ANGB-15	1.96	1.90	3.05	4.67	2.52	1.57	1.59	1.34	2.14
ANGB-16	2.17	1.47	3.01	5.31	2.81	1.55	1.57	1.50	2.18
ANGB-17	2.29	1.35	3.06	6.30	2.96	1.41	1.55	1.67	2.24
ANGB-18	2.17	1.81	2.90	5.98	3.15	1.46	1.55	1.38	2.25
ANGB-19	2.23	2.06	2.84	5.77	3.45	1.55	1.55	1.08	2.25
ANGB-20	2.14	1.98	2.63	4.08	2.77	1.53	1.53	1.13	2.06
ANGB-21	2.04	1.54	2.34	2.36	2.03	1.43	1.52	1.17	1.75
ANGB-22	2.03	1.47	2.25	2.59	1.99	1.42	1.50	1.14	1.74
ANGB-23	2.10	1.03	2.27	2.62	1.92	1.25	1.48	1.11	1.63
ANGB-24	1.37	1.03	1.73	1.58	1.37	1.16	1.32	1.18	1.32

as polluted condition, while $PLI > 4$ signifies significant pollution (Tomlinson et al. 1980; Iqbal et al. 2016). PLI is calculated as the n th root of the (n) number of contaminating factors multiplied together and computed as:

$$PLI = (CF_1 \times CF_2 \times CF_3 \times \dots \times CF_n)^{1/n}$$

where n represents the number of elements and CF signifies the contamination factor.

The PL index for the studied sediments fluctuates from 1.32 to 3.10 with an average value of 2.17. Higher PLI value was found in case of sampling stations designated as ANG-6, 7 and 8. Overall, the PLI (Fig. 11) revealed that all the samples fall under moderately polluted class.

Discussion

The texture analysis of the lake surface sediment reveals that all the samples exhibit clayey to silty texture except one falling under the sand category. These results clearly demonstrate that the lake environment is favourable for the accumulation of fine sediment fractions and the sediment texture is mainly controlled by lake bathymetry and drainage inlets. Higher sand content with a tongue-like feature along the northernmost fringe and along the shallow water

column, particularly at station ANG-24, is found due to the Sindh River inlet in the lake which brings in a lot of coarser sediments from the upper catchment. Higher clay content in the central portion reflects the higher bathymetry of the lake basin and the relatively stagnant depositional environment, which allows finer sediments to settle. Based on Shepard (1954) classification using the ternary diagram, the sediment samples of the present study are classified as clayey, silty clay and sandy in nature.

Aquatic flora, fauna and vegetation growing around the lake are the primary suppliers for the organic material initially supplied to the sedimentary basins. The amount and type of lake biota reflect the ecology and environmental conditions prevalent around the lake (Meyers and Lallier-Verges 1999). The high OM content (Avg. = 9.95) indicates high concentration of detritus materials (terrigenous) and other flora and fauna (autochthonous) occurring within the lake. The high percentage of OM is primarily attributed to the algae and lake flora. However, a significant contribution is also from the terrigenous or the agricultural and horticultural practices presently being carried out by the local population in the catchment areas (Lone et al. 2017). The higher content of OM along the south and south-western areas is probably owing to the predominance of aquatic macrophytes (floating gardens), agricultural fields and anthropogenic inputs.

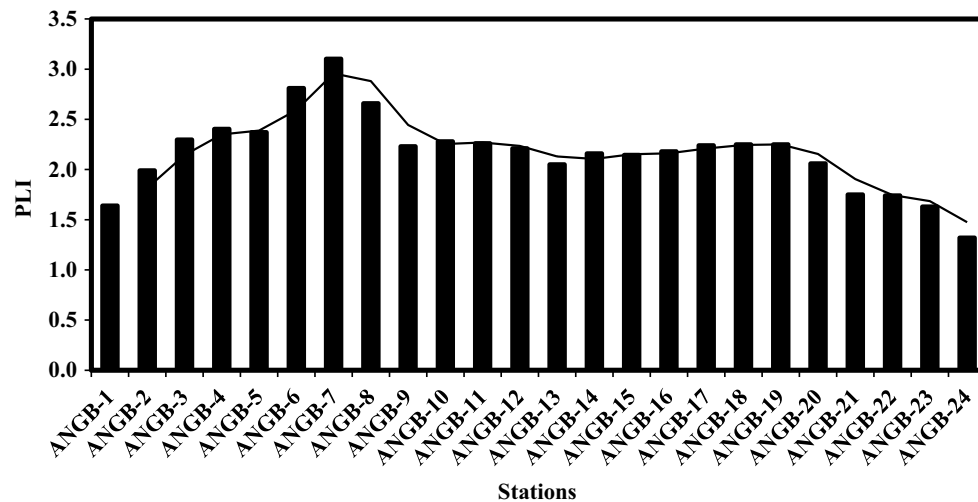


Fig. 11 Pollution load index (PLI) for different sampling stations of Anchar Lake sediments

The high concentration of CaCO_3 (15.22%) found along the northern fringe is attributed to the large influx of weathered material brought by the Sindh River and then depositing at the river–lake water interface. The primary source of CaCO_3 along the central portions of the lake is probably due to the in situ organic shells and allochthonous carbonate sediments delivered to the lake. This observation is also supported by the positive correlation ($r = 0.55$) of CaO with the CaCO_3 suggesting their similar sources. Variation diagram for OM and CaCO_3 shows negative correlation suggesting their different source of input into the lake. The low correlation between OM and CaCO_3 is attributed to the disparity in texture, bathymetry and contributing sources. The similar distribution of OM and finer sediments probably points to a fixation between organic components and finer sediments. TOC content is a primary parameter for assessing the extent of OM and is mainly controlled by the in situ (aquatic flora and fauna) processes and contributions from exogenous vegetation. The high TOC value in the surface sediments indicates that the lake is organically polluted. Higher concentration of TOC in the north-eastern fringes as indicated by spatial distribution map points to the riverine input from the lake catchments and later deposited along the lake margins. The average TOC content of Anchar Lake sediments (4.48%) is significantly elevated when compared to the Wular Lake (2.33%) (Shah et al. 2017). However, the TOC content was found to be lower as suggested for the Manasbal Lake (8.33%) bottom sediments (Babeesh et al. 2017b). This also points to the higher organic activity prevailing in the Anchar Lake in comparison with Wular Lake.

The C/N ratio of lake sediments is an indicator of proportion of allochthonous and autochthonous OM supplied to the lake surface sediments from diverse sources (Meyers 1994; Meyers and Ishiwatari 1993; Meyers and Teranes 2001). The

average C/N ratio of 12.32 indicates that the lake is governed by the mixture of terrestrial and in situ sources for accumulation of OM. This elevated ratio in the C/N is owing to the increased aquatic vegetation and wastewater discharges from the nearby watershed and direct inflow of sewage from the local settlements. The enhanced values of C/N are significantly controlled and contributed by the increased use of land classes along the lake catchment for urban and agricultural activities during the recent years. The average C/N ratio of Anchar Lake sediments (12.32) is consistent with that of Wular lake sediments (12.07) (Shah et al. 2017). However, compared to Manasbal Lake (Avg. = 15.48) (Lone et al. 2017) these sediments exhibit a relatively lower C/N values.

Environmental risk assessment

Environmental risk assessment indices (Igeo, CF, PLI, EF) supplemented by statistical methods were applied to assess the present environmental and trophic status of the lake ecosystem. Metal pollution in lake sediments is well known by the human interference and partly by weathering input from bedrock lithology (Xiao et al. 2014). The environmental risk assessment of trace metals suggests low to moderate contamination of the lake sediments. This is mainly attributed to their incorporation by anthropogenic influences mainly from agriculture practices, urban domestic sewage and land runoff, which is in strong agreement with the sampling stations. The samples collected close to the agricultural and urban land-cover sites show high pollution level index compared to the samples taken towards the central and distal portions. Some of the metals such as Cu, Ni and Zn show elevated values in the sediments either with the OM or finer fraction associated with anthropogenically active stations. Further, the lake surface sediments show mixed origin of OM (in situ

and terrestrial), suggesting contribution from both anthropogenic and natural sources. However, due to the non-existence of major industries and metal mines in the catchment area, the agricultural inputs, domestic effluents and untreated sewage discharge are major source for the increase in heavy metal pollution in the lake sediments. Similarly, Sheikh et al. (2014) and Lone et al. (2017) found that the sediment of the Wular and Manasbal lakes fall in no to moderately polluted classes, respectively. They attributed this low to moderate pollution to the anthropogenic inputs due to the absence of industrial and mining activities in the catchment and nearer to the lake margins. Further, the complex ecological and land system changes occurring rapidly along the lake catchments are the primary reasons responsible for the deteriorating health of the lakes. This also has adversely influenced the erosion and other earth surface processes in and around the lake catchment (Badar and Romshoo 2008; Romshoo and Muslim 2011; Badar et al. 2013; Rashid et al. 2013; Khanday et al. 2016).

The geochemical composition of the lake sediments depend not only on the natural processes such as the catchment erosion, but also on the anthropogenic inputs, including the use of agrochemicals, deforestation and waste disposal and dumping (Chandrajith et al. 2008). The lake geochemistry summarised data reveal that SiO_2 , CaO and Al_2O_3 are the most abundant major oxides and constitute nearly 70% of the total oxide composition. The high CaO concentration is due to both biogenic and lithogenic (terigenous) material delivered to the sediments through various processes and due to weathered calcium-rich sediments transported from dominant catchment limestone lithology (Sheikh et al. 2014). Part of the calcium is also incorporated through the shell fragments from gastropods thriving abundantly in the upper water column. The overall concentration of CaO seems to be controlled by concentration of CaCO_3 and coarser sand particles in the lake sediments as indicated by the positive correlation of CaO with CaCO_3 and sand ($r = 0.55$ and $r = 0.54$). Low concentrations of SiO_2 , Al_2O_3 and Na_2O in the surface sediments is mainly attributed to dilution effects by CaO. Elevated concentrations of S, Cl, V and P_2O_5 signify anthropogenic influences, such as use of various types of agro-fertilisers in the catchment agricultural fields. This is in consistent with the geochemical characterisation of Dal Lake sediments, which reveal differential natural and human impact in the form of sewage from surrounding habitation, agricultural fields, houseboats, hotels, parks (Jeelani and Shah 2006). In order to assess the source and intensity of weathering of the catchment rocks, major oxide and trace element data of the lake surface sediments were compared with the average upper continental crust (UCC) values in the form of normalised multi-element pattern. The negative anomalies of the SiO_2 , Al_2O_3 , Na_2O , K_2O and

enriched values of CaO indicate significant dilution effect, weak to intermediate weathering of the source rocks and significant contribution from limestone lithology (Rashid et al. 2014; Lone et al. 2017). However, Al_2O_3 and Fe_2O_3 show almost a similar trend. With the exception of CaO and P_2O_5 , the other oxides show positive correlation and broadly follow the trend of Al_2O_3 , indicating their strong association with micaceous and/or clay minerals. This suggests that most oxides are present as a result of weathering of alumina-silicate-rich rocks. The rock units present in the lake catchment in the Himalayan ranges are frequently exposed and subsequently weathered/eroded due to the rise of Himalaya in phases (Das and Haake 2003).

Among the trace elements, Rb, Sr and Y are generally similar to UCC data, whereas S, Cl and Cu with the exception of few samples show enriched values with respect to the UCC values. Zr, Pb and Nb show a slightly depleted trend. Enrichment of Cr, Cu, Zn, V, Ni, and Co in the lake can be directly attributed to several anthropogenic sources and partly bedrock lithology. Sedimentary rocks always vary (mafic or felsic) according to the nature and composition of the protolith rocks. The sediment geochemistry has long been used to investigate the provenance and the tectonic setting of the clastic sediments using certain discrimination diagrams (Bhatia 1983; Bhatia and Crook 1986; Roser and Korsch 1986; Floyd and Leveridge 1987; McLennan and Taylor 1991; Graver and Scott 1995). TiO_2 versus Al_2O_3 and TiO_2 versus Zr plots are useful to infer the provenance of lake sediments. The provenance plots for the Anchar Lake sediments (Fig. 12a, b) indicate that all the sediment samples fall along the basalt-granite line indicating a mixed source of sediments varying in composition from mafic to felsic rocks.

The Anchar Lake, located within the intermountain setting, receives large amount of sediments from the nearby surrounding catchments, which consists of diverse lithological formations suggesting a variety of provenance with variable geological settings. The catchment watershed of the Anchar Lake is characterised by varied geological formations ranging in age from Precambrian to recent (Fig. 3). The exposed lithological units of the area consists of the Panjal Volcanic Series (Panjal trap and the Agglomeratic slates), granites and metamorphic schists, Quartzites, Triassic limestone and recent Alluvium (Raza et al. 1978; Thakur and Rawat 1992; Dar et al. 2014; Bali et al. 2016; Ahmad et al. 2017). These rock types form the important source of weathered sediments that are redeposited into the lake through various waterways including the Sindh River and other catchment watershed ephemeral streams. The unique climate of the valley (cold winters) and the steep slopes enhance the physical weathering of the exposed surfaces resulting in increased erosion and subsequent deposition of sediments into the Anchar Lake (Rashid et al. 2014).

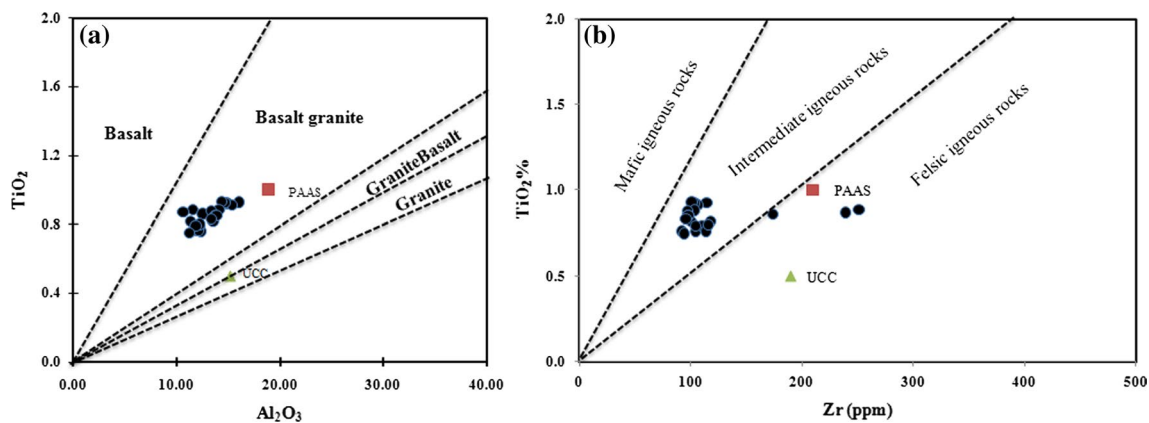


Fig. 12 Scatter plots of **a** Al_2O_3 versus TiO_2 , **b** Zr versus TiO_2 for inferring provenance of lake sediment

Multi-elemental statistics

The multi-elemental statistical techniques offer a better understanding of the geochemical processes taking place within the natural limnic systems. In the present study, PCA and Pearson correlation matrix were applied to explain the variance of interrelated variables with a smaller set of independent variables. Table 3 shows the Pearson correlation matrix obtained for the sediments in which most elements display both significant positive and negative variations. Strong positive correlations occur between SiO_2 and Al_2O_3 ($r = 0.90$), SiO_2 and Fe_2O_3 ($r = 0.86$), and SiO_2 and K_2O ($r = 0.85$). SiO_2 with TiO_2 ($r = 0.81$). Conversely, strong negative correlations were observed for SiO_2 with CaCO_3 ($r = -0.57$), CaO with Cr ($r = -0.78$), CaO with Ni ($r = -0.80$), MgO with P_2O_5 ($r = -0.81$). Al_2O_3 shows a significant positive correlation with most of the major oxides, indicating a detritus source, and its association with clay and/or micaceous minerals. CaO negatively correlates with Pb , Rb , Zn , Cu , Ni , Cr , Cl and all other major oxides signifying its geogenic source. Sr correlates positively with TOC ($r = 0.71$), whereas Rb shows positive correlation with clay and most of the major oxides except for CaO and P_2O_5 . The correlation coefficient of CaCO_3 with CaO ($r = 0.55$) indicates that most of the Ca in the sediments is derived from carbonate-rich source rocks. CaO shows a negative correlation with all the other oxides indicating the dilution effect. A significant positive correlation of S , Cl , V , Cu , Ni , and Zn with each other in the surface sediments indicates their anthropogenic inputs in addition to their detritus origin. Phosphorous and Sulphur are typically associated with lacustrine OM (Wetzel 2001).

The principal component plot for various parameters in rotated matrix (Fig. 13a) analysis followed using varimax normalisation was applied to extract the variables. The significant positive relationship shared between silt and TOC indicates that they serve as a major sink for OM

accumulation. The close affinity of S with P_2O_5 is probably due to their similar source from the nearby agricultural fields. The close association of Cu , Zn , Ni , Cl , Co , S and Cr is due to their similar origin by anthropogenic influences. Close association of major oxides, V and clay in the surface sediments seems to be controlled by weathering of detrital source rocks. The enrichment of trace metals along anthropogenically active stations and their association with OM also points to human sources.

The cluster analyses were applied to verify similarities among the various physico-chemical parameters and to find out similar groups which were mutually correlated within the sediment dataset. The dendrogram (Fig. 13b) indicates two major stable clusters/associations for all the studied parameters. Cluster 1 reveals that sulphur has a positive relationship with Cl signifying strong anthropogenic source into the lake. However, cluster 2 reveals a significant relationship between Sr with other parameters indicating their geogenic sources. Cu , Ni , Zn and Pb were moderately enriched in the studied sediments indicating that these metals were probably governed by anthropogenic sources. The occurrence of various agricultural, horticultural and other land-use sites located along the catchment areas and the use of various types of crop fertilisers, pesticides and cattle slurry ingressed in the lake aid in the anthropogenic pollution of the lake sediments. The repeated application of fertilisers and pesticides in the catchment agriculture and horticulture fields is responsible for the accumulation of Cd , S , As , Pb , Hg , Ni , P , and V in the lake surface sediments coupled with surface runoff processes. Similarly, Co , Mn and Cr are probably accumulated due to sewage sludge and domestic solid wastes sourced from the catchment areas, tourist picnic parks and boating activities.

Further, we have compared the trace metal concentration of Anchar Lake sediments with other reported national and international lake pollution studies (Table 4). The concentration of Mn was lower than the geochemical

Table 3 Pearson correlation matrix for understanding the sediment quality parameters of the Anchar Lake ($r > 0.6$ is significant at 95% confidence level; $n = 24$)

	Sand	Silt	Clay	OM	CaCO ₃	C/N	TOC	SiO ₂	CaO	Al ₂ O ₃	Fe ₂ O ₃	MgO	K ₂ O	Na ₂ O	TiO ₂	P ₂ O ₅	MnO	S	Cl	V	Cr	Co	Ni	Cu	Zn	
Sand	1.00																									
Silt	-0.11	1.00																								
Clay	-0.25	-0.94	1.00																							
OM	-0.32	-0.19	0.30	1.00																						
CaCO ₃	0.46	0.10	-0.26	-0.61	1.00																					
C/N	0.10	-0.04	0.01	-0.46	0.07	1.00																				
TOC	0.09	0.55	-0.57	-0.10	0.12	-0.15	1.00																			
SiO ₂	-0.26	-0.53	0.61	0.12	-0.57	0.18	-0.51	1.00																		
CaO	0.54	0.27	-0.46	-0.23	0.55	0.02	0.44	-0.76	1.00																	
Al ₂ O ₃	-0.28	-0.57	0.66	0.25	-0.57	0.00	-0.57	0.90	-0.67	1.00																
Fe ₂ O ₃	-0.34	-0.55	0.66	0.36	-0.60	-0.15	-0.46	0.86	-0.69	0.96	1.00															
MgO	0.18	-0.39	0.32	-0.04	-0.11	0.23	-0.64	0.49	-0.05	0.62	0.49	1.00														
K ₂ O	-0.37	-0.50	0.62	0.31	-0.57	-0.06	-0.53	0.85	-0.68	0.97	0.97	0.56	1.00													
Na ₂ O	-0.04	-0.62	0.62	-0.02	-0.25	0.35	-0.74	0.59	-0.47	0.62	0.49	0.42	0.56	1.00												
TiO ₂	0.24	-0.62	0.52	-0.04	-0.30	0.23	-0.52	0.81	-0.43	0.71	0.62	0.62	0.59	0.56	1.00											
P ₂ O ₅	-0.24	0.50	-0.40	0.23	-0.01	-0.32	0.38	-0.48	-0.13	-0.55	-0.42	-0.81	-0.45	-0.40	-0.63	1.00										
MnO	-0.14	-0.24	0.28	0.18	-0.54	0.08	-0.12	0.61	-0.43	0.60	0.61	0.29	0.61	0.28	0.46	-0.22	1.00									
S	-0.50	0.34	-0.15	0.24	-0.13	-0.41	0.23	-0.29	-0.30	-0.26	-0.09	-0.72	-0.13	-0.18	-0.60	0.82	-0.17	1.00								
Cl	-0.23	-0.32	0.40	0.07	-0.27	-0.15	-0.13	0.52	-0.64	0.32	0.44	-0.27	0.31	0.31	0.33	0.18	0.24	0.39	1.00							
V	-0.26	-0.03	0.12	0.15	-0.49	-0.18	0.03	0.59	-0.44	0.42	0.46	0.07	0.45	-0.11	0.34	-0.08	0.45	-0.07	0.34	1.00						
Cr	-0.44	-0.35	0.50	0.32	-0.62	-0.19	-0.36	0.82	-0.78	0.90	0.94	0.35	0.93	0.36	0.51	-0.22	0.60	0.07	0.47	0.60	1.00					
Co	-0.29	-0.40	0.49	0.12	-0.10	0.12	-0.46	0.33	-0.30	0.32	0.39	0.33	0.32	0.40	0.30	-0.27	0.08	-0.02	0.32	-0.29	0.17	1.00				
Ni	-0.51	-0.42	0.59	0.46	-0.64	-0.22	-0.30	0.73	-0.80	0.80	0.89	0.16	0.84	0.42	0.42	-0.07	0.61	0.22	0.54	0.32	0.87	0.41	1.00			
Cu	-0.32	-0.20	0.31	0.13	-0.32	-0.04	-0.12	0.56	-0.68	0.53	0.61	0.15	0.50	0.08	0.40	0.00	0.36	0.10	0.52	0.19	0.63	0.46	0.71	1.00		
Zn	-0.49	-0.06	0.23	0.21	-0.29	-0.14	-0.14	0.38	-0.76	0.41	0.51	-0.08	0.45	0.10	0.12	0.32	0.24	0.47	0.53	0.07	0.61	0.39	0.71	0.89	1.00	

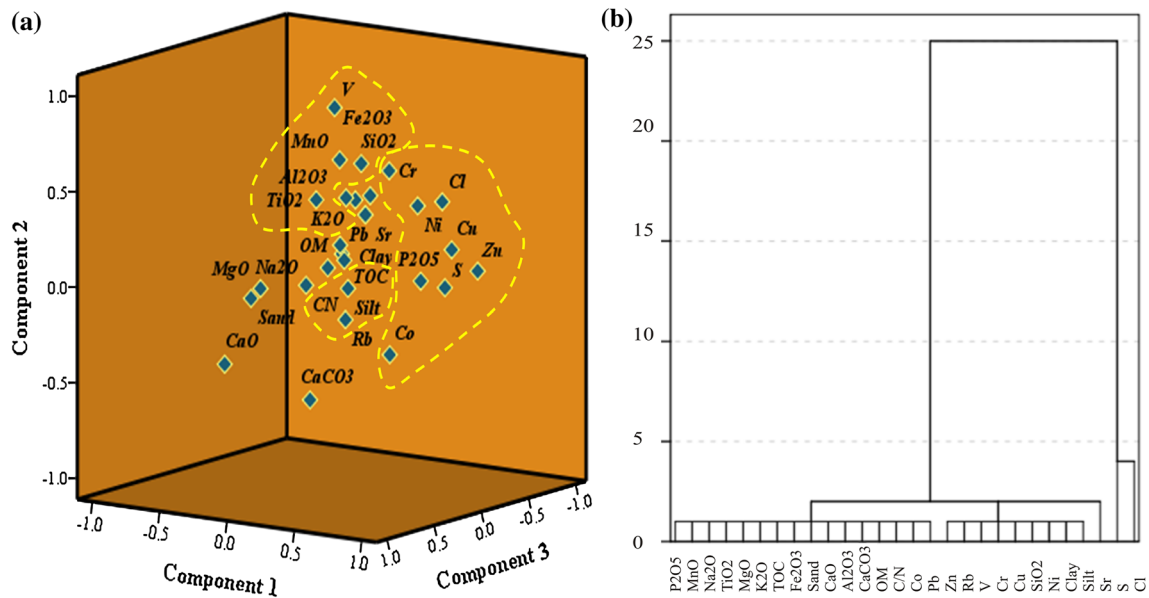


Fig. 13 Principal component plot (rotated matrix) (a) and dendrogram (b) showing association of variables for Anchar Lake sediments

Table 4 A comparison of the investigated trace metals levels ($\mu\text{g/g}^{-1}$) with other national and international studies

S. no.	Lake	Fe	Mn	Cr	Cu	Pb	Zn	Co	Ni	References
1	Rewalsar Lake, India	19,374	387	75	42	39.4	353	–	44	Brijraj and Birgit (2003)
2	Kodaikanal Lake, India	105,229	48	451.8	54.5	44.7	112.5	1402.3	115.3	Balamurugan et al. (2014)
3	Wular Lake, India	54,775	–	160.27	47.33	–	–	19.77	57	Rashid et al. (2014)
4	Aibi Lake, NW China	–	–	51.49	39.89	39.57	114.59	–	28.27	Abuduwaili et al. (2015)
5	Dal Lake, India	10,570	–	–	104.52	25.1	263.2	18.2	15.7	Jeelani and Shah (2006)
6	Chaohu Lake, China	36.5	1.12	81.9	28.9	52.4	152	–	37.2	Liu et al. (2012)
7	Renuka Lake, India	37,583	–	196.3	340	35.87	147.6	–	36.7	Das et al. (2008)
8	Simly Lake, Pakistan	6122	647	41	23.4	41	132	53.2	–	Iqbal et al. (2016)
9	Mansar Lake, India	28,000	–	63	26.4	32.67	67	35	46	Das et al. (2006)
10	Lake Nasser, Egypt	12,418	279.6	30.7	21.78	11.21	35.38	–	27.56	Goher et al. (2014)
11	Anchar Lake	51,601	734.4	81	68.13	26.6	130.93	21.66	54.03	This study
12	Background values	56,300	950	100	55	125	70	25	75	Taylor (1964)

background values but higher than the reported studies. Similarly, Cu and Zn levels were higher than the standard background values. Ni, Fe and Mn content in the Anchar Lake is higher when compared to concentrations reported from other Himalayan lakes. However, Wular Lake has a slightly higher concentration of Ni, Fe and Mn levels when compared to the Anchar Lake trace metal data. The trace metal data of the Anchar Lake were found relatively higher than the other published reports and seems to have gradually increased since the past few decades in the Himalayan lakes particularly Anchar and Wular Lakes (Table 4). This gradual increase is owing to the progressive influence of anthropogenic and natural sources such as increased human activities, untreated sewage dumping

and weathering of catchment rocks (Badar et al. 2013; Sheikh et al. 2014).

Conclusions

The present study is a maiden attempt to examine the source and influence of various anthropogenic pollutants and trace metals that control and alter sediment chemistry of the Anchar Lake. Environmental changes along the lake catchment area since the last few decades have left important geochemical imprints in the lake surface sediments in terms of anthropogenic influences. This study provides detailed data for understanding the major processes (physical and

chemical) that control recent sediment deposition within the Anchar Lake.

The textural analyses of the lake floor sediments indicate that most of the samples are clayey silt to silty clay with only one sample falling in sandy–clay–silt domain. Clay was found to be enriched along central and deeper portions of the lake. The OM, CaCO₃ and C/N ratio results reveal that the sediments are organically rich and the provenance of OM is composed of mixed sources and origin (allochthonous and autochthonous). The major oxide geochemistry reflects a higher concentration of CaO, MgO and TiO₂ compared to the UCC values. The significant enrichment of CaO in silica-poor samples indicates the calcium dilution effect. In the provenance diagrams, all the analysed sediment samples fall along the basalt–granite line indicating mixed sources ranging in composition from mafic to felsic rocks. Environmental assessment indices suggest that the surface sediments are low to moderately contaminated with Cu, Ni, Zn, Co and Cr concentrations. The concentration of other trace metals is relatively low. Further, higher trace metal pollution was found along the sampling stations that receive abundant anthropogenic inputs including the expanded urbanisation zones, agriculture and horticulture sites. These findings offer useful information regarding the sediment quality within the lake. Further, it identifies the surface sediments polluted with respect to trace elements such as S, Cl, Cu, Zn, Ni and Pb that are a direct threat to the health of the lake life (flora and fauna) and thus demands continued monitoring and mitigation efforts.

Acknowledgements Aasif Mohamad Lone is grateful to Anna University, Chennai, for the Anna Centenary Research Fellowship (ACRF) that enabled him to carry out this work.

Rayees Ahmad Shah thanks the DST, New Delhi for the DST PURSE fellowship and Fousiya A A acknowledges the funds received through the Rajiv Gandhi National fellowship, UGC, New Delhi. All the authors thank the manuscript handling editor and the two anonymous reviewers for their constructive comments and suggestions that helped in the better presentation of the work and the manuscript. Mohammad Rafiq is acknowledged for his help during the manuscript preparation.

References

- Abuduwaili J, Zhang ZY, Jiang FQ (2015) Assessment of the distribution, sources and potential ecological risk of heavy metals in the dry surface sediment of Aibi lake in Northwest China. *PLoS ONE* 10(3): e0120001. <https://doi.org/10.1371/journal.pone.0120001>
- Agrawal DP, Kusumgar S, Krishnamurthy RV (1985) Cenozoic climatic changes in Kashmir: the multidisciplinary data. In: Agrawal DP (ed) *Climate and geology of Kashmir: the last four million years*. Today & Tomorrows Publishers and Printers, New Delhi, pp 1–12
- Agrawal DP, Dodia R, Kotlia BS, Razdan H, Sahni A (1989) The Plio-Pliocene geologic and climatic record of the Kashmir Valley, India: a review and new data. *Palaeogeog Palaeoclim Palaeoecol* 73:267–286
- Ahanger IA, Saksena DN, Mir MF (2012a) Seasonal variation in zooplankton community structure of Anchar Lake, Kashmir. *Univ J Environ Res Technol* 2(4):305–310
- Ahanger IA, Saksena DN, Mir MF, Ahanger MA (2012b) Seasonal variations in physic-chemical characteristics of Anchar Lake, Kashmir International. *J Adv Biol Res* 3(2):352–357
- Ahmad I, Chandra R (2013) Geochemistry of loess-paleosol sediments of Kashmir Valley, India: provenance and weathering. *J Asian Earth Sci* 66:73–89
- Ahmad S, Alam A, Ahmad B, Afzal A, Bhat MI, Bhat MS, Farooq M, Ahmad HF (2017) Tectonics and Natural Hazards Research Group, tectono-geomorphic indices of the Erin basin, NE Kashmir Valley, India. *J Asian Earth Sci*. <https://doi.org/10.1016/j.jseaes.2017.10.013>
- Alam A, Ahmad S, Bhat MS, Ahmad B (2015) Tectonic evolution of Kashmir basin in Northwest Himalayas. *Geomorphology* 239:114–126
- Babeesh C, Achyuthan A, Jaiswal MK, Lone A (2017a) Late quaternary loess-like paleosols and edocomplexes, geochemistry, provenance and source area weathering, Manasbal, Kashmir Valley, India. *Geomorphology* 284:191–205
- Babeesh C, Lone A, Achyuthan A (2017b) Geochemistry of Manasbal lake sediments, Kashmir: weathering, provenance and tectonic setting. *J Geol Soc India* 89:563–572
- Badar B, Romshoo SA (2008) Assessment of pollution load of Dal Lake using geospatial tools. In: *Proceedings of Taal 2007: the 12th World Lake Conference*, pp 668–679
- Badar B, Romshoo SA, Khan MA (2013) Modelling catchment hydrological responses in a Himalayan Lake as a function of changing land use and land cover. *J Earth Syst Sci* 122:433–449
- Balamurugan P, Vasudevan S (2014) Spatial distribution of grain size characteristics and its role in interpreting the sedimentary depositional environment, Kodaikanal lake, Tamil Nadu, India. *J Earth Sci Clim Change* 05:217
- Bali BS, Wani AA, Khan RA, Ahmad S (2016) Morphotectonic analysis of the Madhumati watershed, northeast Kashmir Valley. *Arab J Geosci* 9:390. <https://doi.org/10.1007/s12517-016-2395-9>
- Basavaiah N, Wiesner MG, Anoop A, Menzel P, Nowaczyk NR, Deenadayalan K, Brauer A, Gaye B, Naumann R, Riedel N, Stebich M, Prasad S (2014) Physicochemical analyses of surface sediments from the Lonar Lake, central India—implications for palaeoenvironmental reconstruction. *Fundam Appl Limnol* 184(1):51–68
- Bhat SA, Meraj G, Yaseen S, Bhat AR, Pandit AK (2013) Assessing the impact of anthropogenic activities on spatio-temporal variation of water quality in Anchar Lake, Kashmir Himalayas. *Intern J Environ Sci* 3(5):1625–1640
- Bhatia MR (1983) Plate tectonics and geochemical composition of sandstones. *J Geol* 91(6):611–627
- Bhatia MR, Crook KAW (1986) Trace element characteristics of graywackes and tectonic setting discrimination of sedimentary basins. *Contrib Miner Petrol* 92:181–193
- Blumberg S, Schutt B (2004) Character of lake floor sediments from Central Lake Abaya, South Ethiopia. In: *Lake Abaya research symposium 2004-proceedings 4*, pp 1–10
- Boyle J, Rose NL, Appleby PG, Birks HJB (2004) Recent environmental change and human impact on Svalbard: the lake-sediment geochemical record. *J Paleolimnol* 31:515–530. <https://doi.org/10.1023/B:JOPL.0000022549.07298.6e>
- Brijraj KD, Birgit GH (2003) Geochemistry of Rewalsar lake sediment, lesser Himalaya, India: implications for source-area weathering, provenance and tectonic setting. *Geosci J* 7(4):299–312
- Cesari M (2007) Estrategias de análisis y exploración de datos como soporte a la adquisición de conocimiento para modelización de

- sistemas expertos bayesianos causales. Trabajo Final de Especialidad en Ingeniería de Sistemas Expertos, ITBA
- Chandrajith R, Mahatantila K, Jayasena HAH, Tobschall HJM (2008) Geochemical characteristics of sediments from a reservoir (tank) ecosystem in Sri Lanka. *Paddy Water Environ* 6:363–371
- Chapman PM (1992) Sediment quality triad approach. Sediment classification methods compendium. U.S. Environmental Protection Agency (USEPA). Washington, D.C. EPA-823-R-92-006, 10(1), pp 10–18
- Dar RA, Romshoo SA, Chandra R, Ahmad I (2014) Tectono-geomorphic study of the Karewa Basin of Kashmir Valley. *J Asian Earth Sci* 92:143–156
- Das BK, Haake B (2003) Geochemistry of Rewalsar Lake sediment, Lesser Himalaya, India: implications for source-area weathering, provenance and tectonic setting. *Geosci J* 7(4):299–312
- Das BK, Al-Mikhlaifi AS, Kaur P (2006) Geochemistry of Mansar Lake sediments, Jammu, India: implication for source-area weathering, provenance, and tectonic setting. *J Asian Earth Sci* 26:649–668
- Das BK, Gaye B, Kaur P (2008) Geochemistry of Renuka Lake and wetland sediments, Lesser Himalaya (India): implications for source-area weathering, provenance and tectonic setting. *Environ Geol* 54:147–163
- Dean WE (2006) Characterization of organic matter in lake sediments from Minnesota and Yellowstone National Park. In: Open File Report 2006-1053, US Geological Survey Report, Reston, Virginia, pp 40
- Dung TTT, Cappuyns V, Swennen R, Phung NK (2013) From geochemical background determination to pollution assessment of heavy metals in sediments and soils. *Rev Environ Sci Biotechnol* 12:335–353
- Farooq M, Muslim M (2014) Dynamics and forecasting of population growth and urban expansion in Srinagar City—a geospatial approach. *Int Arch Photogramm Remote Sens Spat Inf Sci* 8:709–716. <https://doi.org/10.5194/isprsarchives-XL-8-709-2014>
- Floyd PA, Leveridge BE (1987) Tectonic environment of Devonian Gramscatho basin, south Cornwall: framework mode and geochemical evidence from turbiditic sandstones. *J Geol Soc Lond* 144:531–542
- Ganaie MA, Parveen M, Balkhi MH (2015) Physico-chemical profile of three freshwater flood plain lakes of River Jhelum, Kashmir (India). *Intern J Multidiscip Res Dev* 2(11):527–532
- Goher ME, Farhat HI, Abdo MH, Salem SG (2014) Metal pollution assessment in the surface sediment of Lake Nasser, Egypt. *Egypt J Aquat Res* 40:213–224
- Gopal V, Krishnakumar S, Peter TS, Nethaji S, Kumar S, Jayaprakash M, Maghesh NS (2016) Assessment of trace element accumulation in surface sediments off Chennai coast after a major flood event. *Mar Poll Bull*. <https://doi.org/10.1016/j.marpolbul.2016.10.019>
- Graver JJ, Scott TJ (1995) Trace elements in shale as indicators of crustal provenance and terrain accretion in south Canadian Cordillera. *Geol Soc Am Bull* 107:440–453
- Hakanson L (1980) An ecological risk index for aquatic pollution control. a sedimentological approach. *Water Res* 14(8):975–1001
- Hedges JJ, Stern JH (1984) Carbon and nitrogen determinations of carbonate-containing solids. *Limnol Oceanogr* 29:657–663. <http://doi.org/10.4319/lo.1984.29.3.0657>
- Heiri O, Lotter AF, Lemcke G (2001) Loss on ignition as a method for estimating organic and carbonate content in sediments: reproducibility and comparability of results. *J Paleolimnol* 25:101–110
- Hilton J (1985) A conceptual framework for predicting the occurrence of sediment focusing and sediment redistribution in small lakes. *Limnol Oceanogr* 30:1131–1143
- Holmer M, Storkholm P (2001) Sulphate reduction and sulphur cycling in lake sediments: a review. *Freshw Biol* 46:431–451
- Ingram RL (1970) Procedures in sedimentary petrology. Wiley, New York, pp 49–67
- Iqbal J, Saleem M, Shah MH (2016) Spatial distribution, environmental assessment and source identification of metals content in surface sediments of freshwater reservoir, Pakistan. *Chem Erde* 76:171–177
- Jeelani G, Shah AQ (2006) Geochemical characteristics of water and sediment from the Dal Lake, Kashmir Himalaya: constraints on weathering and anthropogenic activity. *Environ Geol* 50(1):112–123
- Jin Z, Cao J, Wu J, Wang S (2006a) A Rb/Sr record of catchment weathering response to Holocene climate change in Inner Mongolia. *Earth Surf Process Landf* 31:285–291
- Jin Z, Li F, Cao J, Wang S, Yu J (2006b) Geochemistry of Daihai Lake sediments, Inner Mongolia, north China: implications for provenance, sedimentary sorting, and catchment weathering. *Geomorphology* 80:147–163
- Kango RA, Dubey KP, Zutshi D (1987) Sediment chemistry of Kashmir Himalayan lakes: clay mineralogy. *Chem Geol* 64:121–126
- Kasilingam K, Gandhi MS, Krishnakumar S, Magesh NS (2016) Trace element concentration in surface sediments of Palk Strait, southeast coast of Tamil Nadu, India. *Mar Poll Bull* 111:500–508
- Kastratovic V, Jacimovic Z, Bigovic M, Durovic D, Krivokapic S (2016) Environmental status and geochemical assessment sediments of Lake Skadar, Montenegro. *Environ Monit Assess* 188(449):1–15
- Kaul V, Hando VK, Raina R (1980) Physico-chemical characteristics of Nilnag- Ahigh altitude forest lake in Kashmir and its comparison with the valley lakes. *Proc Indian Natl Sci Acad* 46(4):528–541
- Kaushal S, Binford MW (1999) Relationship between C: N ratios of lake sediments, organic matter sources, and historical deforestation in Lake Pleasant, Massachusetts, USA. *J Paleolimnol* 22:439–442
- Khan JA, Gavali RS, Shouche YS (2012) Exploring present status of hydrochemistry and sediment chemistry of Dal Lake, Kashmir and effect of anthropogenic disturbances on it. *Indian J Innov Dev* 1(7):554–571
- Khanday SA, Yousuf AR, Reshi ZA, Rashid I, Jehangir A, Romshoo SA (2016) Management of Nymphoides peltatum using water level fluctuations in freshwater lakes of Kashmir Himalaya. *Limnology*. <https://doi.org/10.1007/s10201-016-0503-x>
- Li F, Huang J, Zeng G, Yuan X, Li X, Liang J, Wang X, Tang X, Bai B (2013) Spatial risk assessment and sources identification of heavy metals in surface sediments from the Dongting Lake, Middle China. *J Geochem Explor* 132:75–83
- Liu E, Shen J, Yang X, Zhang E (2012) Spatial distribution and human contamination quantification of trace metals and phosphorus in the sediments of Chaohu Lake, a eutrophic shallow lake, China. *Environ Monit Assess* 184:2105–2118
- Lone A, Babeesh C, Achyuthan H, Chandra R (2017) Evaluation of environmental status and geochemical assessment of sediments, Manasbal Lake, Kashmir, India. *Arab J Geosci* 10:1–18
- Lottermoser BG, Schutz U, Boenecke J, Oberhansli R, Zolitschka B, Negendank JFW (1997) Natural and anthropogenic influences on the geochemistry of Quaternary lake sediments from Holzmaar, Germany. *Environ Geol* 31(3/4):236–247
- Mahapatra DM, Chanakya HN, Ramachandra TV (2011) C: N ratio of Sediments in a sewage fed Urban Lake. *Intern J Geol* 3(5):86–92
- McLennan SM, Taylor SR (1991) Sedimentary rocks and crustal evolution: tectonic setting and secular trends. *J Geol* 99:1–21
- McManus J, Severmann S, Cohen AS, McKay JL, Bo R, Montanye A, Hartwell AM, Rebecca LP, Brucker B, Wheatcroft R (2015) The sedimentary response to a rapid change in lake level in Lake Tanganyika. *Palaeogeogr Palaeoclimatol Palaeoecol* 440:647–658
- Meyers PA (1994) Preservation of elemental and isotopic source identification of sedimentary organic matter. *Chem Geol* 114:289–302

- Meyers PA (2003) Applications of organic geochemistry to paleolimnological reconstructions: a summary of examples from the Laurentian Great Lakes. *Org Geochem* 34:261–289
- Meyers AP, Ishiwatari R (1993) Lacustrine organic geochemistry—An overview of indicators of organic matter sources and diagenesis in lake sediments. *Org Geochem* 20:867–900
- Meyers PA, Lallier-Verges E (1999) Lacustrine sedimentary organic matter records of Late Quaternary paleoclimates. *J Paleolimnol* 21:345–372
- Meyers PA, Teranes JL (2001) Sediment organic matter. In: Last WM, Smol JP (eds) *Tracking environmental changes using lake sediment physical and geochemical methods*, vol 2. Kluwer Academic, Dordrecht, pp 239–270
- Minyuk PS, Brigham-Grette J, Melles M, Borkhodoev BY, Glushkova O (2007) Inorganic geochemistry of El'gygytgyn Lake sediments (northeastern Russia) as an indicator of paleoclimatic change for the last 250 kyr. *J Paleolimnol*. <https://doi.org/10.1007/s10933-006-9027-4>
- Muller G (1979) Schwermetalle in den sediments des Rheins—Veränderungen seit. *Umaschan* 79:778–783
- Rashid I, Farooq M, Muslim M, Romshoo SA (2013) Assessing the impact of anthropogenic activities on Manasbal Lake in Kashmir Himalayas. *Intern J Environ Sci* 3(6):1–12
- Rashid SA, Ganai JA, Masoodi A (2014) Major and trace element geochemistry of lake sediments, India: implications for weathering and climate control. *J Geosci, Arab*. <https://doi.org/10.1007/s12517-014-1639-9>
- Raza M, Ahmad A, Mohammad A (1978) *The valley of Kashmir, a geographical interpretation of the land*, vol 1. Vikas Publishing House Pvt Ltd, New Delhi
- Romshoo SA, Muslim M (2011) Geospatial Modeling for assessing the nutrient load of a Himalayan Lake. *Environ Earth Sci* 64:1269–1282
- Roser P, Korsch RJ (1986) Determination of tectonic setting of sandstone mudstone suites using SiO₂ content and K₂O/Na₂O ratio. *J Geol* 94:635–650
- Sakan SM, Djordjevic DS, Manojlovic DD, Polic PS (2009) Assessment of heavy metal pollutants accumulation in the Tisza river sediments. *J Environ Manag* 90:3382–3390
- Sampei Y, Matsumoto E (2001) C/N ratios in a sediment core from Nakaumi lagoon, southwest Japan. *Geochem J* 35:189–205
- Sarah S, Jeelani G, Ahmed S (2011) Assessing variability of water quality in a groundwater-fed perennial lake of Kashmir Himalayas using linear geostatistics. *J Earth Syst Sci* 120(3):399–411
- Sarkar S, Prakasam M, Upasana S, Bhushan R, Gaury PK, Meena NK (2016) Rapid sedimentation history of Rewalsar Lake, Lesser Himalaya, India during the last fifty years—estimated using Cs and Pb dating techniques: a comparative study with other North-Western Himalayan Lakes. *Himal Geol* 37(1):1–7
- Shah RA, Achyuthan H, Lone A, Ravichandran R (2017) Diatoms, spatial distribution and physicochemical characteristics of the Wular Lake Sediments, Kashmir Valley, Jammu and Kashmir. *J Geol Soc India* 90:159–168
- Sheela AM, Letha J, Joseph S, Chacko M, Sanalkumar SP, Thomas J (2012) Water quality assessment of a tropical coastal lake system using multivariate-cluster, principal component and factor analysis. *Lake Res Manag* 17:143–159
- Sheikh JA, Jeelani G, Gavali RS, Shah AR (2014) Weathering and anthropogenic influences on the water and sediment chemistry of Wular Lake, Kashmir Himalaya. *Environ Earth Sci* 6:2837–2846
- Shepard FP (1954) Nomenclature based on sand–silt–clay ratios. *J Sedim Petrol* 24:151–158
- Singh IB (1982) Sedimentation pattern in the Karewa Basin, Kashmir Valley, India, and its geological significance. *J Paleontol Soc India* 27:71–110
- Singh AK, Hasnain SI, Banerjee DK (2003) Grain size and geochemical partitioning of heavy metals in sediments of the Danodar River—a tributary of the lower Ganga, India. *Environ Geol* 39:90–98
- Suresh G, Sutharsan P, Ramasamy V, Venkatachalapathy R (2012) Assessment of spatial distribution and potential ecological risk of the heavy metals in relation to granulometric contents of Veeranam Lake sediments, India. *Ecotoxicol Environ Saf* 84:117–124
- Tang W, Shan B, Zhang H, Zhang W, Zhao Y, Ding Y, Rong N, Zhu X (2014) Heavy metal contamination in the surface sediments of representative limnetic ecosystems in eastern China. *Sci Rep* 4(7152):1–7
- Tarras-Wahlberg H, Everard M, Harper DM (2002) Geochemical and physical characteristics of river and lake sediments at Naivasha, Kenya. *Hydrobiologia* 488:27–41
- Taylor SR (1964) Abundance of chemical elements in the continental crust: a new table. *Geochim Cosmochim Acta* 28:1273–1285
- Taylor SR, McLennan SM (1985) *The continental crust: its composition and evolution*. Blackwell Scientific Publication, Carlton, p 312
- Thakur VC, Rawat BS (1992) *Geological map of the Western Himalaya*. Published Under the Authority of the Surveyor General of India. Printing Group of Survey of India, 101 (HLO)
- Tomlinson DC, Wilson JG, Harris CR, Jeffrey DW (1980) Problems in the assessment of heavy-metal levels in estuaries and the formation of a pollution index. *Helgol Mar Res* 33:566–575
- Wang L, Wang Y, Zhang W, Xu C, An Z (2014) Multivariate statistical techniques for evaluating and identifying the environmental significance of heavy metal contamination in sediments of the Yangtze River, China. *Environ Earth Sci* 71(3):1183–1193
- Wedepohl KH (1995) The composition of the continental crust. *Geochim Cosmochim Acta* 59:1217–1232
- Wetzel RG (2001) *Limnology: lake and river ecosystems*, 3rd edn. Elsevier Academic Press, San Diego, p 1006
- Xiao HF, Zhang S, Guan Y, Lu S, Gao Y, Sun Q, Xu H, Li M, Wang J, Pei X (2014) Assessment of potential risks associated with heavy metal contamination in sediment in Aobaopao Lake, China, determined from sediment cores. *Ecotoxicology* 23:527–537
- Yao SC, Xue B (2015) Sedimentary geochemical record of human-induced environmental changes in Huanggaihu Lake in the middle reach of the Yangtze River, China. *J Limnol* 74:31–39
- Yao ZG, Bao ZY, Gao P (2006) Environmental assessments of trace metals in sediments from Dongting Lake, Central China. *J China Univ Geosci* 17:310–319
- Yousuf T, Yousuf AR, Mushtaq B (2015) Comparative account on physico-chemical parameters of two wetlands of Kashmir, Valley. *Intern J Recent Sci Res* 6(2):2876–2882
- Zhang J, Chen X, Liu Q, Wu L (2014) Distribution and potential risk assessment of heavy metals in main estuaries of Lake Poyang's tributaries. *Res Environ Yangtze Basin* 23:95–100
- Zutshi DP, Subla BA, Khan MA, Wanganeo A (1980) Comparative limnology of nine lakes of Jammu and Kashmir Himalayas. *Hydrobiologia* 72:101–112