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Study of hydro-chemical characteristics of Lake Nainital in response of human interventions, and impact of twentieth century climate change

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Abstract In the recent past, lake water is greatly deteriorated due to the global climate change and anthropogenic activities because they affect both quantity and quality of the available water. Lakes in mountainous regions are generally small, and therefore more sensitive to natural/human-induced perturbations. In this study, the effect of twentieth century global climate change and human interventions was analysed for Lake Nainital, located in a densely populated valley of Kumaun Himalaya. For this purpose, gridded ($0.5^0 \times 0.5^0$ and $0.25^0 \times 0.25^0$) climatic (T_{Mean}, T_{Max}, T_{Min}, DTR and rainfall) data of period 1901–2000 available on monthly time steps were employed for detecting an annual and seasonal pattern of change in the climatic variables in the lake region. The samples of water collected between February 1994 and July 1996 for different months from the lake were used for determining the physical and chemical characteristics of the lake water. The samples were analysed for: field parameters (temperature, pH, EC), major ions (Ca^{2+}, Mg^{2+}, Na^+, K^+, HCO_3^-, SO_4^{2-} and Cl^-), and nutrients (NO_3^- and PO_4^-). Results derived from the chemical analysis of water reveal that anthropogenic activities, increased in recent past, have accelerated the deterioration and eutrophication processes of the lake. However, decrease in mean annual and monsoonal rainfall will affect the various components of water balance and may cause reduction in the lake volume in the future.

Introduction

Water is a valuable natural resource as it makes life possible on the earth. Spatial patterns of the earth's terrestrial biomes are largely affected by the availability of water. The distribution of water on the earth is uneven, and a large volume (~ 97 %) of the available water is saline in nature (Thompson 1999). The fresh water resources, easily reachable for direct human use, are less than 1 %. Lakes, although much smaller by volume and area, constitute the principal reserve of surface fresh water with a total volume of 91,000 km^3, i.e. 20 % (Gleick 1993; Musy and Higy 2010). Lakes are originated in the regions where the physical setting help in accumulation of water and the hydro-climatic environment supports the persistence of the water body (Shelton 2009). It is formed in thousands or millions of years depending on the actions of forces such as erosion, deposition, earth movements and volcanic activity. Based on the geology and geomorphology of the region, lakes can either be endorheic or exorheic. The endorheic lakes represent a closed system with no outflow, whereas exorheic lakes are drained by outflowing rivers. The high reliance of endorheic lakes, on the balance of inflows and evaporation, makes them very sensitive to human interventions and climate change (Arnell and Liv 2001). The likely impact of anthropogenic climate change on lakes

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consists of deep stratification and nutrient loss from surface water, reduced hypolimnetic oxygen in deep water (below the thermocline), and expansion in range for many invasive aquatic weeds (Bates et al. 2008). According to Laird et al. (1996), the endorheic lakes of relatively small size are the most vulnerable to these kinds of perturbations.

The study conducted by Qin and Huang (1998) over Qinghai Lake (4186 km^2) in China reported a decrease in the water level as well as shrinkage in the lake area, due to a decrease in precipitation. Similar kinds of results were also observed for Issyk-Kul Lake in eastern Kyrgyzstan (Sevastyanov and Smirnova 1986) and Aral Sea (Glazovsky 1990). According to Delju et al. (2013), Urmia Lake in Iran has lost more than 6 m of its depth out of 16 m, mainly due to a dry climate and change of water consumption patterns for irrigated agricultural operations. The study of Jeelani et al. (2007) showed that the warmer temperature had affected the migrations of phytoplankton and zooplankton in Dal Lake of Kashmir (India). Verburga and Hecky (2009) examined the impact of climate change on physical properties of Lake Tanganyika in Africa. Their study revealed an increase in surface water temperature, density stratification and stability, and reduction in vertical mixing and productivity. The decrease in freshwater inflows caused by low precipitation and the increased rate of evaporation (triggered by high temperature) may bring changes in the lake regime and perhaps lead to salinization of the freshwater part. This may be likely to have an effect on lake water quality through changes in water temperature (Arnell and Liv 2001). The water quality is also deteriorated due to the accumulation of effluents and sediments in the beds of lakes transported from the surrounding area. This could have a significant influence on the lake ecosystem.

Lakes of mountainous regions are generally small and therefore more sensitive to natural or human-induced perturbations in their catchments (Vreca and Muri 2006). A large number of natural fresh water lakes occurring in the Lesser Himalayan region are famous for their quaint view, and most of them are being used for drinking and irrigation purposes. However, increasing anthropogenic activities in the recent past have greatly affected the hydrological regime of the lakes (Kumar et al. 1999). The increasing population pressure has not only raised the demand for fresh water supply but also resulted in deforestation and intensive construction activities within the lake catchment. These activities have accelerated several problems such as pollution, rapid sedimentation, eutrophication, and also affected the groundwater inflow and outflow of the lakes. For example, the inflow of eroded materials and other contaminants from the lake catchment have accelerated the eutrophication process in the Dal and Wular Lakes in Kashmir (Ishaq and Kaul 1988), and the higher rate of

sedimentation has diminished the useful life of the Khajjiar Lake in Himachal Pradesh and Sanasar Lake in Jammu. Out of 60 lakes of Kumaun Himalayan region, only 5 lakes namely, Nainital, Bhimtal, Sattal, Naukuchiatal, and Khurpatal are in existence (Jalal 1988).

The Nainital town (~ 14.32 km^2), surrounding the Lake Nainital, is an important hill station of North India. The town, which was first colonized in the 1850s, nurtured into a town of 7500 people by 1901 and to 40,000 by 2001 (Singh et al. 2001). The study of land use/land cover pattern within the catchment and adjacent hills indicates that ~ 48.4 % area is covered by forest, ~ 19.7 % by built up, 18.3 % by barren land, 9.8 % by lakes, 2.5 % roads, and 1.3 % by Flats, respectively (Saravana Kumar et al. 2001; Singh et al. 2001). The favourable climate and location of Lake Nainital attract a large number of tourists ranging from 300,000 to 400,000 annually. This has accelerated the rate of urbanization within the catchment area as the increase in the construction of buildings and roads was observed. The buildings which were 4053 in 1971, increased to 7836 in 1991, and 9020 in 2001, respectively. This has caused a high influx of heavy metals, phosphate, and nitrate in the lakes. Lake Nainital is the lifeline of the city. Approximately 40 % of the total water used for drinking and household purpose comes directly from the lake (Singh et al. 2001). The augmented anthropogenic activities have caused the increased disposal of domestic waste and other pollutants, into the lake and degraded the lake water quality.

In the past, several researchers (Pant et al. 1980, 1981, 1985; Sharma et al. 1982; Purohit and Singh 1985; Kumar et al. 1999; Chakrapani 2002; Rai et al. 2006; Jain et al. 2007; Choudhary et al. 2009) have evaluated the physical, chemical and biological characteristics of the lakes in this region. However, in none of the previous studies, the impact of climate change was addressed. Therefore, the present study is an effort in this direction where hydro-chemical characteristics and eutrophication status of Lake Nainital has been examined in the response to human interventions and climate change.

Study area

Lake Nainital, a warm monomictic and hyper-eutrophic water body (1937 a.m.s.l), is located in a densely populated valley of Kumaun Himalaya (Nainital district) of Uttarakhand (Fig. 1). The crescent-shaped lake (1.5 km long and 0.36 km wide) basin, bounded between latitudes of 29°22′44″N and 29°24′N, and longitudes of 79°26′13″E and 79°28′5″ E, was discovered in 1841 AD (Choudhary et al. 2009). It is close to the Main Boundary Thrust (MBT) that separates the Siwaliks from the Lesser Himalaya. Lake
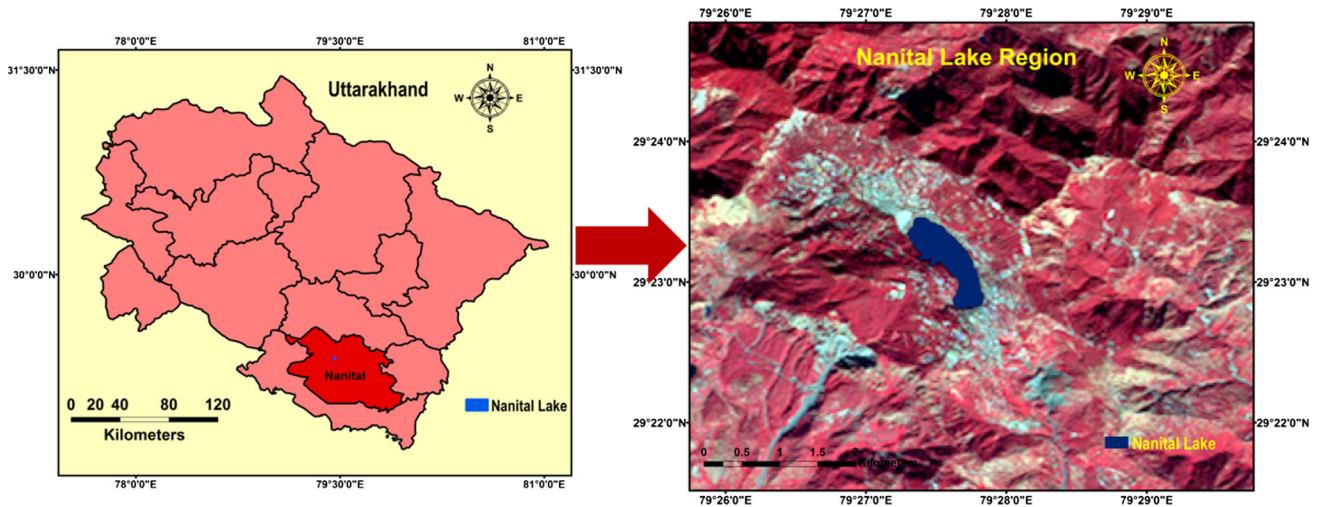
Fig. 1 Location map of study area

Nainital with a surface area of 0.46 km^2 and mean depth of 16.5 m has the maximum capacity of 8.57 million m^3 (Nachiappan et al. 2002). The area of the lake basin is 3.49 km^2 excluding Sukhatal sub-basin. The Nainital Lake is bounded by the Sher-ka-Danda hill in the east, the landslide Flat deposit in the north, the Ayarpatta hill in the west, and Balia ravine in the south. The region is characterized by rugged topography where elevation ranges from 1400 m to more than 2400 m (Fig. 2). A major part of the area has hill slopes varying from 20° to 25° with a mean value of 19°. The maximum observed hill slope is 49° whereas minimum 1° at Flats (Rawat 1987).

The study area experiences the climate of sub-tropical to sub-humid. The salient features of prevailing climate in the lake region are shown in Fig. 3. The long-term (1901–2000) mean annual temperature (T_{Mean}) is recorded 24.50 °C. The mean monthly maximum temperature (T_{Max}) varies between 21.01 °C (January) and 39.56 °C (May), and the mean monthly minimum (T_{Min}) from 7.18 °C (January) to 26.36 °C (June). The minimum (7.76 °C) and maximum (15.97 °C) diurnal variations in temperature are noted between August and April, respectively. The mean annual rainfall is 1897.13 mm, and around 86 % of total annual rainfall is received from southwest monsoon.

The geological formation of Lake Nainital basin is very complex. The sub-rotational movement along the Nani Fault blocked the upper course of Gaula River which led to the impoundment of water of the stream flowing in the Naini valley and resulted in the formation of Lake Nainital (Hashimi et al. 1993). A 100-m wide, transverse underwater ridge (running east–west) which crops out at depths of 7–20 m divided the lake in two sub-basins; Mallital (north-west) basin and Tallital (south-east) (Fig. 2). The basin is highly fragile and prone to landslides. The hill-slope instability in the region is related to the Naini Fault

and associated fractures. According to Kumar et al. (1999), around half of the area of the lake basin is covered with the debris generated by mass movement.

Geologically, the Lake Nainital basin includes folded and faulted rocks of Krol and Tal formations (Valdiya 1988). The Krol formation consists of 6 members such as Manora (calcareous slate, argillaceous limestone, and marlite), Hanumangarhi (purple shales), Barapathar (black shales and carbonaceous limestone), Pashandevi (grey and blue dolomitic limestone), Bist College (greywacke), and Sherwood (cherty and phosphatic massive dolomite) which are highly vulnerable to physical and chemical weathering (Fig. 4). The Tal formation comprises of two members such as Giwalikhet (carbonaceous shale) and Narain nagar (purple and green shale). The whole belt is also cut by numerous N–S and NE/ENE–SW/WSW trending tear faults (Valdiya 1988).

The lake region is characterized by a good network of nullahs (streams) which bring in the runoff water and also act as the major conduits of polluted sludge and silt which drains off into the lake. There are mainly 21 major and 3 minor streams but most of them are seasonal in nature except, Naina Devi and Rickshaw stand, due to spring discharge and domestic waste disposal. The Pardadhara and Chunadhara springs feed the lake. The network of streams is basically controlled by the geology of the regions, e.g. the mainstream follows the line of the Nainital Fault, and smaller streams are aligned along fractures, faults, and joints. Streams are generally scarce where rocks are massive and are made of highly permeable rocks such as dolomite and limestone. Kumar et al. (2001) and Singh et al. (2001) estimated the contribution from surface runoff, subsurface inflow, drain inflow, and direct rainfall, in the hydrological budget of the lake, which was found 25, 43, 17, and 15 %, respectively.

Contour

Digital Elevation Model

Drainage
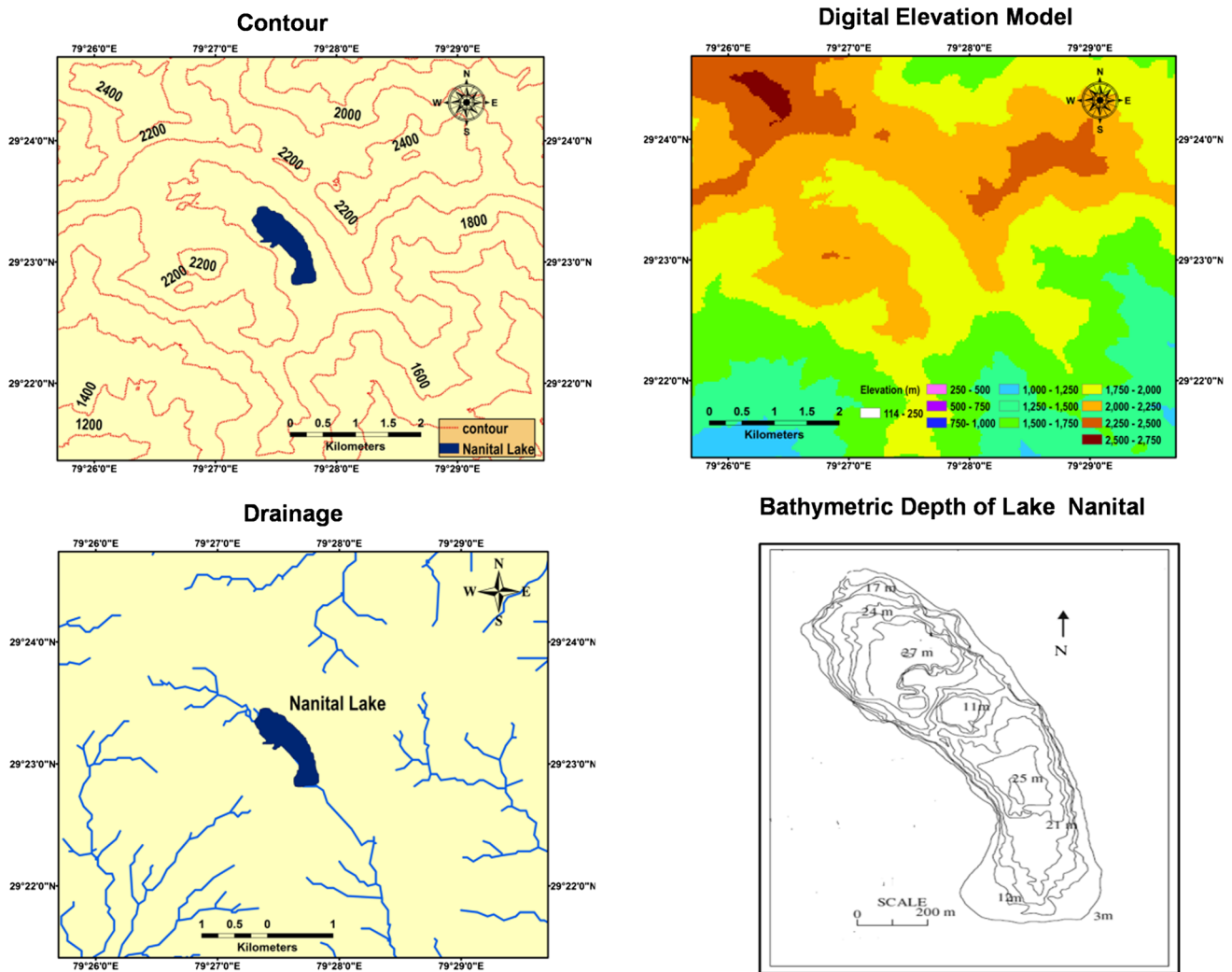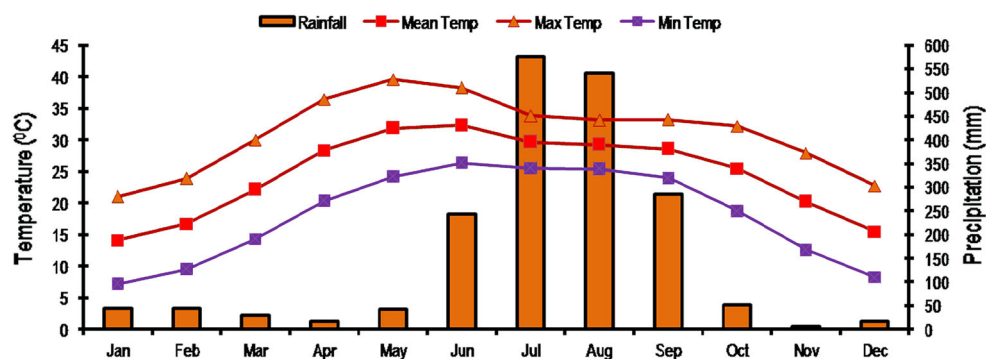
Bathymetric Depth of Lake Nanital

Fig. 2 Major topographical, drainage, and bathymetrical characteristics of Lake Nainital basin

Fig. 3 Climatic characteristics prevailed in study area (average of 1901–2000)

Materials and methods

In the present study, two types of data: (1) climatic and (2) samples of water collected from the lake were used. The mean monthly data of mean temperature (T_{Mean}), maximum temperature (T_{Max}), minimum temperature (T_{Min}), and diurnal temperature range (DTR) for Nainital were obtained from the website of India Water Portal (http://www.indiawaterportal.org/) for the period of 100 years (1901–2000). These data sets were generated from the simple linear averaging of the gridded ($0.5^0 \times 0.5^0$) Climate Research Unit (CRU) dataset. Due to high variability

Geological Settings around Lake Nanital

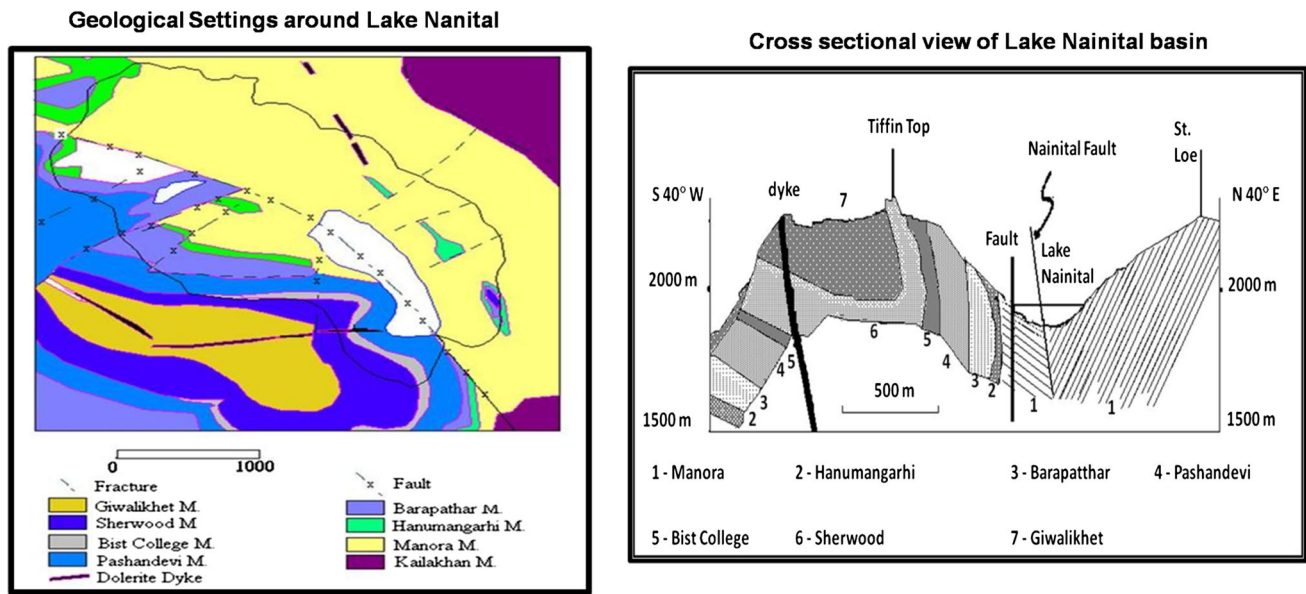**Cross sectional view of Lake Nainital basin**

Fig. 4 Geological characteristics around Lake Nainital basin (Modified after Valdiya 1988)

in rainfall pattern over the Himalayan region, high resolution ($0.25^0 \times 0.25^0$) gridded data of rainfall, procured from Indian Meteorological Department, were used in this study. The entire data sets were visually scrutinized for detecting any obvious outliers, trends, and potential discontinuities. Cumulative deviation method described by Buishand (1982) was applied for spotting inhomogeneities or discontinuities in the time series. To determine yearly fluctuations in T_{Mean}, T_{Max}, T_{Min}, DTR and rainfall, and to identify the warmest and coldest phases, 5-year moving averages technique was adopted. The modified Man Kendall (MK) rank-based test at 5 % level of significance was used for detecting a trend in time series over time (Hamed and Rao 1998), and the magnitude of change was estimated from Sen's Slope method (Sen 1968). The MK test is a powerful nonparametric test method and has been widely used for analysing trends in hydrologic and climatologic variables (Mann 1945; Singh et al. 2015). In MK test, the null hypothesis (H_0) of no trend is checked with the alternative hypothesis (H_i) of increasing or decreasing trend.

Lake Nainital was monitored between February 1994 and July 1996, and samples for different months were collected in order to assess the hydro-chemical characteristics of the lake (Table 1).

Sampling in the lake was carried out at three different depths: surface, middle, and bottom of the lake, at every 3-metre depth interval. In the year 1994, sampling was carried out during four months, which were considered to be reprehensive of the four different seasons. However, realizing the dynamics and the possible short hydraulic residence time of the lake water, the sampling was carried

out during eight months in the year 1995. In the last year of the investigation, sampling was carried out in January, April, and July with a view of complementing the available information on the lake's quality.

The samples from the lake were collected using a depth sampler of 2L capacity with a built in thermometer of 0.02 °C least count. The electrical conductivity (EC) and pH were measured in situ using a 5-parameter field water testing kit. The collected samples were mainly utilised for two different aspects: (1) In situ measurement of physical and chemical characteristics and (2) water quality aspects. While in situ measurements were made every three metres, samples for water quality of aspects were made only at three or four different depths viz. epilimnion (0 m), mesolimnion (6–9 m depending on season), and hypolimnion (1–4 m above the bottom, depending on the season). The water samples were collected directly from the sites, filtered, and preserved as per standard procedures (Appelo 1988). The samples were analysed for: field parameters (temperature, pH, EC), major ions (Ca^{2+}, Mg^{2+}, Na^+, K^+, HCO_3^-, SO_4^{2-} and Cl^-), and nutrients (NO_3^- and PO_4^-) as per standard procedures (APHA 1999). Chloride was estimated by Argentometric method, alkalinity by Titrimetric method, sulphate by Turbidimetric method, total hardness and calcium hardness by EDTA Titrimetric method. Calcium and magnesium concentrations were calculated by stoichiometry from total and calcium hardness. Sodium and potassium were determined using flame photometer. The Secchi depth was measured by manually prepared Secchi disc. Nitrogen in the form of Nitrate was determined by using spectrometric methods. Phosphate was estimated by stannous chloride in the form

Table 1 Month and numbers of samples collected from Lake Nainital between February 1994 and July 1996

Month	Number of samples	Month	Number of samples	Month	Number of samples
9–10 February 1994	4	22–23 March 1995	37	24–25 November 1995	20
20–21 May 1994	9	29–31 May 1995	18	29–30 December 1995	19
3–5 October 1994	28	30 June 1995	6	12–15 January 1996	20
14–20 December 1994	11	17–21 August 1995	20	27–30 April 1996	27
22–26 February 1995	26	26–28 September 1995	20	22 July 1996	8

Table 2 Results of homogeneity test using cumulative deviations method

Cumulative deviation test statistics	Climatic variables				
	T_{Max}	T_{Min}	T_{Mean}	DTR	Rainfall
Q/square root (n)	1.39	1.53	1.53	1.12	2.91
R/square root (n)	1.54	1.67	1.68	2.1	2.91

of molybdenum blue while Turbidimetric method in the form of barium sulphate crystals. The overall accuracy of the chemical analysis as determined by replicate measurements was found to be better than ±5 %.

Results and discussion

Preliminary analysis of climatic data

The monthly time series of temperature (T_{Mean}, T_{Max}, T_{Min},), DTR, and rainfall was inspected for the entire period (1901–2000). Cumulative deviations method was employed for detecting inhomogeneities in the data at 1 % level of significance. The series is homogenous if the critical values of Q/square root (n) and R/square root (n) for 100 sample sizes are less than 1.55 and 1.86, respectively. The results shown in Table 2 indicate that all the series are homogeneous except rainfall. The rainfall data were made homogeneous by adjusting time series of data for break periods. The statistical parameters such as arithmetic mean, standard deviation (SD), coefficient of skewness, coefficient of kurtosis, and coefficient of variation (CV) were computed for the mean annual temperature (T_{Mean}, T_{Max}, T_{Min}), DTR, and rainfall over the period of 1901 to 2000. The arithmetic mean and standard deviation, which are a measure of central tendency and dispersion, respectively, are employed for grasping the significance of statistical data (Table 3).

The coefficient of skewness which is a measure of asymmetry in a frequency distribution around the mean varied between −0.17 (rainfall) to 0.56 (T_{Mean}). The negative value, observed for rainfall, indicates that this is asymmetrically distributed and lies to the left of the mean. However, positive skewness was seen for T_{Mean}, T_{Max}, T_{Min}, and DTR. Kurtosis is a statistic describing the

peakedness of a symmetrical frequency distribution, varied from −0.47 (rainfall) to 4.33 (DTR) within the lake region. The CV, a statistical measure of the dispersion of data points in a data series around the mean, was computed for studying variability in temperature (T_{Mean}, T_{Max}, T_{Min},), DTR, and rainfall over the study area. The CV varied between 1.63 % (T_{Max}) to 25.94 % (rainfall).

Annual and seasonal pattern of change in T_{Max}, T_{Min}, T_{Mean}, DTR and rainfall over the period of 1901–2000

The changes in climatic variables (T_{Mean}, T_{Max}, T_{Min}, DTR and rainfall), over the period of 1901–2000, were computed with respect to baseline period, i.e. 1961–1990. For detecting trends in T_{Mean}, T_{Max}, T_{Min}, DTR and rainfall, modified MK test was employed over the anomalies which were found more accurate in describing climatic variability. Anomalies in T_{Mean}, T_{Max}, T_{Min}, DTR and rainfall were derived by subtracting annual and seasonal time series from the yearly mean value averaged over the period of 1961–1990. The results of MK test (Z_s) showing annual trends in T_{Mean}, T_{Max}, T_{Min}, DTR and rainfall are presented in Table 4. The annual temperature (T_{Mean}, T_{Max}, and T_{Min}) over Nainital showed long-term statistically insignificant increasing trend with the rate of 0.002 °C/year. No specific trend in DTR was detected during this period. However, the study of 5-year moving average (Fig. 5) and decadal analysis (Fig. 6) revealed significant episodic variations in annual temperature and DTR. A remarkable phase of cooling persisting from 1901–1940 was observed in T_{Mean}, T_{Max}, and T_{Min}. After the 1940s, more fluctuated patterns of cooling (1971–1980) and warming (1941–1970 and 1991–2000 for T_{Max} and T_{Min}, and 1951–1970 and 1991–2000 for T_{Mean}) were observed in temperature.

Table 3 Statistical parameters computed over the period of 1901–2000

Climatic variables	Statistical parameters				
	Arithmetic mean (°C; mm)	SD (°C; mm)	Coefficient of skewness (°C; mm)	Coefficient of kurtosis (°C; mm)	CV (%)
T_{Max}	31.01	0.50	0.52	1.19	1.63
T_{Min}	18.03	0.49	0.51	1.54	2.76
T_{Mean}	24.50	0.48	0.56	1.81	1.96
DTR	12.97	0.28	0.10	4.33	2.20
Rainfall	1897.18	492.09	−0.17	−0.47	25.94

Table 4 Annual trend analysis of temperature and rainfall for 1901–2000 performed at Nainital

Station	Climatic variables									
	T_{Mean}		T_{Max}		T_{Min}		DTR		Rainfall	
	Z_s	Q (°C/year)	Z_s	Q (°C/year)	Z_s	Q (°C/year)	Z_s	Q (°C/year)	Z_s	Q (mm/year)
Nainital	(+)	0.002	(+)	0.002	(+)	0.002	0	NT	(−)*	9.50

* Values are statistically significant at 5 % level of significance
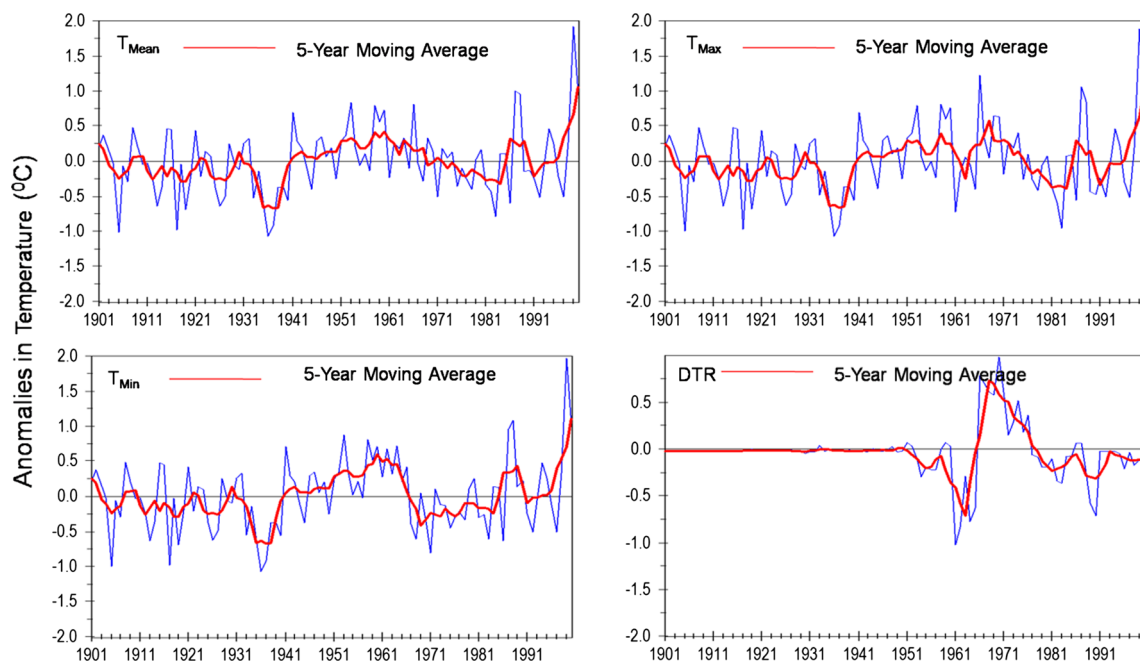

Fig. 5 Inter-annual change (*blue line*) and 5-year moving average (*red line*) of T_{Mean}, T_{Max}, T_{Min} and DTR in Nainital Lake region (1901–2000)

This period was mainly dominated by warming trends. There were significant variations in magnitude of changes among T_{Mean}, T_{Max}, and T_{Min}, as the highest decrease and increase were observed in T_{Mean} and T_{Min} in the decades of 1930s and 1950s, respectively. The five-year moving averages in annual DTR at Nainital either showed no or insignificant change in DTR until the 1950s, indicating more or less similar magnitude of change in T_{Max}, and T_{Min}. However, abrupt peaks of rise and fall were found after the 1950s. The comparative increase observed, in

T_{Min}, was held responsible for the decline of DTR during 1951–1963 and 1979–2000. Conversely, the abrupt increase in annual DTR monitored during 1971–1980 was the result of the decline in the T_{Min}.

The annual trend analysis of MK test, which had shown statistically significant downward trend for rainfall during the period of 1901–2000, indicates a decline in the total amount of annual rainfall. The rate of decrease in the annual rainfall was observed 9.50 mm/year. The graphs showing five-year moving average and decadal change for

Fig. 6 Decade to decade change in annual T_{Mean}, T_{Max}, T_{Min}, and DTR in Nainital Lake region (1901–2000)
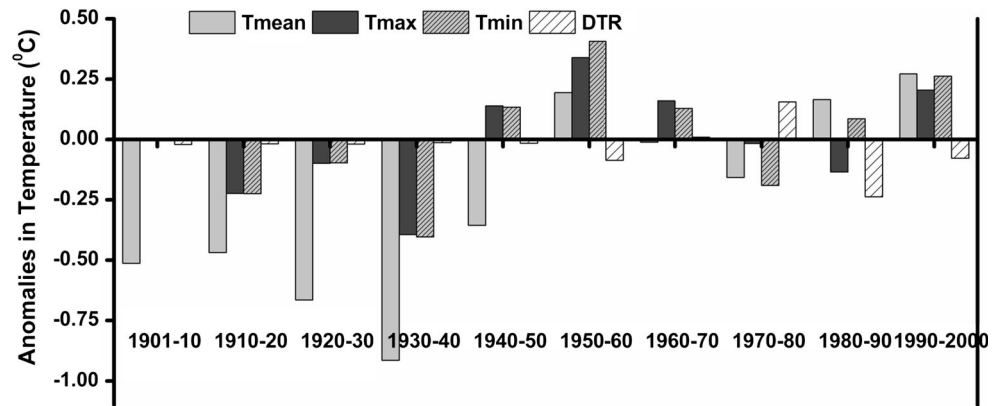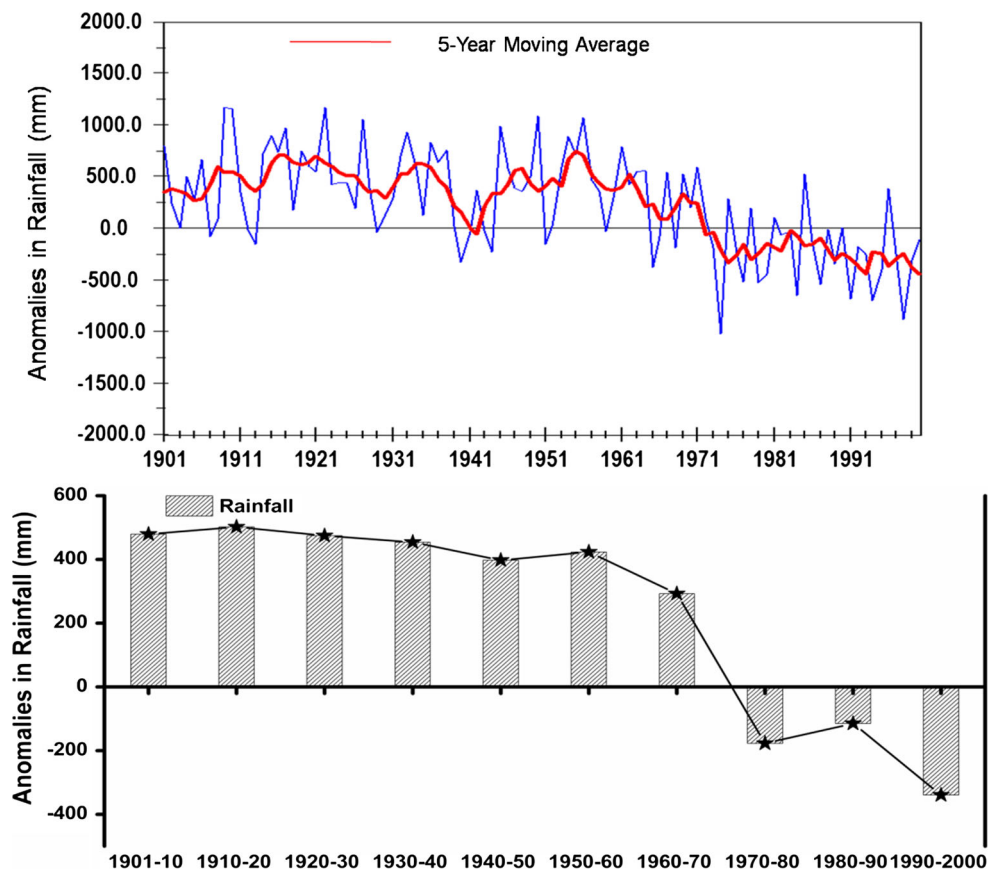

Fig. 7 Interannual and 5-year moving average (*red line*), and decadal change of rainfall in Nainital Lake region (1901–2000)

rainfall were plotted for the detailed explanation of prevailing trend in the rainfall (Fig. 7). The rainfall was relatively high from 1901 to 1970, while it was comparatively low from 1971 to 2000. However, there was a gradual decrease in the annual rainfall starting from 1912 till 2000. This was also corroborated with the results of trend analysis performed for 1901 to 1970 and 1971–2000. The early phase of the century was characterized by a relatively lower downward trend (2.88 mm/year) in annual rainfall compared to that of later phase, i.e. 1971–2000 (12.71 mm/ year).

The study also examined changes in the daily extreme events of rainfall (Table 5): RX1day (max 1-day precipitation amount), RX5day (max 1-day precipitation amount), R10 (number of heavy precipitation days >10 mm), R20 (number of very heavy precipitation days >20 mm), R95p (very wet days), CDD (consecutive dry days), CWD CDD (consecutive wet days) and SDII (Simple Daily Intensity Index) on the annual basis for 1901–2000. The statistically significant decreasing trends were detected in the number of heavy precipitation (R10 and R20), wet days (CWD), amount (RX1day, RX5day, and R95p), and intensity (SDII)

(Fig. 8). Thus, a decline in the frequency and intensity of rainfall was also reported during 1901–2000.

The results of MK test (Z_s) showing seasonal trends in T_{Mean}, T_{Max}, T_{Min}, DTR and rainfall are given in Table 6. The rise in temperature (T_{Mean}, T_{Max} and T_{Min}) was observed during the pre-monsoon (March, April and May), post-monsoon (October and November), and winter seasons. However, the results were statistically significant only during winter season. The maximum increase in T_{Mean} (0.008 °C/year), T_{Max} (0.008 °C/year), and T_{Min} (0.009 °C/year) were also reported during this season of the year. Opposite to this, a decrease in the temperature (0.004 °C/year) was found during the monsoon season. DTR exhibited no trend for all the four seasons.

The inter-decadal seasonal analysis of temperature and DTR is shown in Fig. 9. Large fluctuations in the pattern of temperature were observed throughout the seasons with one similarity, i.e. increase in T_{Mean}, T_{Max} and T_{Min} during 1990–2000 for all the seasons. The continuous decline from the 1940s to the end of the twentieth century, in the negative anomalies of T_{Mean}, T_{Max}, and T_{Min}, during the winter season was considered accountable for the increased trends in temperature during this season of the year. Similarly, the episodic decline (from the 1910s to 1930s and from 1950s to 1990s) in T_{Mean}, T_{Max}, and T_{Min} could be the factor for downward trends observed in T_{Mean}, T_{Max}, and T_{Min} during monsoon season.

The downward trend in rainfall was revealed for the pre-monsoon (statistically insignificant), monsoon (statistically significant), post-monsoon (statistically insignificant), and winter (statistically significant) seasons. The rate of decrease was 0.047 mm/year, 8.538 mm/year, 0.122 and 0.537 mm/year during pre-monsoon, monsoon, post-monsoon, and winter seasons, respectively. The inter-decadal study of seasonal rainfall performed at Nainital showed a sharp decline in monsoonal rainfall after 1970s onwards (Fig. 10). The monsoonal rainfall, which had shown a maximum positive anomaly of 480 mm during the 1930s reduced, to the negative anomaly of 256 mm at the end of twentieth century.

Table 5 Definition and description of extreme rainfall events

| ID	Indicator name	Definitions	Units
RX1day	Max 1-day precipitation amount	Monthly maximum 1-day precipitation	mm
RX5day	Max 5-day precipitation amount	Monthly maximum consecutive 5-day precipitation	mm
R10	Number of heavy precipitation days	Annual count of days when PRCP ≥10 mm	days
R20	Number of very heavy precipitation days	Annual count of days when PRCP ≥20 mm	days
R95p	Very wet days	Annual total PRCP when RR >95th percentile	mm
CDD	Consecutive dry days	Maximum number of consecutive days with RR <1 mm	days
CWD	Consecutive wet days	Maximum number of consecutive days with RR ≥1 mm	days
SDII	Simple daily intensity index	Annual total precipitation divided by the number of wet days (defined as PRCP ≥1.0 mm) in the year	mm/day
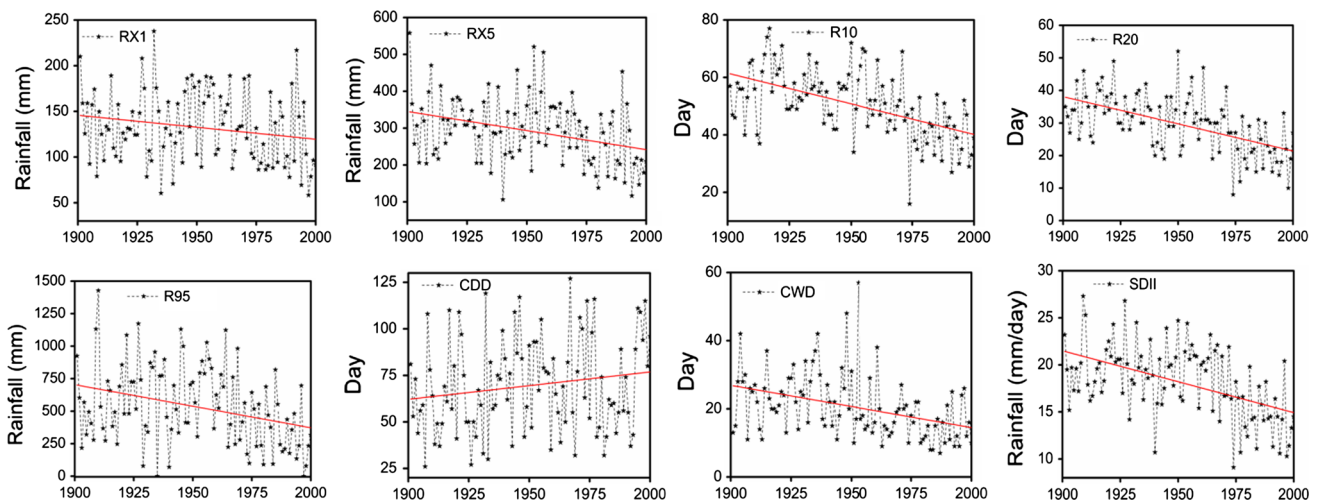
Fig. 8 Trends in extreme events of rainfall in Nainital Lake region (1901–2000)

Table 6 Seasonal trend analysis of temperature and rainfall for 1901–2000 performed at Nainital

Station	Season	T_{Mean}		T_{Max}		T_{Min}		DTR		Rainfall	
		Z_s	Q (°C/year)	Z_s	Q (°C/year)	Z_s	Q (°C/year)	Z_s	Q (°C/year)	Z_s	Q (mm/year)
Nainital	Pre-Monsoon	(+)	0.004	(+)	0.004	(+)	0.004	0	NT	(−)	−0.047
	Monsoon	(−)*	0.004	(−)*	0.004	(−)*	0.004	0	NT	(−)*	8.538
	Post-Monsoon	(+)	0.005	(+)	0.005	(+)	0.005	0	NT	(−)	−0.122
	Winter	(+)*	0.008	(+)*	0.008	(+)*	0.009	0	NT	(−)*	−0.537

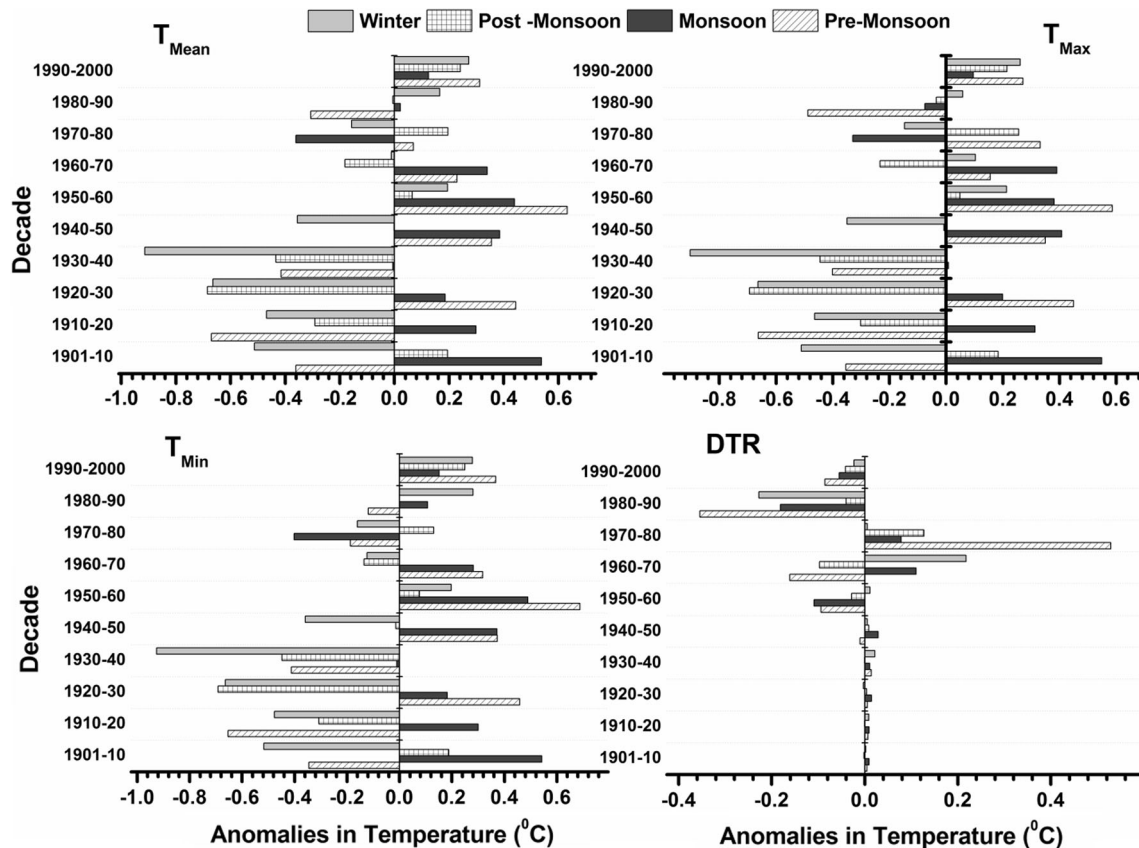* Values are statistically significant at 5 % level of significance)

Fig. 9 Decade to decade change in seasonal T_{Mean}, T_{Max}, T_{Min}, and DTR in Nainital Lake region (1901–2000)

Water balance scenario for Lake Nainital

As a natural process, the lake level changes with respect to time. However, the change in the water level within 24 h (a day) or within a month/year, indicates the change in storage of the lake. The general water balance equation showing change in the storage of the lake is written as:

$$\Delta S = \text{inflow} - \text{outflow} \qquad (1)$$

In the case of Lake Nainital, the inflow term includes surface inflow (S_i), subsurface inflow (SS_i), inflow through drains (D_i), and direct precipitation (P_i). The outflow term includes controlled surface outflow through sluices and surface leakage through sluice gates (S_o), free water evaporation (E_o), subsurface outflow (SS_o), and pumping by government agencies (W_o). Incorporating the above, Eq. (1) can be written as:

$$\Delta S = S_i + SS_i + D_i + P_i - S_o - SS_o - E_o - W_o \qquad (2)$$

Based on the stable isotopic signatures of lake water and ground water, it was estimated that the proportion of lake water, in the water, that was being pumped varied from 25 % during winter season, 20 % during summer season, 80 % during monsoon season, and 40 % during post-monsoon season (Nachiappan et al. 2002). Based on this information, the values of W_o were corrected accordingly

Fig. 10 Decade to decade change in seasonal rainfall in Nainital Lake region (1901–2000)
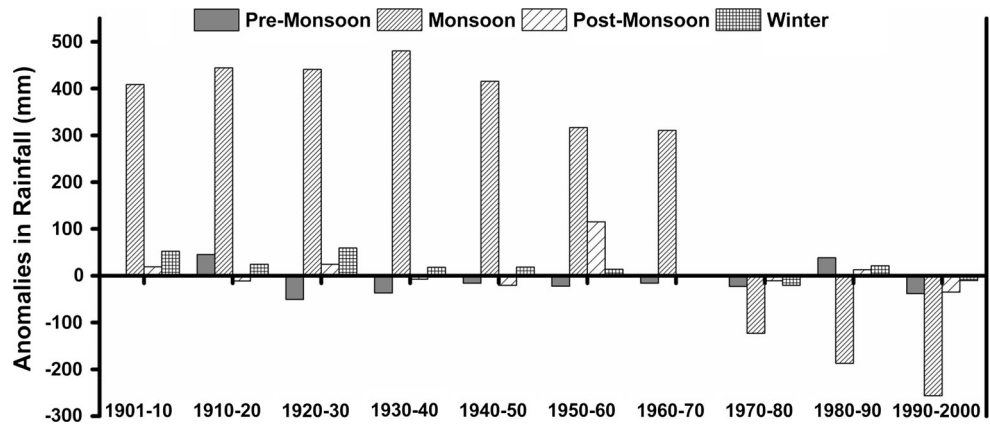
and included in water balance calculations. The values of various water balance components measured during the period of 1994 and 1995 for the Lake Nainital are presented in Table 7.

The study showed significant monthly variations in water balance components. In general, negative changes in the storage (ΔS) were observed during the pre-monsoon, post-monsoon, and winter seasons. The surplus observed in the storage (ΔS) during monsoon season was the result of heavy precipitation occurred in the catchment during this season of the year. The surface inflow (S_i) was the major component which contributed around 39 % of the annual flow to the lake, whereas the subsurface inflow (SS_i) had a contribution of about 30 %. The remaining was contributed by direct precipitation over the lake surface (16 %) and by inflow through the perennial drains (15 %). The variation in the subsurface inflow to the lake was also corresponding to the nature of precipitation. The significant inflows during the months of February, March, and April were influenced by the heavy snowfall and rainfall during late winter. The subsurface inflow which declined during May and June showed an increasing trend up to September and again declining trend afterwards in line with the precipitation with a lag period of approximately one month. It was also notable that in spite of zero rainfall in the month of October, the lake level continued to rise. This was mainly due to subsurface inflow. Pumping was one of the major sources of outflow which accounted 32 % of the total annual outflow, while 41 % of annual outflow was accounted by discharge through sluices. Further, increase in annual water loss due to the free water evaporation (E_o) and consumption through pumping (W_o) were also detected.

In order to analyse the effect of past developmental activities, a plot of surface outflow versus rainfall was generated for the period of 1901–1970 and 1971–1995 (Fig. 11). There was a noticeable decrease in the surface outflow for the given rainfall in the latter period. This was mainly due to the decline in rainfall amount as well as the increase in pumping from the lake.

Physio-chemical characteristics of Lake Nainital

The samples collected from the lake water between February 1994 and July 1996 were analysed for asserting the physio-chemical characteristics of Lake Nainital, and their results are summarized in Table 8. The temperature data revealed that lake was thermally well mixed during the period from December to February. The thermocline, developed during March and the onset of stratification, was seen to develop in the month of April. The stratification intensified during the month of May and remained until November. The vertical temperature difference was maximum during the month of June, where the thermocline was at 7.5 m below the surface. The thermocline was disappeared totally during the third week of December. The lake water is alkaline in nature, but significant variations in the seasonal pattern of pH values were reported. This was found in range of 6.4–8.7 during winter, 7.8–9.4 during pre-monsoon (epilimnion), 7.2–8.9 during pre-monsoon (hypolimnion), 6.9–9.6 during monsoon (epilimnion), 7.0–9.4 during monsoon (hypolimnion), 7.7–8.5 during post-monsoon (epilimnion), and 6.7–8.3 during post-monsoon (hypolimnion) seasons, respectively. The EC of the lake water ranged from 360–890 µS/cm, and it was higher in hypolimnion zone compared with surface water. This may be attributed to the mineralization of organic matter under reducing conditions that prevailed in the hypolimnion zone. Secchi disc transparency was recorded to be low during the whole study period (0.45–1.52 m). Pant et al. (1980) reported that Secchi's values ranged between 0.77 and 1.40 m, which indicates that the transparency has reduced significantly during summers in the last two decades, and this could be ascribed to the growth of phytoplankton.

Table 7 Values of water balance component of Lake Nainital for 1994 and 1995

Year	Water balance parameter (10^3 M^3)	Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec	NET
1994	ΔS	−8	−53	−92	−94	−126	2	191	192	66	−60	−80	−91	−153
	S_i	0	0	0	0	0	56	417	354	0	0	0	0	827
	SS_i	34	19	30	15	38	1	343	467	598	288	93	80	2006
	D_i	54	53	48	41	40	40	75	121	104	75	62	59	772
	P_i	29	7	0	28	13	109	223	197	20	2	2	1	631
	S_o	0	0	0	0	0	0	427	569	389	185	0	0	1570
	SS_o	34	43	46	47	52	48	64	117	127	65	74	66	783
	E_o	30	28	50	64	73	62	54	47	51	47	29	29	564
	W_o	61	61	74	67	92	94	322	214	89	128	134	136	1472
1995	ΔS	−73	−46	62	−95	−156	−110	363	209	231	−64	−129	−142	50
	S_i	0	0	0	0	0	0	458	610	423	0	0	0	1491
	SS_i	11	43	190	42	20	10	114	389	816	227	36	19	1967
	D_i	54	53	48	41	40	40	75	121	104	75	62	59	772
	P_i	21	27	28	3	8	40	228	289	157	0	0	5	805
	S_o	0	0	0	0	0	0	40	775	998	212	0	0	2025
	SS_o	34	43	46	47	52	48	64	117	127	65	74	66	783
	E_o	32	37	56	62	72	57	55	51	47	45	35	26	575
	W_o	93	89	102	72	100	94	353	257	97	94	118	133	1602
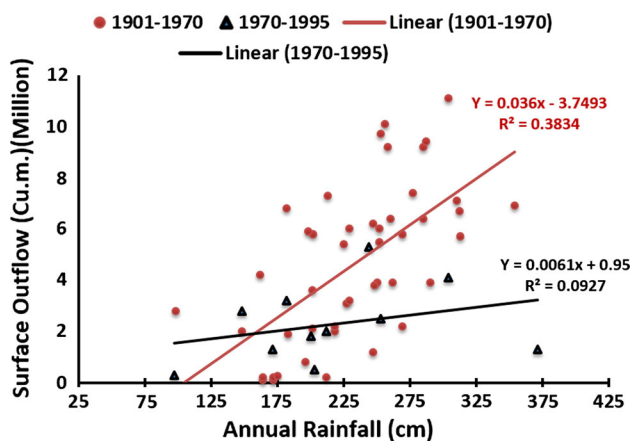
Fig. 11 Annual rainfall-surface outflow relationship for Lake Nainital

The interpretation of chemical data reveals that the lake water belongs to magnesium bicarbonate type. Among the major cations, Ca and Mg dominate over Na and K, and among the major anions, HCO_3^- dominates followed by SO_4^{2-}, Cl^-, and NO_3^-. The seasonal variation in HCO_3^- is mainly due to the phytoplankton activity in the lake. The reduction of HCO_3^- in epilimnion between winter and monsoon seasons is accompanied by an increase in pH. This results in precipitation of Ca^{2+} in the form of $CaCO_3$ which is evidenced by the reduction in the concentration of Ca^{2+} in both, epilimnion and hypolimnion. The subsequent increase in the Ca^{2+} in the post-monsoon season is then due to the increased subsurface inflow with higher Ca^{2+} concentration.

The concentrations of Mg^{2+} as well as EC (that is a function of total dissolved solids) are also lower during monsoon season as compared to other seasons. This is due to higher inflow of ground water to the lake. Na^+ and K^+ are influenced by anthropogenic activities, unlike Ca^{2+} and Mg^{2+} that are brought into the lake system, mainly from the dissolution of the limestones/dolomites. Higher concentration of K^+, observed in monsoon as compared to other seasons, is mainly due to increased transport of refuse by the storm runoff into the lake. The increase in Na^+ and PO_4^- during both monsoon and post-monsoon seasons also indicate the anthropogenic influence on the lake water quality. It is evident from the above discussion that except for Cl^-, all other ions are not behaving conservatively in the lake environment. The possibility of oxidation of pyrites in the Nainital basin has been pointed by several geologists: Middlemiss (1890) and Coulson (1939). The oxidation and hydrolysis of pyrite produce sulphuric acid and soluble sulphates as given below (Karanth 1987):
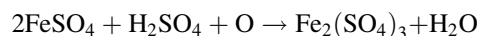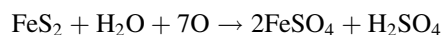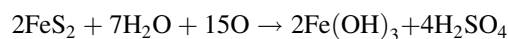
$$2FeS_2 + 7H_2O + 15O \rightarrow 2Fe(OH)_3 + 4H_2SO_4$$

$$FeS_2 + H_2O + 7O \rightarrow 2FeSO_4 + H_2SO_4$$

$$2FeSO_4 + H_2SO_4 + O \rightarrow Fe_2(SO_4)_3 + H_2O$$

Table 8 Physio-chemical characteristics of Lake Nainital (Values presented in parentheses indicate number of samples)

| Season*	Physio-chemical variables										
	Temp. (°C)	pH	EC (μS/cm)	HCO_3^- (mg/L)	SO_4^{2-} (mg/L)	Cl^- (mg/L)	NO_3^- (mg/L)	Ca^{2+} (mg/L)	Mg^{2+} (mg/L)	Na^+ (mg/L)	K^+ (mg/L)
Winter											
Range	7.9–16	6.4–8.7	230–350	49–145	370–680	3–32	0–5	28–74	32–96	5–14	3–7
Mean	9.4 (72)	7.5 (51)	275 (52)	93.3 (56)	500 (71)	14 (66)	1.05 (67)	53 (71)	55 (71)	10 (67)	5 (68)
Pre-E											
Range	14.9–21.3	7.8–9.4	197–268	68–126	440–890	10–26	0	33–57	45–63	9–14	4–9
Mean	18.8 (21)	8.5 (14)	237 (18)	89.6 (21)	600 (21)	16 (17)	0 (8)	43 (21)	55 (21)	11 (14)	5 (14)
Pre-H											
Range	8.2–17.2	7.2–8.9	234–304	64–135	360–860	6–22	0.0–1.3	36–80	41–61	8–15	4–5
Mean	9.3 (61)	8.0 (45)	259 (55)	90.7 (61)	620 (60)	15 (55)	0.8	49 (61)	54 (61)	12 (45)	5 (45)
Mon-E											
Range	20.0–23.8	6.9–9.6	170–208	55.4–120	380–650	0–28	0.0	22–46	32–53	11–19	3–8
Mean	21.5 (14)	8.6 (15)	196 (16)	89.1 (14)	460 (16)	14 (16)	0.0 (12)	33 (16)	43 (16)	15 (14)	6 (14)
Mon-H											
Range	8.0–13.4	7.0–9.4	242–318	56.4–120	480–850	0–72	0–3.3	26–64	46–74	9–21	4–8
Mean	10.1 (29)	7.7 (30)	268 (35)	94.1 (29)	600 (35)	21 (34)	1.09 (25)	39 (35)	60 (35)	16 (29)	6 (29)
Post-E											
Range	13.1–20.5	7.5–8.8	174–235	74.1–118	510–590	6–37	0.1–1.1	27–58	41–70	14–40	4–5
Mean	16.4 (13)	8.0 (14)	210 (14)	89.5 (14)	550 (14)	16 (14)	0.46	436 (14)	52 (14)	24 (6)	4 (6)
Post-H											
Range	9.2–13.5	6.7–8.3	218–274	45.3–98	580–770	5–21	0.0–7.0	43–80	38–69	17–14	4–5
Mean	10.3 (23)	7.2 (30)	256 (30)	80.2 (25)	660 (30)	13 (30)	2.67 (30)	60 (30)	49 (30)	21 (10)	5 (10)

* *Pre* pre-monsoon, *mon* monsoon, *post* post-monsoon, *E* Epilimnion, *H* Hypolimnion

Table 9 Long-term quality changes in Lake Nainital. *Source*: Rai et al. (2004)

Parameter	Year			
	1954	1975	1978–1979	1994–1996
Secchi (m)	1.9	1.12	0.90	0.90
DO (mg/l)	15.5	14.2	9.95	7.3
Alkalinity (mg/l)	–	400.0	–	221
NO_3^- (μg/l)	Traces	338	345	370
NH_3^-N μg/l	19.0	165	191	445
PO_4^- (μg/l)	Traces	6.5	14.7	53

Sulphuric acid thus formed reacts with calcite in the weathered zones and calcareous rocks, to produce soluble calcium sulphate:

$$H_2SO_4 + CaCO_3 \rightarrow H_2CO_3 + CaSO_4$$
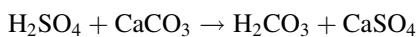
The nature of slates and dolomites being pyritiferous in the Nainital basin has been reported by earlier investigators (Ashraf 1978; Valdiya 1988). Therefore, the origin of sulphates in the lake water is oxidation of pyrites. Further, the continuous increase is observed in the nutrient elements (NO_3^- and PO_4^-) of the lake water (Table 9).

The concentration of NO_3^- in the lake water is significant; however, there is no use of fertilizer in the lake catchment. Rainwater analysis also shows the absence of NO_3^- in rainfall; hence, domestic effluents are the major sources of nitrate nitrogen in Lake Nainital. Likewise, PO_4^- is mainly fed by the drains which are carrying the domestic and other effluents. The annual areal loading to the lake in the present scenario is around 1150 mg/m². If the two major drains namely, Naina Devi and Rikshaw Stand drains, are excluded, then the annual areal loading reduced to 450 mg/m². Thus, diversion of drain water away from the lake catchment reduces loading by a significant proportion (60 %). Further, the higher concentration of K^+ and Na^+ observed in monsoon as compared to other seasons is mainly due to increased transport of refuse by the storm runoff into the lake. The study signifies that the anthropogenic activities have accelerated nutrients loading and affected the lake chemical characteristics due to which it has reached a hypereutrophic stage in past few decades. Carlson TPTSI used for determining trophic state index reveals that Lake Nainital is the most eutrophic lake in the Kumaun region (74) followed by Bhimtal lake (51), Khurpatal (44), Sattal (32), and Naukuchiatal (20), respectively (Rai et al. 2004).

Conclusion

The effects of increased anthropogenic activities and climate change of twentieth century on hydro-chemistry of Lake Nainital, which receives runoff from catchments, wastes from surrounding areas, and residues of construction activities through small and large drains, have been studied. Remarkable, increase in concentrations of nutrients (NO_3^- and PO_4^-) has been observed over time. NO_3^- and PO_4^- which were measured as trace amounts in the lake water in 1954 have attained concentrations in the order of 370 (μg/l) and 53 (μg/l), respectively. Dissolved oxygen (DO) which is an indicative of water quality parameter observed a significant decline in its level for the same period. Its value in the lake water has been reduced to 7.3 (mg/l) from 15.5 in 1954. Reduction in the visibility of lake water is also detected as the decrease in the values of Secchi's disc has been reported. The study implies that the anthropogenic activities have accelerated nutrients loading and affected the lake chemical characteristics due to which Lake Nainital has attained hypereutrophic stage in past few decades.

The study of climatic data has shown a rise (statistically insignificant) in annual mean temperature (T_{Mean}), maximum temperature (T_{Max}), and minimum temperature (T_{Min}), and decrease in rainfall amount over the Lake catchment for the twentieth century, i.e. 1901–2000. A gradual decrease in the magnitude of annual rainfall has been observed starting from 1912 until 2000. The rate of decrease is 9.5 mm/year. In addition, statistically significant decreasing trends are also perceived in the number of heavy precipitation (R10 and R20), wet days (CWD), amount (RX1day, RX5day, and R95p), and intensity (SDII). The continuous decrease in total annual rainfall and monsoonal rainfall, and the increase in temperature will affect the availability of surface and groundwater in the lake catchment which may likely cause a decline in total volume of lake water and affect the availability of per capita water in the near future, making the lake more vulnerable to anthropogenic activities.

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