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Sedimentation Pattern and its Controlling Factors in Indian Lakes

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ABSTRACT

Sedimentation in lakes occurs from the time of its formation and continues till the final deposition. The rate of sedimentation varies depending upon climate, geology, soil cover and relief. In the present study, an attempt has been made to investigate the distribution and variation of sedimentation rate in Indian lakes. For this purpose, Indian lakes are classified into three zones viz., North Indian lakes (NIL), Central Indian lakes (CIL), South Indian lakes (SIL) and 27 sampling points distributed throughout India has been considered among all three zones. Correlation of rate of sedimentation data with catchment area, surface area and lithology is done in order to understand the controlling factors, rainfall and temperature data are also taken into consideration to know the effect on the sedimentation rate. In all three zones, the highest precipitation observed 2488, 1800 and 4000 mm/yr in the Nainital lake, Chilika lake and Pookot lake, respectively and temperature fluctuations in the northern region of India is higher than the central and southern region. The results showed that the NIL have relatively higher sedimentation rate compared to the CIL and SIL due to slopy terrain, higher precipitation, temperature and lithological inconsistency in northern Indian region whereas all these factors are less effective in other two zones with a minor contribution from other independent factors. NIL have ~0.634-0.804 cm/yr and ~0.636-1.117 cm/yr more sedimentation rate than CIL and SIL, respectively.

KEYWORDS: *Indian Lakes, Dating techniques, Sedimentation rate, Temperature and Precipitation*

INTRODUCTION

The sedimentation is one of the vital problems in Indian lakes and largely responsible for reducing the numbers, depth, and size of the basins which further resulted in reducing the life of the lake (Singh et al., 2008). In India, lakes provide sustenance and strength to the people of the concerned regions as these are used for fishing, drinking, irrigation, recreation, and other basic needs. The exact information of sedimentation rate and the factors responsible for it; can assist in the preservation and future planning of lakes (Kumar et al., 2007).The sedimentation rate generally varies from one lake to another and it depends on catchment lithology, rock type, vegetation, slope, and erosional factors like river and wind. The lakes receive sediments from the catchment area in the form of clay, silt, sand, gravels, and inorganic and organic matters, which got deposited at the lake bottom. The sedimentation rate in the lakes also increases due to eutrophication caused by the incompletely decomposed matter settled down at the bottom of lakes (Hasler, 1947). The anthropogenic activities are also responsible for increasing sedimentation inside lakes (Rai et al., 2007). The eutrophication and anthropogenic activities in the catchment areas of Indian lakes are increasing gradually which indicates probabilistic more sedimentation in the nearby future. Ecological succession which is a natural process also continues to play the role of reducing lakes; without the intervention of human beings. The sedimentation from the catchment area brings a lot of contaminants to the lakes which hamper the natural scenario of lakes. The deposition thus has decreased the use of small-sized lakes and others are reducing at a worrisome rate (Kumar et al., 2007).

Several studies have been carried out in the past to know about hydro-geochemistry of several lakes in country (Bhat and Pandit, 2014; Chakrapani, 2002; Chandrakiran, 2013; Das and Kaur, 2008; Jain et al., 2007; Khadka and Ramanathan, 2013; Kumar et al., 2006; Mondal et al., 2012; Nautiyal et al., 2012; Sarah et al., 2011; Singh and Jain, 2013; etc.) but very few are there to know the sedimentation rate in Indian lakes (Fort et al., 1989; Kumar et al., 2007; Kusumgar et al., 1992; Rai et al., 2007; Shukla et al., 2002; etc). The number of studies by several workers were mostly concentrated on the local parameters. There are certain techniques to know the sedimentation rate like hydrographical mapping, physical measurement, in-situ surveying, and applications of radioisotopes (Gharibreza et al., 2013; Routh et al., 2007). The sediments contain various types of a radionuclide that come from external sources and get deposited with sediments which in turn provide help to understand the mystery of sediments accumulation at the bottom. The most common technique to know about the sedimentation rate is the use of ^{210}Pb and ^{137}Cs radioisotopes which get deposited in the sediments and the actual age of these isotopes is the age of sediment deposition. In the present study an attempt has been made to know the sediment rate in Indian lakes by comparing and reviewing the earlier studies.

The detrital input in the lake is presumed to be associated with the climatic factors, geomorphology, hydrogeology, and catchment slopes of the lake and therefore, thedetritus can be used to infer the dynamics of drainage morphology and basin size (Henderson and Last 1998; Olsen 1990). Whereas, an authigenic and biogenic contribution can inform on the autochthonous sediment production and nutrient availability. These are primarily considered to be a causal factor for the sedimentation in the lakes. The lakes can thus be an essential archive of long climatic and environmental variability. However, the sedimentation rates derived from radionuclides produced by atomic explosion can help to derive short term historical changes in lake catchment and imply to the understanding of natural versus anthropogenically forced factors in lake evolution (Ayana et al., 2014; Gharibreza et al., 2013; Sindhu et al., 2007; Tibor et al., 2014). The mountain lakes exhibit a higher sedimentation rate because they are commonly surrounded by steep slopes and the eroded materials directly transport to the lake due to rainwater, seasonal variation in the different plant canopy, and more recent developmental activities (Das et al., 1994). This higher sedimentation rate has reduced the life of several small-sized lakes of Indian regions, and several lakes are on the verge of extinction due to higher sedimentation (Humane et al., 2016; Singh et al., 2008). The present study aims to understand the scenario of the sedimentation rate and its pattern in the different geographical Indian regions.

STUDY AREA AND METHODOLOGY

The present study concentrates on the sedimentation rate and its pattern in the Indian lakes. For this purpose, the lakes of India have been classified into three types (Figure 1) mainly based on their geographic location as NIL, CIL and SIL.In total 27 lakes spread throughout India in which 8 lakes from northern region, 12 lakes from central region and 7 lakes from southern region have been chosen randomly to assess the rate of sedimentation and its pattern. The data on the rate of sedimentation is compiled from the published works of several investigators also the geology of the catchment, morphometric features, temperature and annual rainfall has been consideration to achive our goal. The studies on sedimentation pattern and geochronology of the lake sediments by the earlier workers are mainly based on the ^{14}C (radiocarbon), ^{137}Cs (cesium-137), and ^{210}Pb (lead-210) dating techniques. The regional comparison of sedimentation rate data followed by the study of controlling factors for the higher and lower sedimentation rate in the selected lakes have been carried out in present study.

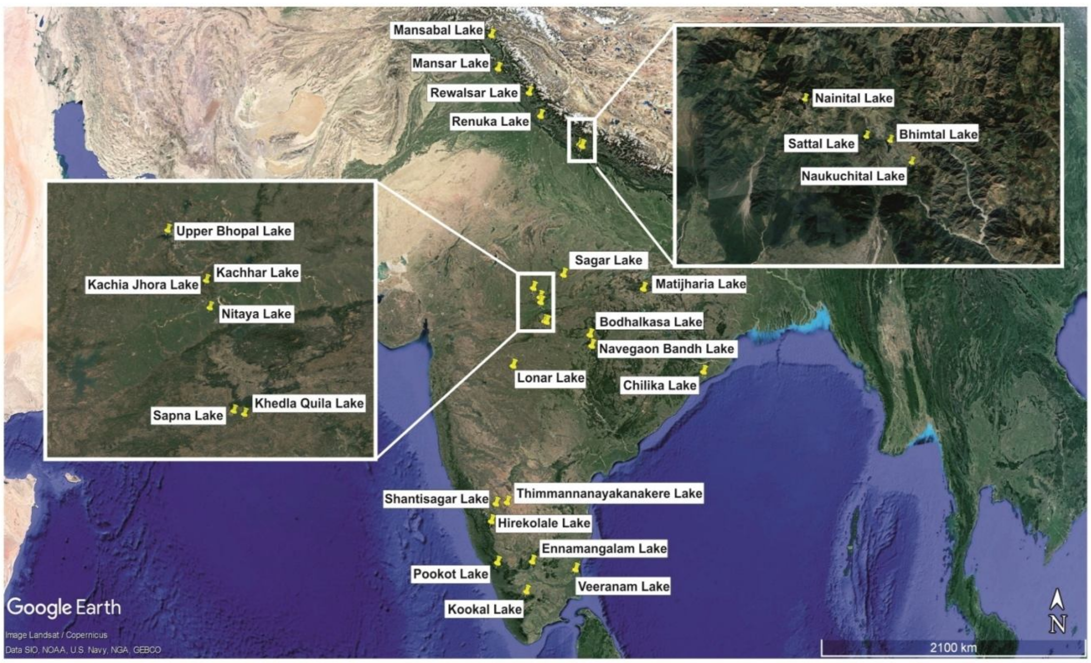

Figure 1: Geographical locations of the selected lakes in three different zones in India; (i) Northern Indian Lakes, (ii) Central Indian Lakes, (iii) Southern Indian Lakes.

RESULTS AND DISCUSSION

Sedimentation rate in the North Indian Lakes

Deposition rate of sedimens of NIL calculated by ^{137}Cs, ^{210}Pb dating techniques (Table 1) show a wide range of sediments depositional rate. Bhimtal lake witnessed 0.43-1.50 cm/yr (Kumar et al., 2007), Nainital lake recorded 0.60-1.35 cm/yr (Kumar et al., 1999), Naukuchiatal (0.38-0.95 cm/yr) (Kumar et al., 2007), Sattal (0.66-0.81 cm/yr) (Kumar et al., 2007), Dal (0.40-1.60 cm/yr) (Kumar et al., 2007) and Mansar lake (0.14-0.37 cm/yr) (Rai et al., 2007) sedimentation rate. The lower sedimentation rate of Mansar lake (0.23 cm/yr) and higher sedimentation rate of Rewalsar lake (3.35 cm/yr) indicated a huge variation despite locating in the same climatic zone (Rai, 2007; Sarkar et al.,2016) further establishes and support the role of other controlling factors other than geomorphology and slope. The average sedimentation rate of the NIL is~0.743-1.231 cm/yr.

Sedimentation rate in the Central Indian Lakes

The sedimentation rate of CIL shows a decrease in sedimentation rate compared to north Indian lakes which are mainly the Himalayan lakes. The sedimentation rate of CIL viz., Upper lake Bhopal (0.21-1.27 cm/yr) (Kumar et al., 2007), Chilikalake (0.28-0.78 cm/yr) (Warrier et al., 2009), Lonarlake (0.018-0.58 cm/yr) (Menzel et al., 2014), Nitayalake (0.01-0.027 cm/yr) (Quamar et al., 2012), Sagar lake (0.31-1.08 cm/yr) (Kumar et al., 2007), Sapna lake (0.045 cm/yr) (Chauhan et al., 2012), Kachhar lake (0.077-0.172 cm/yr) (Quamar et al., 2011), Khedla Quila lake (0.077-0.25 cm/yr) (Quamar et al., 2014), Matijaria lake (0.028 cm/yr) (Quamar et al., 2014), Navegaon Bandh lake (0.931 cm/yr) (Humane et al., 2016), Bodhalkasa lake (0.68 cm/yr) (Humane et al., 2016) and Kachia Jhora-lake (0.037 cm/yr) (Quamar et al., 2015) determined by AMS^{14}C,^{137}Cs and ^{210}Pb radioisotopes is shown in Table 1. Nitaya Lake, Madhya Pradesh received least depositional rate of sedimentation (0.01-0.027 cm/yr) and Upper lake Bhopal, Madhya Pradesh is highest (0.21-1.27 cm/yr) sedimentation rate in central Indian region (Kumar et al., 2007; Quamar and Chauhan 2012). Inspite of Nitaya village receiving quite higher average rainfall (1340 mm/yr) compared to Upper Bhopal Lake (1200 mm/yr), the sedimentation rate of Nitaya village (0.01-0.027 cm/yr) is lower compared to Upper Bhopal lake. This anomaly can be explained by the fact that the sedimentation rate of Upper Bhopal Lake is higher because of the silt load carried by the Kolans stream.

Lakes in the central region i.e. Lonar lake, Sagar lake, and Chilika lake have sedimentation rate 0.018-0.58, 0.31-1.08, and 0.28-0.78 cm/yr respectively (Kumar et al. 2007; Prasad et al. 2014; Warrier et al. 2009). As comparing the average rainfall data from central Indian region lakes, the Lonar lake, Maharashtra receives the lowest annual rainfall (680 mm/yr) and Chilika lake, Orissa has highest annual rainfall (1800 mm/yr) (Anoop et al. 2013; Zachmann et al. 2009).

The two contrasting lakes of Central India located in Gondia District of Maharashtra under two different geographical settings were also taken into consideration, Bodhalkasa Lake is a pristine lake situated in dense forest while the other one Navegaon Bandh Lake near to city with high anthropogenic influence which is also a major source of fishing and recreation. The average rate of sedimentation in the Bodhalkasa Lake was found to be 0.6797 cm/yr and the Navegaon Bandh Lake was 0.9307 cm/ yr. The pristine Bodhalkasa Lake shows less rate of sedimentation owing to the dense forest around it that limits rate of erosion thereby less supply of sediments. Whereas the Navegaon Bandh Lake shows higher rate of sedimentation owing to higher erosion because of anthropogenic activities going around it. This view is supported by the fact that the core sediments of the Bodhalkasa Lake show enrichment of Pb (1.03 times) in contrast with no enrichments in the Navegaon Bandh Lake (Humane et al., 2016).The average sedimentation rate of the CIL are~0.109-0.427 cm/yr.

Sedimentation rate in the South Indian Lakes

In the southern part of India, the sedimentation rate has been discussed for different lakes located in Karnataka, Tamil Nadu and Kerala states. In Karnataka state, Thimmannanayakanakere (TK) lake covering an area of 0.17 km^2, Hirekolale lake (HK) with an area extent of ~0.109km^2 and Shantisagara lake (SS)~25 km^{2}are considered. The TK Lake receives an average rainfall of ~640 mm/yr where as Shantisagar lake receives an annual rainfall varying in between 419 to 1400mm/yr with an average rainfall of 795 mm/yr in comparison to HK lake that receives high rainfall 1925mm/yr (Figure 5). The average water depth of lakes TK, HK, and Shantisagar are 5.5m, ~6m and 5m, respectively (Radhakrishna and Vaidyanadhan, 1997). Measured sedimentation rate obtained from ^{14}C dates in TK is 0.099cm/yr(Shankar et al., 2006; Warrior et al., 2014) while in HK sedimentation rate varies from 0.084 to 0.096 cm/yr with mean sedimentation rate of the entire column is0.09cm/yr (i.e comparable with 0.099 cm/yr for TK) (Shetty et al., 2018).However, the sedimentation rate varies from 0.04to 0.006 cm/yr with an average sedimentation rate of 0.019 cm/yr in Shantisagar lake (Sandeep et al., 2017). This suggest that, the catchment received sediment during south-west monsoon in Shantisagara lake (Sandeep et al.,2017) and recorded a low sedimentation rate due to low-rainfall area and delivered less sediment in the Shantisagara lake.

In Tamil Nadu, geologically, the catchment of the Ennamangalam lake comprises of Al, Fe rich charnockites, hornblende-biotite gneiss and granites forming a part of southern granulite provinces. In the Ennamangalam Lake having a surface area of the lake is ~1.54 km^2, sedimentation rate varies from 0.032 to 0.036 cm/yr with an average 0.034cm/yr (Basu et al., 2017; Mishra et al., 2019). The Kukkal Lake covering an area of 0.18 km^2 reveals that the average sedimentation rate (0.01cm/yr). It is suggested that human activity reflects this increasing rate that may be caused by the agricultural, deforestation, and urbanization practices around the lake areas (Rajmanickam et al., 2017). Presently, the lake has a catchment area of 2to3 km^2 mostly forested and undisturbed by human activities and geologically composed of Precambrian charnockite as bedrock associated with hornblende-biotite gneiss, granite and quartzite (Rajmanickam et al., 2017).The catchment receives 1690mm/yr annual rainfall. Furthermore, the Veeranam Lake in Cuddalore district of Tamil Nadu exhibits that the rate of sedimentation based on ^{137}Cs and ^{210}Pb dating which reveals that the life span of the Veeranam lake is around 965.71 yrs and 1056.25 yrs respectively (Pruthiviraj et al., 2014). The sedimentation rate in the Veeranam lake shows mean accumulation rate of 0.32cm/yr (^{210}Pb) and 0.35 cm/yr (^{137}Cs) with an average 0.34 cm/yr. The Pookotor Pookode lake covers an area of less than 0.1 km^2, surrounded by the Wayanad Group of rocks (charnockite and hornblende-biotite gneiss), the maximum water column is~7m and the average rate of sediment accumulation is 0.02cm/yr. It receives maximum rainfall of ~4000mm (Sandeep et al., 2012) from both South West and North East monsoons. In the Pookot lake basin, climatic fluctuations are shown by wet and dry conditions that are represented by the occurrence of sandy clay and the presence of finer sediments such as silty clay and clayey silt. Since mid-Holocene (6240B.P.) to present shows a dry phase with wetter intervals of a short period caused by the intense south-west monsoon (Veena et al., 2014).The average sedimentation rate of the SIL is ~0.107-0.114 cm/yr.

Factor Controlling Sedimentation Rate in Indian Lakes

The sedimentation rate in a lake is the combined effect of natural factors such as rainfall, lithology, and slope of the area as well as the anthropogenic activities. The water and wind are the main sources of the weathering and erosion of any area. The evaporation and eutrophication (natural/man-made) are also the reasons for the lake diminishing. The Indian monsoon system is unpredictable all over the Indian sub-continent that accelerates the erosion and sediment supply to therivers, streams and lakes. The rate of catchment erosion is higher where deforestation has occurred. The sedimentation rate in the near-shore is high while the rate is less in the central portion of the lakes (Kumar et al., 2007). It is important to note that due to sedimentation the average loss worldwide of storage in lakes is between 0.5 and 1.0 percent/annual (White, 2012). Other important factors which control the sediment accumulation rate in lakes like: (i) Rainfall (ii) Lithology and (iii) Slope have been described in detail to understand their significance.

Rainfall

The main source of precipitation on the Indian sub-continent is the south-west and north-east Indian monsoon, and the Mid Latitude Westerlies. The south-west monsoon can precipitate over the Western Ghats, central India, the Ganga Plain and then some parts of the Himalaya while a little part of southern India receive rainfall by the north-east monsoon or retreat monsoon (Gadgil, 2003). When the precipitation occurs, the raindrop interacts with the soft rocks and sediment particles that made it to break due to shear stress generated by the kinetic energy of raindrop and soil surface (Hudson, 1975; Wischmeir, 1960). These eroded sediments are broken into tiny pieces due to attrition (wind/river), and the transportation of these fine sediments (clay/silt) by suspension and coarse sediments (boulders) occurs by rolling.

So, the rivers, streams and lakes get more/less sediment supply due to the variability in rainfall. The sediments deposited in the lake are mainly by surface runoff and eutrophication. The Himalaya is the main source of the water for the Indian sub-continent and receives rainfall by the south-west monsoon and westerlies. The Himalayan lakes lie in the tropical/subtropical, temperate and semi-arid to arid climatic zone and receive average annual rainfall of 1196-2488 mm/yr (Figure 2). At the time of monsoon season, the Lesser Himalayan and Siwalik Himalayan lakes are getting silted higher as compared to the central and southern Indian lakes (Figure 5). The average sedimentation rate of the NIL is ~0.743-1.231 cm/yr. In the Himalayan region, increased tourist activities and the local population also affects the NIL environment. The NIL recorded higher sedimentation rates due to the interference of mankind as well as variation in the Himalayan geomorphological, annual rainfall temperature and lithological conditions. The annual rainfall and temperature in the NIL is high (Fig. 5) as compared to both CIL and SIL. The sedimentation rate in the Rewalsar, Bhimtal, Renuka, Sattal, and Nainital lakes is higher relative to Naukuchiatal, Mansar and Mansabal (Table 1). The main reason for the high sedimentation rate is due to the anthropogenic activities and the lithology of the Rewalsar, Bhimtal, Renuka, and Nainital lakes which make them more prone to weathering activities so that the catchments rocks have faster erosion (Table 1).

The central part of Indian lakes lies in the tropical/subtropical monsoonal zone and gets precipitation between June and September. Average annual rainfall received by the CIL is in between 680-1800 mm/yr. The average sedimentation rate of the CIL is ~0.109-0.427 cm/yr. The sedimentation rate of Upper Bhopal, Chilika, Lonar and Sagar is higher than the Nitaya, Sapna, Kachhar, Khedla Quila, Matijaria and Kachia Jhora lakes (Table 1).

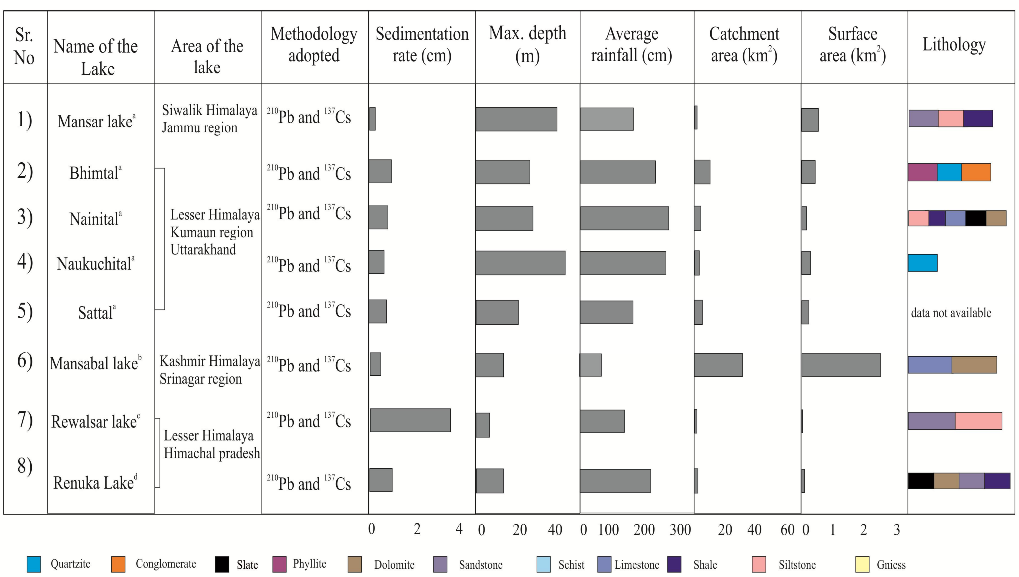

Figure 2: Details of the different lake parameters from the North Indian lakes (modified after Diwate et al., 2020).

Table 1: The list of lakes with their geographical information and the dating techniques used to calculate sedimentation rate

S. No.	Lake Name	Altitude (mamsl)	Latitude	Longitude	Sedimentation Rate(cm/yr)	Dating technique	References
1	Mansar Lake	666	32.48	75.23	0.14-0.37	^{137}Cs	Rai et al., 2007
2	Mansabal Lake	1583	34.9	74.52	0.23	^{137}Cs, ^{210}Pb	Kumar et al 2007
3	Rewalsar Lake	1400	31.55	76.83	2.78-3.92	^{137}Cs, ^{210}Pb	Sarkar et al., 2016
4	Renuka Lake	672	77.45	30.61	0.72	^{137}Cs, ^{210}Pb	Diwate et al.,2020
5	Bhimtal	1340	29.21	79.24	0.43-1.50	^{137}Cs, ^{210}Pb	Kumar et al., 2007
6	Nainital Lake	1937	29.24	79.28	0.60-1.35	^{137}Cs, ^{210}Pb	Kumar et al., 1999
7	Naukuchital	1300	29.32	79.58	0.38-0.95	^{137}Cs, ^{210}Pb	Kumar et al., 2007
8	Sattal Lake	1280	29.34	79.53	0.66-0.81	^{137}Cs, ^{210}Pb	Kumar et al., 2007
9	Lonar Lake	563	19.97	76.5	0.018-0.58	AMS^{14}C	Menzel et al., 2014
10	Sagar Lake	517	23.83	78.75	0.31-1.08	^{137}Cs, ^{210}Pb	Kumar et al., 2007
11	Nitaya Lake	250	22.667	77.7	0.01-0.027	^{14}C	Quamar et al., 2012
12	Chilika Lake	2	19.74	85.33	0.28-0.78	^{210}Pb	Warrier et al., 2009
13	Bhopal Lake	508.65	23.17	77.25	0.21-1.27	^{137}Cs, ^{210}Pb	Kumar et al., 2007
14	Sapna Lake	658	21.88	77.91	0.045	AMS^{14}C	Chauhan et al., 2012
15	Kachhar Lake	502	22.87	77.67	0.077-0.172	^{14}C	Quamar et al., 2011
16	Kachia Jhora-Lake	502	22.87	77.67	0.037	AMS^{14}C	Quamar et al., 2015
17	KhedlaQuila Lake	658	21.88	77.91	0.077-0.25	AMS^{14}C	Quamar et al., 2014
18	Matijharia Lake	551	23.25	82.55	0.028	^{14}C	Quamar et al., 2014
19	Veeranam Lake	11	11.15	79.35	0.34	^{137}Cs, ^{210}Pb	Pruthiviraj et al., 2014
20	Shantisagar Lake	612	14.14	75.88	0.006-0.04	AMS^{14}C	Sandeep et al., 2017
21	Kukkal Lake	1887	10.16	77.22	0.01	AMS^{14}C	Rajmanickam et al., 2017
22	Pookot Lake	775	11.54	76.03	0.175	AMS^{14}C	Kizhur et al.,2019; Sandeep et al., 2015
23	Hirekolale Lake	1120	13.21	75.42	0.084-0.096	AMS^{14}C	Shetty et al., 2018
24	Ennamangalam Lake	263	11.65	77.59	0.032-0.036	AMS^{14}C	Basu et al., 2016; Mishra et al., 2019
25	Thimmannanayakanakere Lake	732	14.2	76.4	0.099	AMS^{14}C	Shankar et al., 2006; Warrier et al., 2014
26	Bodhalkasa Lake	314	21.33	80.02	0.6797	^{210}Pb	Humane et al., 2016
27	NavegaonBandh Lake	314	20.88	80.1	0.9307	^{210}Pb	Humane et al., 2016

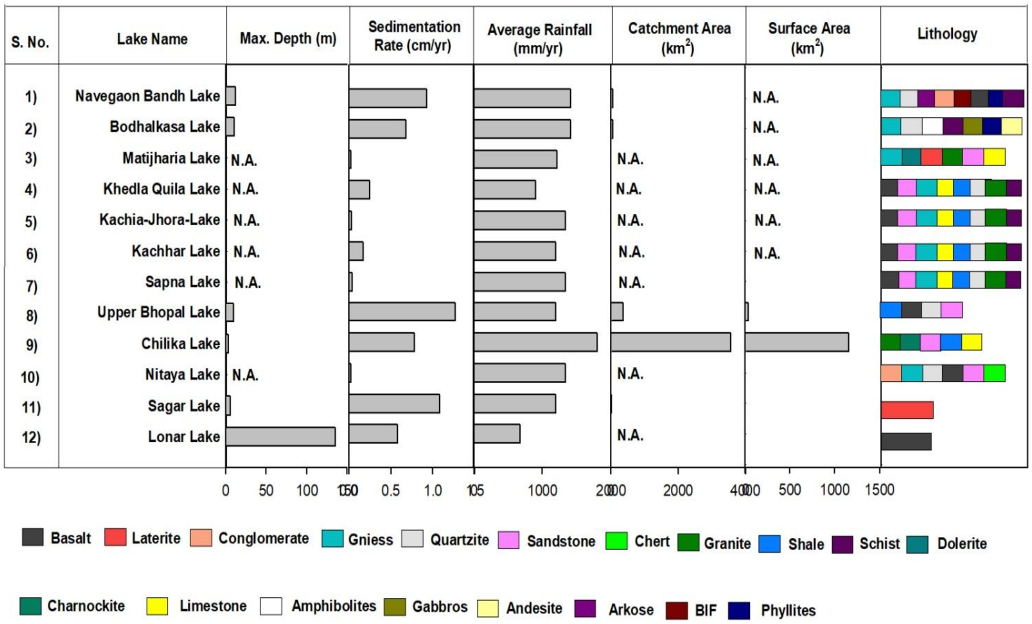

Figure 3: Details of the different lake parameters from the Central Indian lakes.

The Higher sedimentation rate in Sagar and Upper Bhopal lakes is due to the silt load carried out by Kanera canal and Kolans stream respectively. The Chilikalake gets high sediments due to the high annual rainfall in this area (1800 mm/yr) and supply of sediments by the Daya River and Bhargavi River (tributaries of Mahanadi River). Lonar Lake is a natural saline lake formed by meteoritic impact and the water level of the lake mainly depends on the low/high south-west monsoon rainfall and groundwater condition. The sedimentation rate of Nitaya, Sapna, Kachhar, Khedla Quila, Matijaria and Kachia Jhora lakes is low due to the low sediment supply due to low water input. The annual rainfall of Nitaya, Sapna, Kachhar, KhedlaQuila, Matijaria and Kachia Jhora lakes lies between 900-1340 mm/yr and sediments get deposited by water through surface runoff at the time of the south-west monsoon (Fig. 3).

The SIL experiences the tropical semi-arid climate and precipitation received mainly from the south-west and north-east monsoons. Average annual rainfall received in the SIL ranged from 640-4000 mm/yr. The SIL mostly get sediment due to rainfall, catchment erosion and the anthropogenic activities. The average sedimentation rate of SIL is ~0.107-0.114 cm/yr which is less than the NIL and SIL. So the variation in the sedimentation pattern in SIL is mainly due to rainfall and anthropogenic activities. Veeranam Lake has the highest sedimentation rate while the Kukkal lake hasthe lowest (Table 1), both get precipitation by the north-east monsoon. In Veeranam lake, the sediment deposited gradually in swampy or marshy land whereas in Kukkal lake was undisturbed by human activities and geomorphologically, the lake is controlled by faults and lineaments in and around the basin which may also lead to the low sedimentation rate. The Veeranam and Kukkal lakes sedimentation rate vary due to the human activities and the catchment erosion. The highest rainfall (4000 mm/yr) is received by the Pookot lake while the lowest by the Thimmannanayakanakere lake (640 mm/yr) (Fig. 4).

The Pookot Lake gets precipitation from the south-west as well as north-east monsoons, the Shantisagara catchment from south-west monsoon and the Ennamangalam lake from north-east monsoon. Veeranam, Pookot, Hirekolale and Thimmannanayakanakere lakes have ahigh sedimentation rates as compared to the Shantisagara, Kukkal and Ennamangalam lakes due to the rainfall variation, human interference and the catchment erosion. However, Shantisagar lake rainfall is highly variable which is also seen in the magnetic parameters like χlf, χfd, χARM and Saturated Induced Remanent Magnetism (SIRM),also the high clay content (Sandeep et al., 2017) experiences low sedimentation rate. The lake-level variations in the closed basin are controlled especially by the percentage of carbonate in the lake system (Bischoff et al., 1997).

Temperature and humidity variations also play an important role (Wetzel, 2001). The lake productivity is further enhanced due to temperature which favours the production of autochthonous carbonate within the lake. High temperature shows algal productivity which results in CO_2 content depletion in the lake water and favours to form DIC (dissolved inorganic carbon). However, increased and decreased the carbonate percentage of lacustrine sediments indicated the high and low lake level, respectively. In TK Lake as magnetic parameters like χfd, $\chi fd\%$, χARM and SIRM, as the low (high) values indicate arid (humid) conditions (Warrior et al., 2014). Furthermore, the HK sediment magnetic signal shows that the sediment rate is derived by and not caused by anthropogenic magnetite, greigite and biogenic magnetite or dissolution of magnetic minerals (Shetty et al., 2018) so it has low sedimentation (Figure 5).

Hence the HK is not influenced by anthropogenic activities and it is far away from human settlement. Additionally, Pookot lake also experienced low erosion and low rainfall with uniform catchment erosion and detrital influx as an abundance of C_4 plant (Kizhur et al., 2019). However, increased sediment in the Pookotlake is mainly contributed by organic matter with high content of C_{org} in the sediment samples suggested that derived influx of organic matter from the surrounding area and May also occurs from aquatic plants. On the other hand in Ennamangalam Lake the sediment deposits due to surface runoff with high rainfall as evident from end-member mixing analysis derived from grain size (Mishra et al., 2019). So, these processes affect the health of lakes due to the high sedimentation rate and decreases the volume of water.

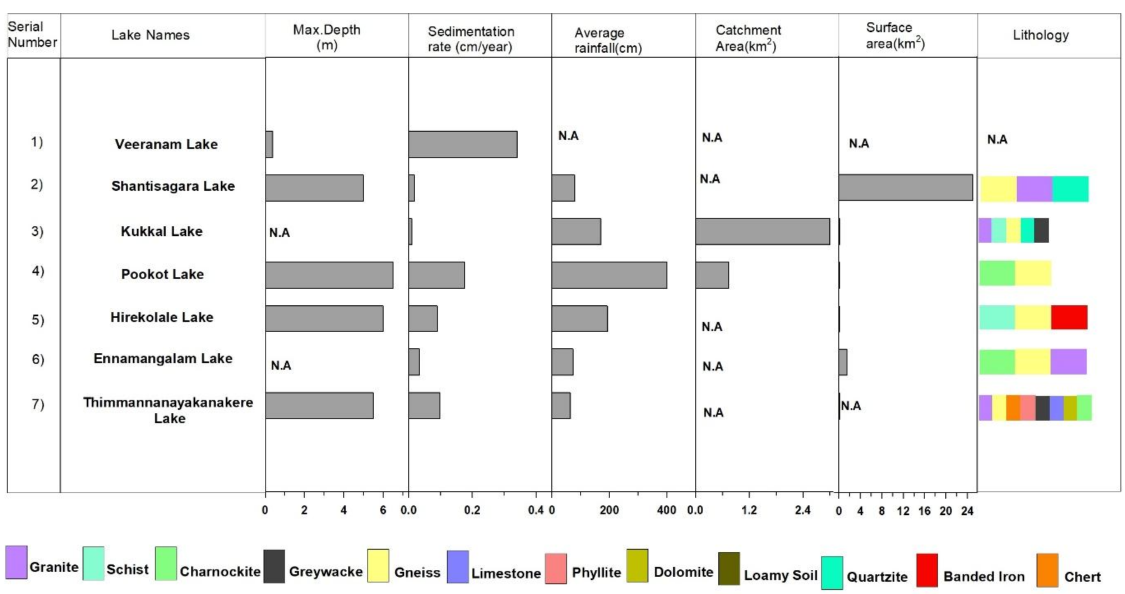

Figure 4: Details of the different lake parameters from the South Indian lakes

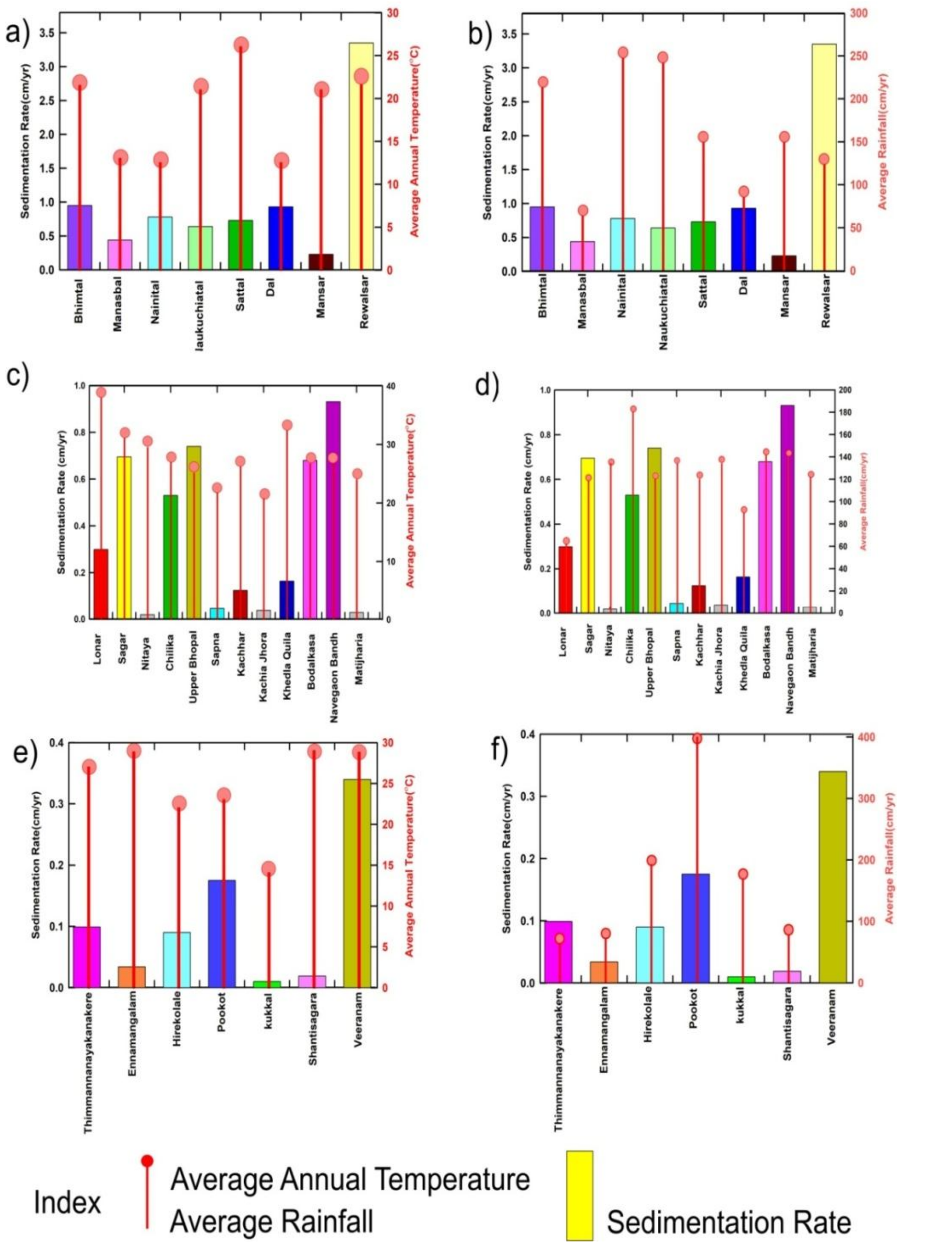

Figure 5: Temperature and rainfall data correlation with sedimentation rate of Indain lakes; a) and b) shows the corelation of sedimentation rate (cm/yr) with average rainfall (cm/yr) and average annual temperature of NIL; c) and d) shows the corelation of sedimentation rate (cm/yr) with average rainfall (cm/yr) and average annual temperature of CIL; e) and f) shows the corelation of sedimentation rate (cm/yr) with average rainfall (cm/yr) and average annual temperature of SIL.

Lithology and Slope

One of the major components that affect the sedimentation rates in lakes is lithology and the physical properties of rocks such as its resistance to erosion (soft rock less resistant and hard rock more resistant). Rainfall and lithology are the main factors that cause erosion of the rocks but slope accelerates this erosive power. It is high when the slope is steep and low when the slope is gentle. So, steepness and length of the slope cause higher erosion than the gentle slope but it depends on the rainfall (high/low) and lithology (soft rocks/hard rock's) (Dutta, 2016; Liu et al. 1994). These parameters are essential for the variations in sedimentation rates and impacts on Indian lake's storage capacity. The Himalayan rocks are more susceptible to physical and chemical weathering while the central and southern India is less susceptible. Where the catchment rocks are shale, siltstone, dolomite, limestone and sandstone; these rocks are more susceptible (soft rocks) to the erosion than (hard rock) quartzite, slate, phyllite, schist, gneiss. Changes in the intensity of erosion in the catchment are usually accompanied by an increase of elements, such as Mg, Na, K, or Fe (Boyle 2001; Engstrom and Wright 1984; Dearing and Foster 1993). Also, the Himalayan Mountain has gentle to a steep slope that speeds up the erosional activities. So, these are the causes of the high sedimentation rate in NIL. The central and southern India mostly has flat terrain that are susceptible to less weathering and erosion and hence the CIL and SIL get less sediments supply resulting in lesser sedimentation rate.

The NIL study islocated in the Himalayan regions which have hillslope as well as the lithological and geomorphological variation that control the sediment supplies to the lakes and rivers (Figure 2). Most part of the north India are underlain by quartzite, conglomerate, slate, phyllite, dolomite, sandstone, schist, granite, limestone, shale, siltstone and gneiss (Fig. 2). Therefore the rate of sediment supplies to the basins in the Himalayan lakes increases. The central parts of India have mostly flat regions except for the Vindhyan and the Satpura ranges. The CIL has basalt, laterite, conglomerate, gneiss, quartzite, chert, granite, shale, schist, dolerite, charnockite and limestoneas the dominant lithology (Figure 3). The rate of erosion in CILregions mainly depends upon the anthropogenic activities and the effect of summer months (Figure 5) due to high annual rainfall and temperature. The SIL has lithology granite, schist, charnockite, greywacke, gneiss, limestone, phyllite, dolomite, loamy soil, quartzite, banded iron and chert (Figure 4). The southern part of India is also flat except the Eastern and Western Ghats mountain ranges that affect the monsoonal winds in these regions. Due to these climatic changes (rainfall and temperature) and human activities, the lakes in these regions are silted (Figure 5).

CONCLUSION

As per the analysis,it is found that the NIL has high sedimentation rate because of the Himalayan climate, its geological and geomorphological variability that prone to a high rate of weathering and erosion as compare to the CIL and SIL. Sedimentation rate in Himalayan lakes were mostly affected by the anthropogenic activities that have accelerated the sedimentation rate in the past 50 years. The slope is considered as one of the important controlling factors for high sedimentation rate in NIL. A higher rate of sedimentation has diminished the usefulness of several small lakes and many others are shrinking at an alarming rate. Besides the slope, the variation in geology also play a vital role in controlling the sedimentation rate in the northern and lakes of other parts of India. The present study suggests the paucity of sedimentation rate records in the Central Himalayan region compared to the other. From this study it is strongly recommended o frame the policy for measurement of the sedimentation rate from time to time, considering the importance of lakes for livelihood. The rate of the sedimentation is the major controlling unit for the life of the lake and hence should be given due importance. Accordingly, policy makers and ruling government should design and implement the policy for the lakes towards sustainable development.

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