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ORIGINAL ARTICLE

# Assessment of hydrological response as a function of LULC change and climatic variability in the catchment of the Wular Lake, J&K, using geospatial technique

Fayma Mushtaq[1] · Mili Ghosh Nee Lala[1]

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**Abstract** The present study aims to identify the relationship and effect of various hydrological processes on the Wular Lake ecosystem. The study focused on assessment of combined hydrological response of LULC change and climatic variability in the upper catchment of Wular Lake. Multi-temporal satellite data were used for assessment of temporal dynamics of the lake catchment. The spatiotemporal pattern of annual soil loss and sediment yield has been assessed using the Revised Universal Soil Loss Equation approach and sediment delivery ratio adopted from USDA Soil Conservation Service in GIS environment. The runoff was estimated in the watershed using SCS curve number. The main impelling forces that led to the changes in land use/land cover in the catchment is mainly due to increased human activities, which ultimately leads to the increased erosion and sediment yield. The anticipated mean annual soil loss which was found 123.23 t $ha^{-1}$ $year^{-1}$ in the year 1992 increased to 942.52 t $ha^{-1}$ $year^{-1}$ in the year 2013. Similarly, estimated mean annual sediment yield also indicated an increase from 34.7 t $ha^{-1}$ $year^{-1}$ in the year 1992 to 233.4 t $ha^{-1}$ $year^{-1}$ in the year 2013. In addition, the decrease in rainfall from the last 35 years has led to the decline in runoff and consequent reduction in the surface water supply. The results of the present study indicate due to the changes in LULC and consequent hydrological changes like decreased runoff, increased erosion and sedimentation reduce the water holding capacity of lake day by day, thus leading to its deterioration.

**Keywords** Geospatial technique · Hydrological processes · Land use/land cover change · RUSLE · Sediment yield (SY) · Soil conservation service curve number (SCS CN) · Wular Lake

## Introduction

The watershed resources worldwide are facing acute pressure in order to support the needs of rapidly growing population, which leads to deforestation and intensified agricultural practices ultimately resulting in problems to water resource (Maharjan et al. 2013). Due to this, many regions face shortage of freshwater due to the alterations in land use types, agriculture, pollution, human activities, and climate change (Torbick et al. 2013). In order to deal with the issues of water management, there is a need to investigate and quantify the impact of various elements on the hydrological processes of the watershed (Liu and Li 2008). The hydrological process of a watershed is complex and involves interaction among various factors like topography, weather, land use, geology, and anthropogenic impacts (Ghoraba 2015). The changes in hydrological processes are induced by intensified human activities as well as due to the climate change (Dwarakish and Ganasri 2015).

The changes in the land use type have adverse impact on vegetation cover, variations in surface runoff, and increased soil erosion in the watershed (Phuong and Choung 2013). Soil erosion not only causes loss of fertile soil but also results into the sedimentation of lakes, hence consequential negative environmental impact on the water

✉ Fayma Mushtaq
fayma1987@gmail.com

Mili Ghosh Nee Lala
mili@bitmesra.ac.in

1 Department of Remote Sensing, Birla Institute of Technology Mesra, Ranchi 835215, India

quality (Pimentel et al. 1995). On the other hand, the rate of sediment yield in a watershed reflects the deteriorating condition of the watershed (Lane et al. 2001), and the deposited sediments reveals the functioning and lifespan of reservoirs, lakes, etc. (Lane et al. 1997). Moreover, it affects the aquatic ecosystem and water quality due to the presence of harmful fertilizers and chemicals present in agricultural land (Wang et al. 2009; Dukic and Radic 2014). Therefore, it is essential to quantify the repercussions of land use changes, soil erosion, and sediment yield at watershed level from the perspective of anticipating and curtailing potential environmental impacts (Liu and Li 2008).

Wular Lake (Wetland of International Importance under Ramsar Convention—1990), the largest freshwater lake within Jhelum River Basin, is important for its biodiversity and socio-economic facets. The lake acts as a huge absorption basin for floodwater and maintains flows to support the hydropower generation and agricultural activities. The lake is an imperative habitat for migratory aquatic birds and major fisheries resource in Kashmir Valley and accounts for 60% production of fish in the state of Jammu and Kashmir. In spite of its importance, the lake is dwindling in recent years due to the changes in the LULC in the peripheral areas of Wular Lake and contamination caused by various human activities (Mushtaq and Pandey 2014; Mushtaq et al. 2015; Mushtaq and Lala 2016a, b). In addition, the rapid degradation of forest in the catchment areas and overgrazing of the pastures result in soil erosion and subsequent sedimentation of the lake (Wetlands International 2007).

Therefore, it is vital to monitor the changes and its negative environmental impacts in the catchment areas of Wular Lake. The research aims to assess the hydrological response of the upper catchment of Wular Lake in terms of LULC change, soil erosion, sediment yield, and runoff in order to identify the relationship and effect of various hydrological processes on the lake ecosystem. In the present study, RUSLE approach was used to assess the spatiotemporal soil loss due to its simplicity and a greater availability of input parameters (Renard et al. 1997; Perovic et al. 2013). The sediment delivery ratio (SDR) model was used to estimate the sediment yield because RUSLE model cannot be used directly to estimate the sediment yield. In addition, the SCS CN method was used to quantify the amount of runoff generated in the catchment.

## Study area

The upper catchment of the Wular Lake is located in the northern periphery of the lake and stretches approximately from 34°18′–34°34′N latitude to 74°30′–74°55′E longitude (Fig. 1). The catchment covers total area of 712 $Km^2$ with altitude and slope varying at 1578–5056 m a.m.s.l and 0 to 66.41 degrees, respectively. The catchment comprises of two main watersheds, i.e. Madhumati and Erin, which accounts for 32 and 20% of the catchment area, respectively. Madhumati also known as Bod Kol originates from the northern slopes of Harmukh glacier. Adjacent to the Madhumati catchment on the northern side is Erin catchment. The river is formed from the outflow of Sukha Sar and Shir Sar flowing through Chitrar, Titwan Kain, and Kubnai Nar streams which finally joins together at Isrur tar to form Erin. The rivers fall under the jurisdiction of Bandipora district and finally drain into the Wular Lake in north-west of Kashmir region, nearly 55 km from capital city of Srinagar.

## Materials and methods

### Input data used

The Landsat 5 TM satellite image of 1992, IRS LISS III image of 2004, and Landsat 8 OLI satellite image of 2013 were incorporated in the study for the generation of LULC map and change analysis. The Landsat TM and OLI satellite images of 1992 and 2013 were obtained from USGS Global Visualization Viewer web server (USGS—http://www.glovis.usgs.gov). The IRS LISS III image of 2004 was obtained from NRSC Bhuvan (bhuvan.nrsc.gov.in). For the generation of topographic variables of the catchment like elevation map and slope map, the digital elevation model (DEM) from Shuttle Radar Topography Mission (SRTM) was used. A soil map of the catchment area was generated using the soil map acquired from National Bureau of Soil Survey and Land Use Planning (NBSS and LUP) on 1:500,000 aided with the laboratory analysis of soil samples. Survey of India toposheet of study area on 1:50,000 scale was used to delineate the watershed boundary. A time series of precipitation data for the period of 1979 to 2013 was acquired from Climate Forecast System Reanalysis (CFSR) for the estimation of rainfall erosivity factors and for the calculation of runoff.

### LULC change analysis

The LULC change was analysed to find out the changes in the land systems and its consequent impact on the patterns of hydrological response in the catchment. The false colour composite images were created after processing like georeferencing and resampling for onscreen visual interpretation for mapping various LULC classes. Ground validation was carried out to acquire field characteristics of various mapped land cover classes and to relate them with

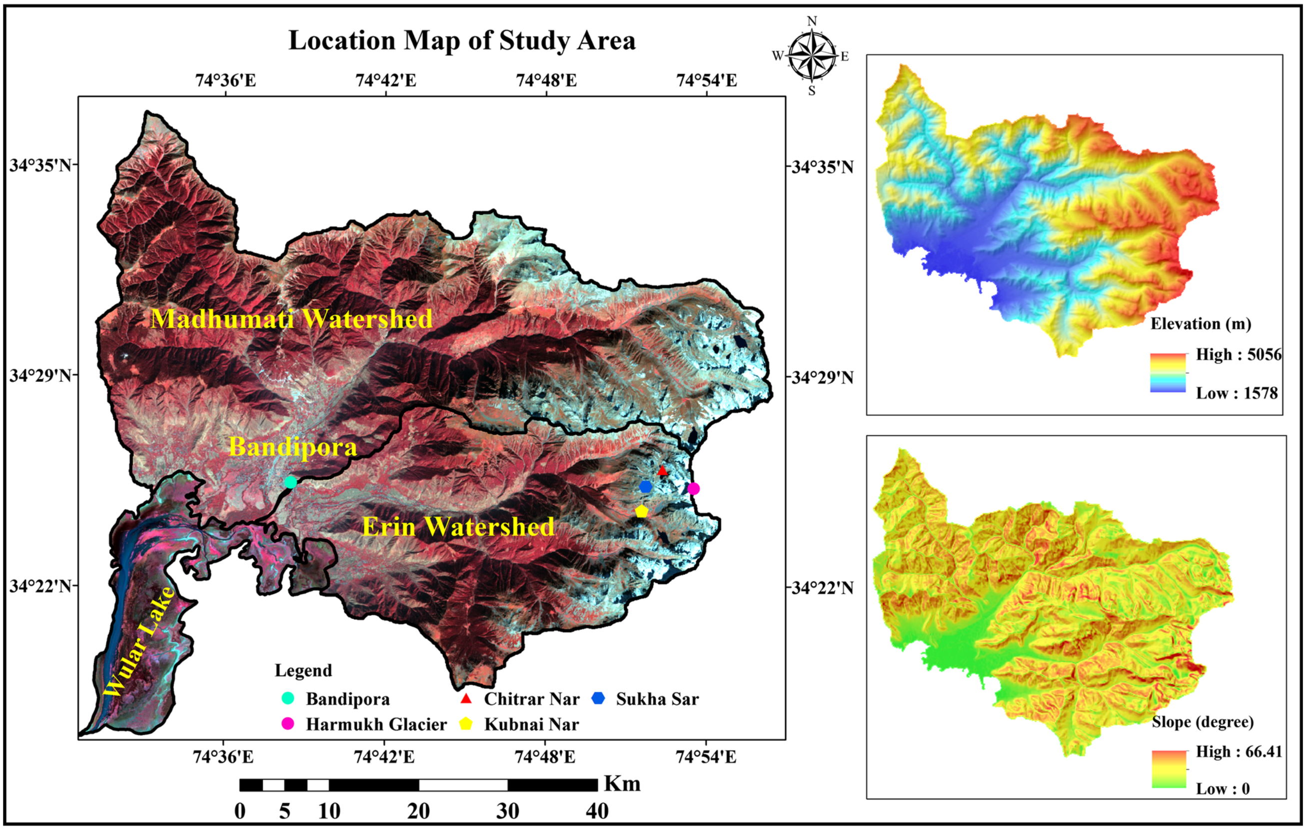


**Fig. 1** Location map of upper catchment of Wular Lake

corresponding image characteristics. Finally, the area coverage of visually interpreted LULC classes was computed using GIS.

The percentage of LULC change statistics during different time periods was assessed by the following formula (Mahmud and Achide 2012):

$$K = \frac{U_b - U_a}{U_a} \times 100 \quad (1.1)$$

where $K$ is the percentage of land use change and $U_a$ and $U_b$ are the land use types at the beginning and at the end of a period, respectively. Positive and negative values of this expression indicate an increase or decrease in the land use area with reference to the previous year, respectively.

## Assessment of erosion

The average annual soil loss was estimated using Revised Universal Soil Loss Equation (RUSLE) (Renard et al. 1997), given by the following equation:

$$E = R \times K \times \mathrm{LS} \times C \times P \quad (1.2)$$

where $E$ is the average soil loss per unit area by erosion (t ha$^{-1}$ year$^{-1}$), $R$ is the rainfall erosivity factor (MJ/mm/ha/h/yr), $K$ is the soil erodibility factor (t/ha/h/MJ/ha/mm), LS is the slope length and steepness factor (dimensionless), and $C$ and $P$ are the cover management and conservation support practice factor, respectively (dimensionless).

### *R factor calculation*

The daily rainfall data for the period of 35 years (1979–2013) obtained from Climate Forecast System Reanalysis (CFSR) were used for the estimation of rainfall erosivity factor. The $R$ factor for the year 1992, 2004, and 2013 was calculated employing the linear equation given by Singh et al. (1981) and adopted by Jain et al. (2010), Kumar and Kushwaha (2013), Kumar et al. (2014) due to the unavailability of rainfall intensity data in the study area. The equation used is given below:

$$R_{\mathrm{factor}} = 79 - 0.363R \quad (1.3)$$

where $R_{\mathrm{factor}}$ is rainfall erosivity factor in MJ mm ha$^{-1}$ h$^{-1}$ year$^{-1}$. $R$ is annual average rainfall in mm. Finally, the erosivity map for the year 1992, 2004, and 2013 was prepared by the interpolation of $R$ factor values using inverse distance weighted (IDW) interpolation technique of ArcGIS.

*K factor calculation*

The $K$ factor is derived from the type of soil through field observation and analysis of soil samples. The soil boundaries were digitized over georeferenced soil map in ArcGIS environment, and soil attributes were added to the digitized map. The soil samples were collected from different soil group and were analysed for sand, silt, clay, and organic matter content of each sample. The value of the $K$ factor in the present study was calculated using algebraic approximation of the nomograph proposed by Wischmeier and Smith (1978), Renard et al. (1997) which is also based on the equation given below:

$$K = 2.1 \times 10^{-4} M^{1.14} (12 - \mathrm{OM}) + 3.25(S - 2) + 2.5(P - 3)/100 \times 0.1317 \quad (1.4)$$

where OM = percentage of organic matter, $M$ = (% silt + % very fine sand)* (100–% clay), and $S$ and $P$ = soil structure and permeability class (Shinde et al. 2011).

Finally, the $K$ factor map was generated in the ArcGIS environment using the feature to raster conversion tool of spatial analyst in order to covert the $K$ factor map to a raster of desired cell size same as that of the DEM.

*LS factor calculation*

A digital elevation model of SRTM and the watershed boundary were used in the present study as input variables for the estimation of the topographic LS factor, employing the raster grid cumulation and maximum downhill slope method established by Hickey (2000) and Remortel et al. (2001) and adopted by Qing et al. (2008), Rodriguez and Suarez (2010), Suhua et al. (2013). The program for Arc Macro Language (AML) used for the estimation of LS factor was obtained from website of Van Remortel (www.onlinegeographer.com/slope/slope.html).

*C factor calculation*

The satellite imageries of Landsat TM (1992), LISS III (2004), and OLI (2013) were used after processing for onscreen visual interpretation to map various LULC classes, in order to estimate the values of $C$ factor. The LULC maps comprised of eight classes, namely built-up, agriculture, forest, plantation, scrub, barren, waterbody, and snow. The $C$ factor for various land use types was assigned using values already present in the literature (Table 1). The value of $C$ factor was found ranged from 0 to 1. The higher values of $C$ factor were assigned to the class with no cover effect, and the lower values nearly zero were assigned to the well-protected land.

**Table 1** LULC classes and their "C" values *Source*: Morgan (2005), Jayappa and Narayana (2009), and Bhandari et al. (2015)

| Land use/land cover classes | *C* values based on the literature |
|---|---|
| Built-up | 1 |
| Agriculture | 0.45 |
| Forest | 0.05 |
| Plantation | 0.35 |
| Scrub | 0.01 |
| Barren | 1 |
| Waterbody | 0 |
| Snow | 0 |

*P factor calculation*

The values of $P$ factor vary from 0 to 1, and the high values are assigned to the areas where no conservation practice is prevalent. In the present study, it was found during the field visit that the only conservation practices followed is the contour-farmed terraced plots in agricultural fields. The values were obtained from the literature as suggested by Wischmeier and Smith (1978) and adopted by Kumar et al. (2014). The value of 0.7 was assigned to agricultural fields at slope nearly 15%. The conservation factor varied between 0.70 and 1.00.

## Assessment of soil loss and risk zones

The spatiotemporal annual soil loss was obtained by multiplying all the required thematic maps ($R$, $K$, LS, $C$, and $P$) in the ArcGIS environment. The calculated soil loss values were finally categorized into five erosion classes on the basis of the obtained erosion rate value and the local terrain condition (Dabral et al. 2008; Karydas et al. 2009). The classification used by Naqvi et al. (2013) for the Himalayan region was used in the present study due to the almost similar conditions of terrain. The outcomes can be observed in two aspects, the spatial pattern which is influenced accordingly to their spatial distribution and the temporal pattern which is dependent on the rainfall distribution. Annual soil loss map was overlaid with the land use/land cover and slope maps in the ArcGIS environment in order to find out the risk zone areas.

## Assessment of sediment yield (SY)

Sediment delivery ratio (SDR) adopted from the USDA SCS (1972) was used for the calculation of sediment yield (Arekhi et al. 2012; Kamaludin et al. 2013). The formula used is as follows:

$$\mathrm{SDR} = 0.51 \times A^{-0.11} \quad (1.5)$$

where $A$ = area in $\mathrm{Km}^2$.

The values of sediment yield (SY) were estimated using the values of SDR from expression (1.5) by employing the formula Wischmeier and Smith (1978) given below:

$$SY = SDR \times SE \quad (1.6)$$

where SY = sediment yield (t $ha^{-1}$ $year^{-1}$), SDR = sediment delivery ratio, and SE = average annual soil loss (t $ha^{-1}$ $year^{-1}$).

## Rainfall runoff modelling

The runoff was computed by employing the soil conservation service (SCS) runoff curve number (CN) method, which calculates direct runoff on the basis of hydrological soil group, land cover, antecedent moisture condition, and the curve number (SCS 1972; Gupta and Panigrahy 2008). The inputs required for rainfall runoff modelling are as follows:

### *Land use/land cover*

The LULC is one of the significant characteristics of the runoff process that effects the infiltration, erosion, and evapotranspiration. The infiltration, evapotranspiration, and runoff vary from one land cover to another. The runoff yield is increased gradually from forest cover, grassland, farmland, barren land, and urban built-up land (Yu 1990). For example, the area covered by forest comprises increased infiltration and reduced runoff components. The loose soil structure, good aeration, and high organic content in the soil enhance the function of infiltration in a forested catchment. The various LULC classes were interpreted from Landsat 8 OLI imagery of 2013. The land use classes were classified into built-up, agriculture, forest, plantation, scrub, barren, waterbody, and snow.

### *Rainfall*

Runoff is generated by rainstorms, and its occurrence and quantity are dependent on the characteristics of the rainfall event, i.e. intensity, duration, and distribution. The daily precipitation data from 1979 to 2013 for the period of 35 years acquired from Climate Forecast System Reanalysis (CFSR) were used for calculation of runoff. The storm events which were higher than the initial abstractions were considered for runoff estimation because storm event less than initial abstraction produces no runoff (Anbazhagan et al. 2005).

### *Hydrological soil group (HSG)*

The HSG map was developed considering soil infiltration and drainage characteristics from the soil map of watershed. The different hydrological soil groups were classified in order to assign the CN, based on infiltration rate, depth, soil texture, water transmission capacity, and drainage condition (Anbazhagan et al. 2005). In Madhumati and Erin watershed, the soil was classified based on the USDA SCS (1985) method into two hydrological soil groups A and B and the area covered by each HSG was calculated (Table 2).

### *Soil conservation service model*

The relationship between hydrological soil group, land cover, and antecedent moisture conditions was used to assign the curve number. The thematic maps, i.e. land use/land cover and hydrological soil group map prepared in ArcGIS environment, were intersected, and the area under hydrological similar units (HSUs) was calculated in order to assign the CN values for runoff estimation. The hydrological similar units are those areas in the watershed that have similar soil type and land use. Finally, the applicable CNs were allocated to every HSU considering average moisture condition (AMC-II) as given in standard tables (SCS 1985; USDA NRCS 1986).

After assigning CN to various land entities, the weighted curve number was estimated employing expression (1.7) followed by the potential maximum soil retention ($S$) using expression (1.8) for the watershed.

$$\text{Weighted curve number(WCN)} = \frac{\sum(CN_1 \times a_1 + CN_2 \times a_2 + CN_n a_n)}{\sum a} \quad (1.7)$$

where $CN_1$ and $CN_n$ = curve number for 1 and $n$th land entity, respectively, $a_1$ and $a_n$ = area of 1 and $n$th land entity, respectively, and $\sum a$ = summation of entire area. The WCN for the watershed is given in Table 3.

**Table 2** Distribution of LULC and runoff CN

| LULC class | HSG | CN | Area $km^2$ |
|---|---|---|---|
| Built-up | A | 49 | 2 |
| Built-up | B | 69 | 20 |
| Agriculture | A | 62 | 4 |
| Agriculture | B | 71 | 32 |
| Forest | A | 36 | 166 |
| Forest | B | 60 | 76 |
| Plantation | A | 32 | 6 |
| Plantation | B | 58 | 25 |
| Scrub | A | 35 | 86 |
| Scrub | B | 56 | 38 |
| Barren | A | 98 | 117 |
| Barren | B | 86 | 44 |
| Waterbody | A | 0 | 3 |
| Waterbody | B | 0 | 2 |
| Snow | A | 0 | 88 |
| Snow | B | 0 | 3 |

$$S = \frac{25{,}400}{\text{CN}} - 254 \quad (1.8)$$

After the calculation of weighted curve number and potential maximum soil retention estimation, the initial abstractions ($I_a$) were estimated using Eq. (1.9). Initial abstraction is the losses due to infiltration, interception, and surface storage. Equation (1.9) shows the relationship between potential maximum retention and initial abstractions developed by Vandersypen et al. (1972) and adopted by Gupta et al. (2011) for Indian conditions which is as follows:

$$I_a = 0.3 \times S \quad (1.9)$$

where $I_a =$ initial abstractions and $S =$ potential maximum retention. The initial abstraction of the watershed is given in Table 3.

The runoff equation derived from the water balance equation under the critical assumption that the ratio of the actual runoff to the potential runoff (rainfall less initial abstraction) is equal to the ratio of the actual retention to the potential retention (SCS 1972).

$$\frac{P - I_a - Q}{S} = \frac{Q}{P - I_a} \quad (1.10)$$

After solving Eq. (1.10) for $Q$, actual direct runoff is given as

$$Q = \frac{(P - I_a)^2}{(P - I_a + S)} \quad (1.11)$$

where $Q =$ actual direct runoff expressed as a depth (mm), $P =$ total rainfall (mm).

Equation (1.11) can be simplified as initial abstraction is related to potential maximum retention. The storm events which were higher than the initial abstractions were considered for runoff estimation because storm event less than initial abstraction produces no runoff (Anbazhagan et al. 2005).

Since $I_a = 0.3$ S for AMC-II condition, Eq. (1.11) can be written as:

$$Q = \frac{(P - 0.3S)^2}{(P + 0.7S)} \quad (1.12)$$

**Table 3** Weighted curve number, retention parameter, and initial abstraction of the Madhumati and Erin watershed

| Parameters | Computed values |
|---|---|
| Weighted curve number | 51.4 |
| Soil retention parameter ($S$), mm | 240.6 |
| Initial abstraction ($I_a$), mm | 72.2 |

## Result and discussion

### LULC assessment in 1992, 2004, and 2013

The spatial distribution of LULC classes in 1992, 2004, and 2013 is depicted in Fig. 2, and Table 4 shows the LULC change statistics. Eight different types of classified land use and cover classes are: built-up, agriculture, forest, plantation, scrub, barren, waterbody, and snow.

Results revealed that in the year 1992, the most dominant class in the study area was forest which covered 314 km$^2$ (44.10%) followed by scrub 196 km$^2$ (27.53%), snow 126 km$^2$ (17.70%), agriculture 37 km$^2$ (5.20%), and plantation 28 km$^2$ (3.93%). The least dominant classes in the year 1992 were built-up 3 km$^2$ (0.42%), barren 3 km$^2$ (0.42%), and waterbody 5 km$^2$ (0.70%).

In the year 2004, it was observed that the forest covers majority of the area of watershed 266 km$^2$ (37.36%) followed by scrub 222 km$^2$ (31.18%), snow 135 km$^2$ (18.96%), agriculture 39 km$^2$ (5.48%), and plantation 29 km$^2$ (4.07%). The least representative of the classes was barren 11 km$^2$ (1.54%), built-up, and waterbody 5 km$^2$ (0.70%).

In the year 2013, the forest class again covers majority of the portion of watershed 242 km$^2$ (33.99%) followed by scrub 124 km$^2$ (17.42%), barren 161 km$^2$ (22.61%), snow 91 km$^2$ (12.78%), agriculture 36 km$^2$ (5.06%), and plantation 31 km$^2$ (4.35%). The least representative class was built-up 22 km$^2$ (3.09%) and waterbody 5 km$^2$ (0.70%).

The change analysis for the period 1992–2013 indicates significant changes in the upper catchments of Wular Lake, i.e. in Madhumati and Erin watershed particularly for barren, built-up, scrub, snow, and forest. The built-up class recorded an increase of 19 km$^2$ (633.33%) from 1992 to 2013. The plantation increased by 3 km$^2$ (10.71%), while agriculture decreased by − 1 km$^2$ (− 2.70%).

The forest cover and the scrub land in the watershed exhibited a decreasing trend with − 72 km$^2$ (− 22.93%) and − 72 km$^2$ (− 36.73%), respectively. The most significant change was recorded in the barren land which increased by 158 km$^2$ (5266.67%). It was observed that the area covered by the snow and glaciers also decreased by − 35 km$^2$ (− 27.78%) and no change was observed in the waterbody.

### RUSLE factors

The statistics of the RUSLE factors are presented in Table 5. The analytical details of RUSLE parameters are described as follows:

The annual $R$ factor was estimated for three different years, i.e. 1992, 2004, and 2013 (Fig. 3). The annual

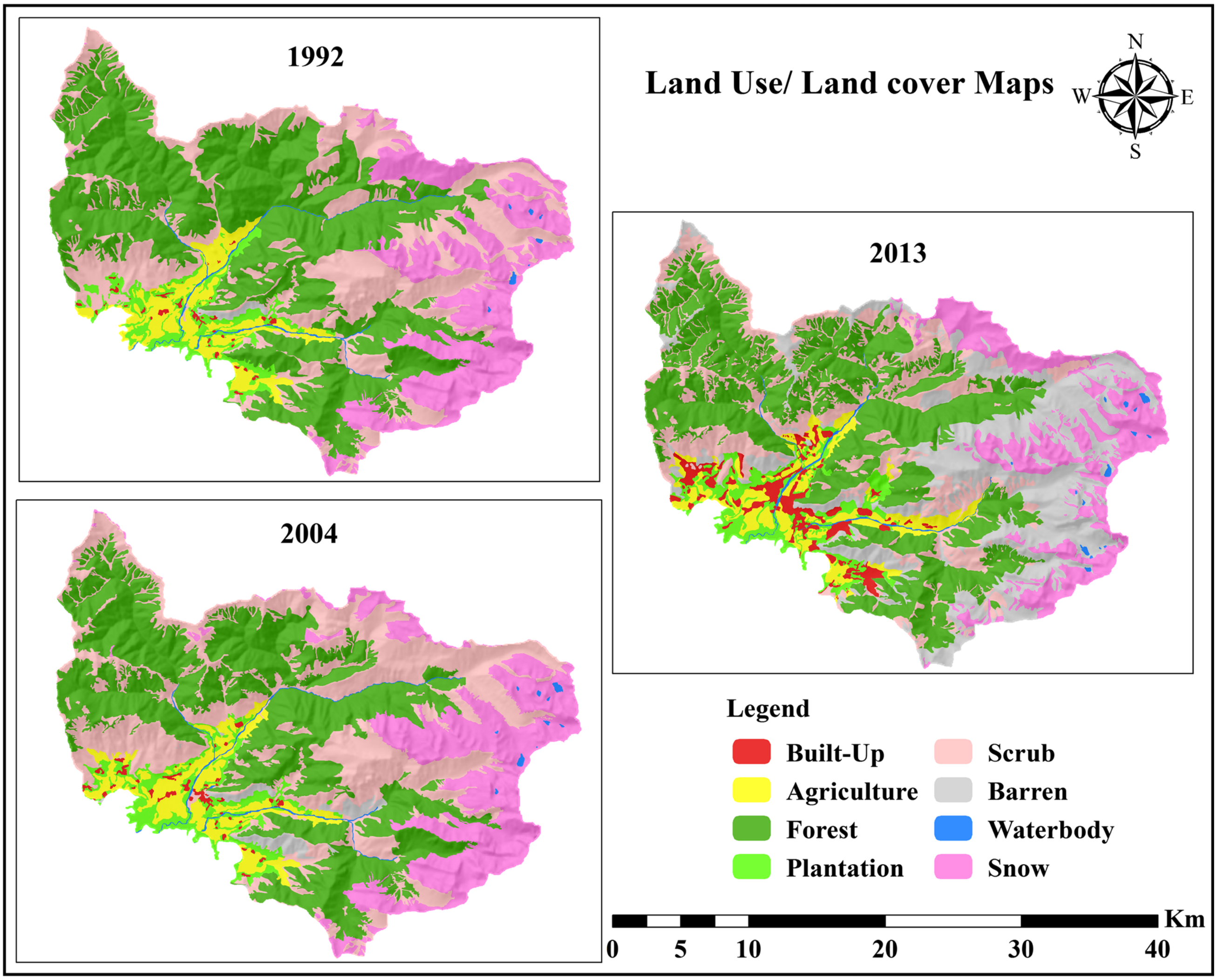


**Fig. 2** LULC maps of upper catchment of Wular Lake (1992–2013)

**Table 4** Land use/land cover change statistics in the upper catchment of Wular Lake (1992–2013)

| Year | 1992 | | 2004 | | 2013 | | Total change | |
|---|---|---|---|---|---|---|---|---|
| Area | (Km$^2$) | (%) | (Km$^2$) | (%) | (Km$^2$) | (%) | (Km$^2$) | (%) |
| Built-up | 3 | 0.42 | 5 | 0.70 | 22 | 3.09 | 19.00 | 633.33 |
| Agriculture | 37 | 5.20 | 39 | 5.48 | 36 | 5.06 | − 1.00 | − 2.70 |
| Forest | 314 | 44.10 | 266 | 37.36 | 242 | 33.99 | − 72.00 | − 22.93 |
| Plantation | 28 | 3.93 | 29 | 4.07 | 31 | 4.35 | 3.00 | 10.71 |
| Scrub | 196 | 27.53 | 222 | 31.18 | 124 | 17.42 | − 72.00 | − 36.73 |
| Barren | 3 | 0.42 | 11 | 1.54 | 161 | 22.61 | 158.00 | 5266.67 |
| Waterbody | 5 | 0.70 | 5 | 0.70 | 5 | 0.70 | 0.00 | 0.00 |
| Snow | 126 | 17.70 | 135 | 18.96 | 91 | 12.78 | − 35.00 | − 27.78 |

*R* factor for 1992 varies from 352.9 to 448.3 MJ/mm/ha/h/yr, and the mean value is 378.4 MJ/mm/ha/h/yr with standard deviation of 12.3 MJ/mm/ha/h/yr. For the year 2004, the *R* factor ranged from 332.2 to 418.6 MJ/mm/ha/h/yr with the mean and standard deviation of 351.3 and 10.9 MJ/mm/ha/h/yr, respectively. In the year 2013, the annual *R* factor ranged from 328.9 to 411.1 MJ/mm/ha/h/yr with the mean value of 351.38 and standard deviation of 10.99 MJ/mm/ha/h/yr. The highest value of rainfall erosivity was observed at higher elevations along the north-west and north-east of the watershed. The decreasing value of the *R* factor had the strong relationship with decreasing elevation of the watershed. In addition, it was observed that the erosivity decreased for the year 2004 and 2013 as compared to the year 1992.

The average value of K estimated for the textural groups varied from 0.32 to 0.48 t/ha/h/MJ/ha/mm (Fig. 4a), and the mean value was 0.41 t/ha/h/MJ/ha/mm. The standard deviation is 0.05. The study area has four types of soil textures such as loam, loamy sandy loam, sandy loam, and loamy sand. The highest value of soil erodibility was witnessed in the north-east portion of the catchment which depicts greater susceptibility of soil erosion in the region.

In the Erin and Madhumati watershed, rise in the altitude values was identified from south to north. The eastern and western side of the watersheds has the higher variability in altitude, and the steeper slopes had greater LS values. It can be observed from Fig. 4b that the LS factor value in the watershed varies from 0 to 184 with mean and standard deviation of 23.3 and 17.06, respectively.

The value of *C* and *P* factors was obtained from the literature depending on the basis of LULC of the watershed. The study area comprises built-up, agriculture, forest, plantation, scrub, barren, waterbody, and snow. The values of *C* and *P* factor ranged from 0 to 1 and 0.7 to 1, respectively. Figure 5a and b shows the resulting *C* and *P* factor raster maps for 1992, 2004, and 2013, respectively. The mean values of *C* factor for the year 1992, 2004, and 2013 are 0.6, 0.08, and 0.3, respectively, with standard deviation of 0.1, 0.1, and 0.4, respectively. The mean and standard deviation of *P* factor are 0.9 and 0.06.

## Spatial pattern of anticipated soil loss

The anticipated amount of annual soil loss as per the RUSLE model ranges from 0 to 7949.10 t $ha^{-1}$ $year^{-1}$ in the year 1992. The mean annual rate of soil loss was estimated to be 123.23 t $ha^{-1}$ $year^{-1}$ with standard deviation of 255.65 t $ha^{-1}$ $year^{-1}$ (Fig. 6a).

In the year 2004, the amount of soil erosion increased and it varied from 0 to 14,200.22 t $ha^{-1}$ $year^{-1}$. The mean annual rate of soil erosion was 140.31 t $ha^{-1}$ $year^{-1}$ with standard deviation of 496.44 t $ha^{-1}$ $year^{-1}$ in the year 2004 (Fig. 6a). Similarly, in the year 2013, the amount of soil erosion again increased and it varied from 0 to 18,078.18 t $ha^{-1}$ $year^{-1}$. In the year 2013, the mean annual rate of soil erosion was 942.52 t $ha^{-1}$ $year^{-1}$ and standard deviation of 1923.23 t $ha^{-1}$ $year^{-1}$ (Fig. 6a). Some of the pixels displayed extremely high range of soil loss mainly confined towards the eastern part of the watershed. In addition, as regard to spatial variation, it can be observed that Erin watershed has more erosion as compared to Madhumati watershed. The reason for the soil loss in that portion of the watershed has a close relationship with land use, elevation, and soil type.

## Soil erosion risk zonation

The results of anticipated soil loss classified into five classes for further analysis as shown in Table 6. The result of the study indicates that in the year 1992, the very large portion of the total area is covered under least to low risk of soil erosion. The majority of the area (68,451 ha) falls under the least risk of soil erosion, which approximately covers the 96.14% of the area of the watershed. About 2.93% (2084 ha) area falls under low risk zone of soil erosion. It was observed that in the year 1992, only 0.35% (215 ha), 0.33% (232 ha), and 0.26% (182 ha) falls under the moderate, high, and extreme risk of soil erosion.

In the year 2004, the area under least risk reported a decrease in the area from 96.14% in 1992 to 95.65% (68,102 ha) 2004. Similarly, decrease was also observed in the area under low risk from 2.93% in 1992 to 2.64% (1881 ha) in 2004. However, the increase in area was recorded for the classes under the moderate, high, and extreme risk. The area under moderate and high risk increased from 0.35 to 0.70% (495 ha) and 0.33 to 0.67% (476 ha), respectively. The increase of 0.35% (246 ha) was observed in the extreme risk class of soil erosion.

The condition in 2013 degraded markedly as the area under moderate, high, and extreme risk increased and under least risk of erosion deceased. The area under

**Table 5** Statistics of RUSLE factors

| Year | *R* factor | | | *K* factor | | | LS factor | | | *C* factor | | | *P* factor | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1992 | 2004 | 2013 | 1992 | 2004 | 2013 | 1992 | 2004 | 2013 | 1992 | 2004 | 2013 | 1992 | 2004 | 2013 |
| Maximum | 448.3 | 418.6 | 411.1 | 0.47 | 0.47 | 0.47 | 184 | 184 | 184 | 1 | 1 | 1 | 1 | 1 | 1 |
| Minimum | 352.9 | 332.2 | 328.9 | 0.31 | 0.31 | 0.31 | 0 | 0 | 0 | 0 | 0 | 0 | 0.7 | 0.7 | 0.7 |
| Mean | 378.4 | 355.1 | 351.3 | 0.41 | 0.41 | 0.41 | 23.2 | 23.2 | 23.2 | 0.6 | 0.08 | 0.3 | 0.9 | 0.9 | 0.9 |
| SD | 12.3 | 11.2 | 10.9 | 0.05 | 0.05 | 0.05 | 17.0 | 17.0 | 17.0 | 0.1 | 0.1 | 0.4 | 0.06 | 0.06 | 0.06 |

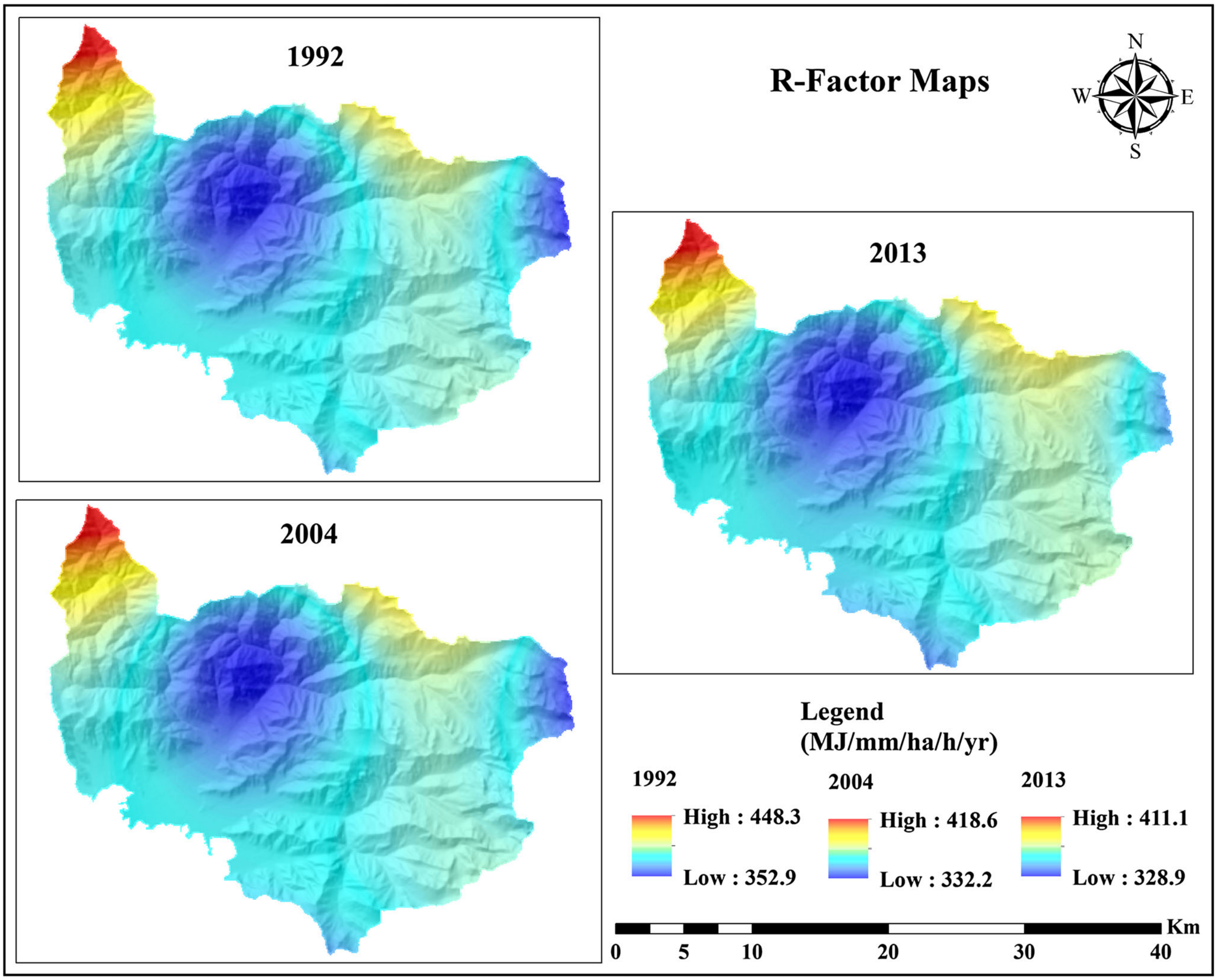


**Fig. 3** *R* factor maps of upper catchment of Wular Lake (1992–2013)

extreme risk increased from 0.35% in 2004 to 4.38% (3117 ha) in 2013. Similarly, the area under high risk increased from 0.67% in 2004 to 5.25% (3736 ha) in 2013. About an increase of 5.22% (3719 ha) from 0.70% in 2004 was observed in the moderate risk erosion zone. On the other hand, the least risk erosion zone decreased from 95.65% in 2004 to 73.52% (52,347 ha) in 2013, with an increase in low-risk erosion from 2.64 to 11.63% (8281 ha). The results revealed that the areas with high peril of soil loss are mostly observed confined to the eastern part of the watershed.

The soil erosion associated with different slopes is presented in Table 7. It was observed that 43% of the erosion area is coming under slope less than 24°. Higher values were observed in the area with slope between 24° and 36° with 47% of the erosion area. Most of the least to low soil erosion was found with slope greater than 36° (i.e. approximately 10% of the total area). Therefore, the areas having slopes between 24° and 36° are major contributors to soil loss where soil protection methods should be taken to curb further soil loss in future.

The impact of different land use types to erosion were analysed by overlaying soil erosion map with LULC map (Table 8). It was observed that the forest and scrub land are the key contributors to soil erosion in the year 1992 and 2004. In the year 1992, the forest covers 43.7% of total area of watershed under least to low category of soil erosion. The scrub constitutes 27.5% under the least category of erosion. Similarly in the year 2004, the forest covers 37.2% under least to low risk of erosion and scrub covers 30.9% under least risk of soil erosion. In the year 2013, in addition to the forest and scrub, barren land also contributes maximum percentage of soil loss from the watershed. The barren land constitutes 23.2% of the total area of watershed under soil erosion risk zones. The barren land covers 14.6% of the area under moderate to extreme risk of

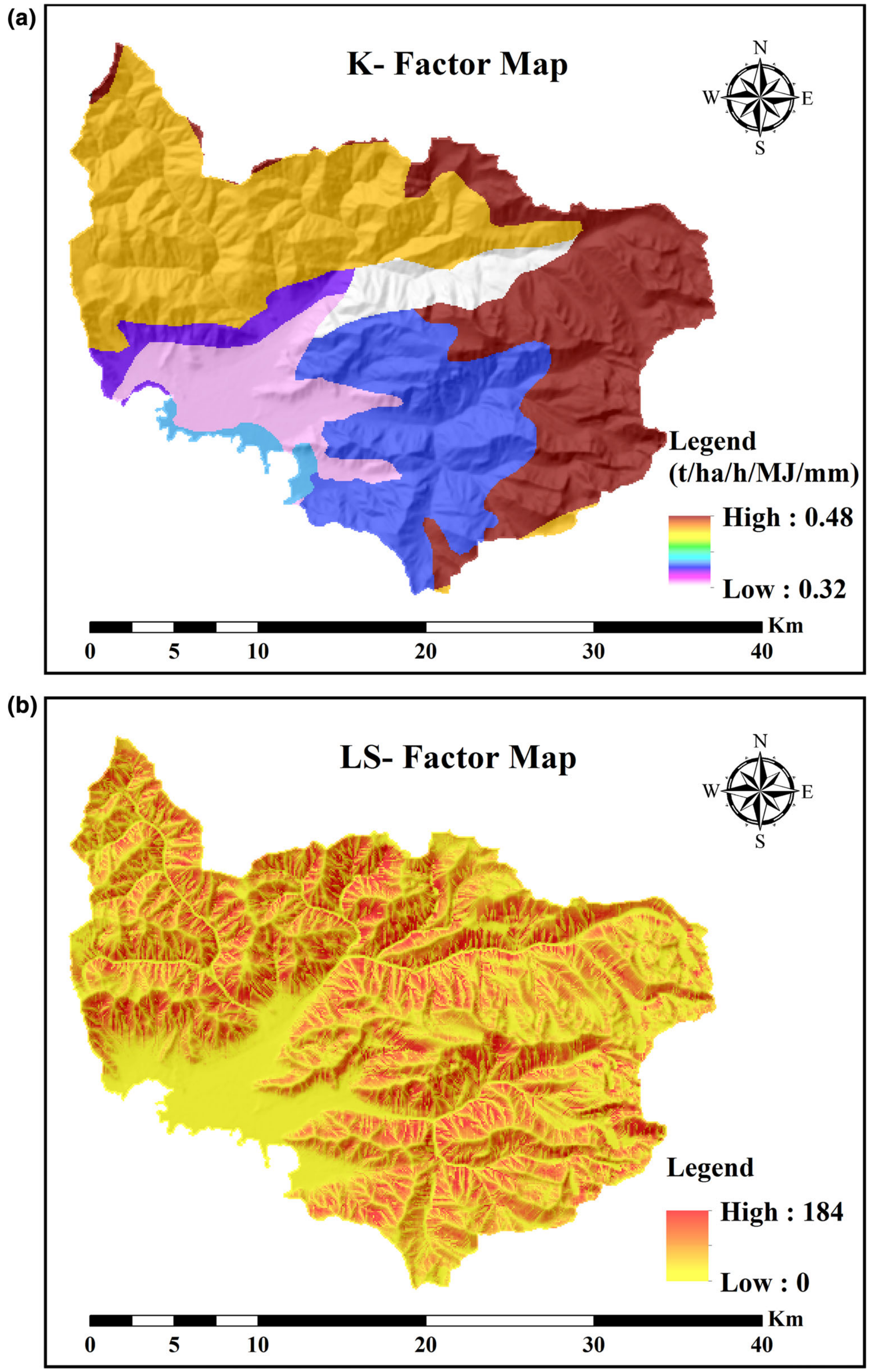


**Fig. 4** **a** *K* factor map of upper catchment of Wular Lake. **b** LS factor map of upper catchment of Wular Lake

soil erosion. It was noticed that although forest and scrub land constitute largest area susceptible to soil erosion, the severity of erosion is less as compared to barren class. The reason being these are covered by vegetation that prevents soil erosion. The areas such as barren land are more prone to soil erosion. The changes in LULC along with altered soils, steep slopes, and bare soils result in the greatest soil loss. Although the barren land is more affected in terms of soil erosion, it can be perceived that entire watershed contributes to soil erosion. The severe soil loss in the

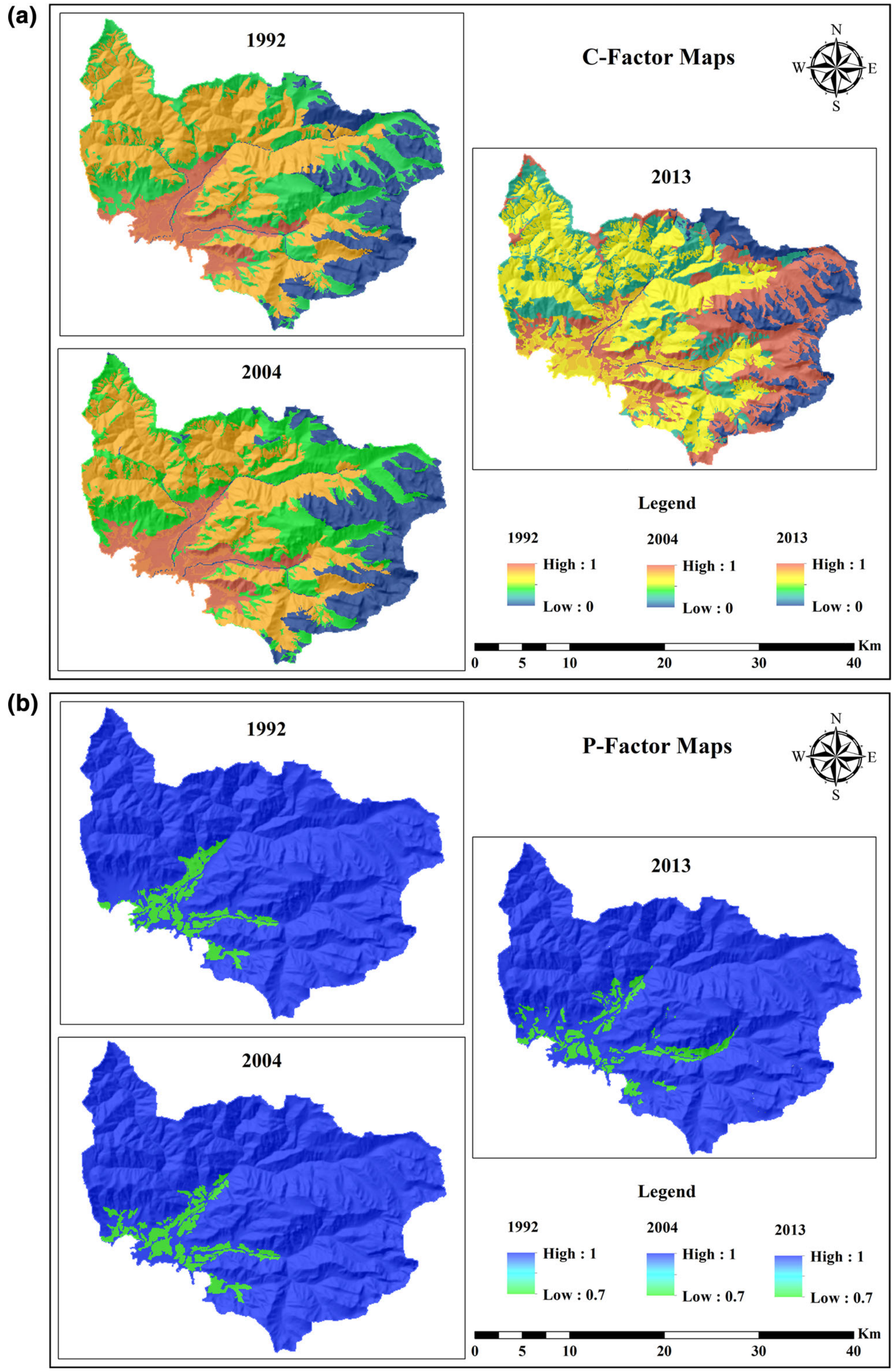


**Fig. 5** **a** *C* factor maps of upper catchment of Wular Lake (1992–2013). **b** *P* factor maps of upper catchment of Wular Lake (1992–2013)

catchment is leading to the sedimentation and siltation, thus affecting the overall water holding capacity of the Wular Lake.

Table 9 indicates differences in amount of soil loss in each land use type. It was observed from the analysis that the total soil loss in the built-up, plantation, and barren land has increased from 1992 to 2013. It can be discerned that the expansion of built-up area from 300 to 2200 ha in the year 1992 to 2013 leads to the increased amount of soil loss in the built-up class. The degree of severity, risk, and amount of soil erosion increases in managed landscapes generally due to the anthropogenic activities like

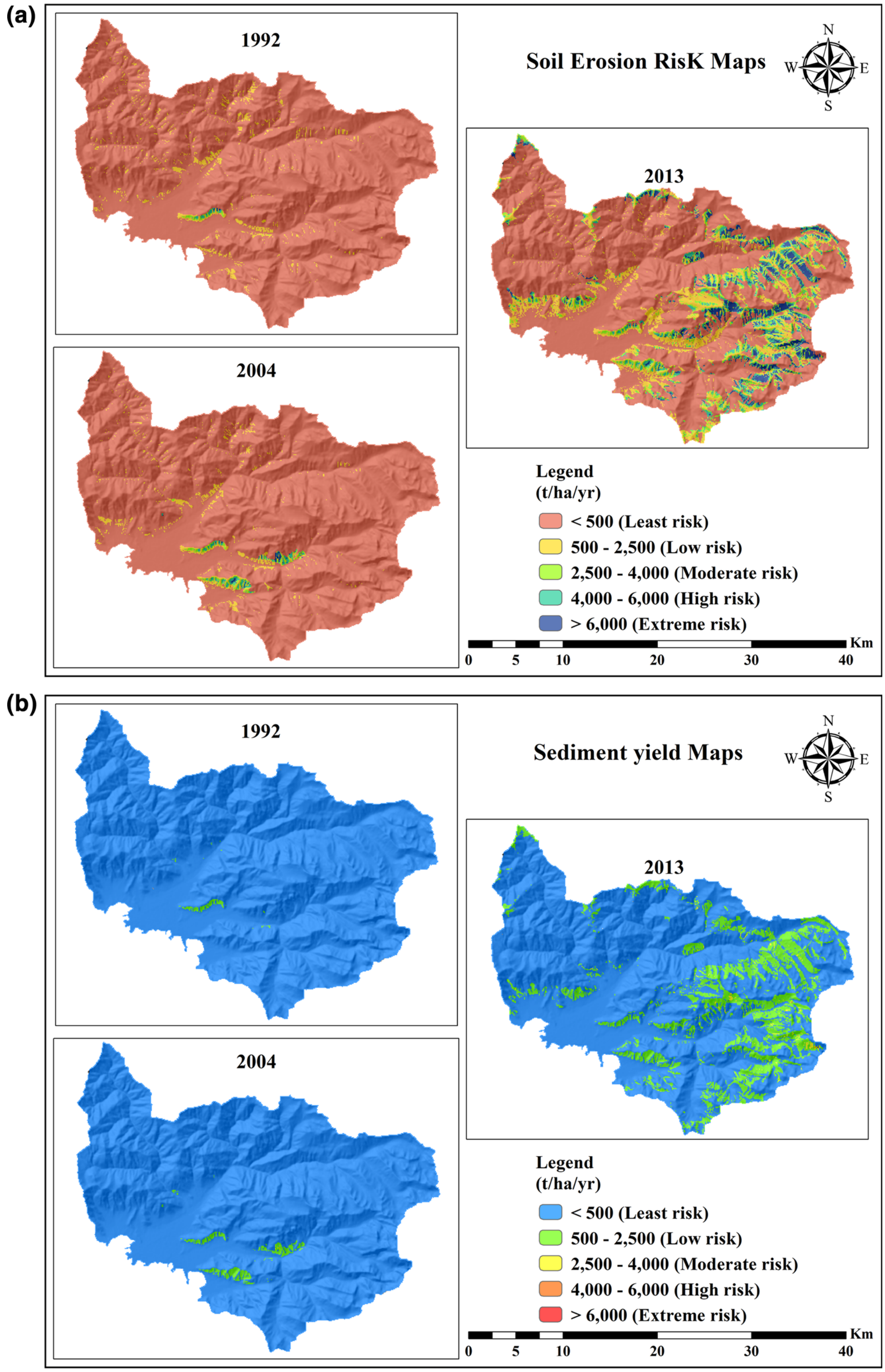


**Fig. 6** **a** Annual soil loss maps of upper catchment of Wular Lake (1992–2013). **b** Sediment yield maps of upper catchment of Wular Lake (1992–2013)

urbanization (Badar et al. 2013; Bhandari et al. 2015; Htwe et al. 2015). Results showed that the plantation increased at the expense of agriculture leading to increased erosion in plantation and decreased erosion in agriculture. The soil loss under forest and scrub land decreased due to the tremendous increase in the barren land leading to more erosion on barren land. Total soil loss in barren land increased due to the deforestation and decrease in snow covered area. Through the field survey, it was observed that large portion of area under forest and scrub land has been

Table 6 Areal extent of various erosion classes in Wular catchment

| Soil loss (t ha$^{-1}$ year$^{-1}$) | 1992 (area) | | 2004 (area) | | 2013 (area) | |
|---|---|---|---|---|---|---|
| | Ha | % | Ha | % | Ha | % |
| < 500 (least risk) | 68,451 | 96.14 | 68,102 | 95.65 | 52,347 | 73.52 |
| 500–2500 (low risk) | 2084 | 2.93 | 1881 | 2.64 | 8281 | 11.63 |
| 2500–4000 (moderate risk) | 251 | 0.35 | 495 | 0.70 | 3719 | 5.22 |
| 4000–6000 (high risk) | 232 | 0.33 | 476 | 0.67 | 3736 | 5.25 |
| > 6000 (extreme risk) | 182 | 0.26 | 246 | 0.35 | 3117 | 4.38 |

Table 7 Area in (%) of soil erosion risk classes on different slopes

| Slope (degree) | 1992 | | | | | 2004 | | | | | 2013 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Least | Low | Moderate | High | Extreme | Least | Low | Moderate | High | Extreme | Least | Low | Moderate | High | Extreme |
| < 8 | 10.3 | 0.0 | 0.0 | 0.0 | 0.0 | 10.3 | 0.1 | 0.0 | 0.0 | 0.0 | 9.6 | 0.7 | 0.0 | 0.0 | 0.0 |
| 8–17 | 13.7 | 0.5 | 0.0 | 0.0 | 0.0 | 13.5 | 0.7 | 0.0 | 0.0 | 0.0 | 9.3 | 4.2 | 0.6 | 0.6 | 0.0 |
| 17–24 | 18.2 | 0.6 | 0.0 | 0.0 | 0.0 | 18.0 | 0.6 | 0.1 | 0.0 | 0.0 | 12.5 | 3.2 | 1.7 | 1.1 | 0.4 |
| 24–30 | 23.2 | 0.5 | 0.0 | 0.0 | 0.0 | 23.0 | 0.5 | 0.2 | 0.1 | 0.0 | 17.5 | 2.0 | 1.6 | 1.5 | 1.3 |
| 30–36 | 21.9 | 0.7 | 0.3 | 0.2 | 0.3 | 21.8 | 0.5 | 0.3 | 0.3 | 0.2 | 17.8 | 1.1 | 1.0 | 1.7 | 1.5 |
| > 36 | 8.9 | 0.5 | 0.0 | 0.1 | 0.0 | 9.0 | 0.3 | 0.1 | 0.2 | 0.2 | 6.8 | 0.4 | 0.3 | 0.9 | 1.2 |

cleared up and converted to the construction site for the Kishanganga Hydroelectric Plant. The anthropogenic activities such as deforestation, urbanization, and mismanaged agricultural practices are leading to high erosion risk.

## Spatial pattern of estimated sediment yield (SY)

Due to the lack of measured sediment yield data, the SDR method was used to compute the sediment yield because as suggested by various authors, this method gives almost exact values to the measured sediment yield (Lim et al. 2005; Arekhi et al. 2012; Kamaludin et al. 2013). In the year 1992, the values of sediment yield varied from 0 to 1960.7 t ha$^{-1}$ year$^{-1}$ with a mean of 30.5 and standard deviation of 63.3 (Fig. 6b). The sediment yield varied from 0 to 3516.4 t ha$^{-1}$ year$^{-1}$ in the year 2004 with mean and standard deviation of 34.7 and 122.9, respectively (Fig. 6b). In the year 2013, the sediment yield varied from 0 to 4476.6 t ha$^{-1}$ year$^{-1}$ (Fig. 6b). The mean and standard deviation observed in sediment yield in the year 2013 were 233.4 and 476.2, respectively.

## Variability of hydrometerological parameters

Table 10 shows the total precipitation, actual direct runoff, and total runoff volume for the period of 35 years (1979–2013). It was observed that average rainfall and runoff of 535.3 mm and 316.2 mm, respectively, were recorded for the period of 35 years with a declining trend. For the period from 1979–2013, the total runoff volume recorded in the Madhumati and Erin watershed was 225,145 m$^3$. While comparing the total amount received for the year 1992, 2004, and 2013, fluctuating pattern of precipitation was observed. It can be seen from Fig. 7 that the actual direct runoff and total runoff volume increase with the increase in rainfall and vice versa. Furthermore, the reduction in the runoff is due to the decrease in the snow cover area in the watershed, which also could lead to the decreased runoff. The discharge of the rivers in the watershed is mainly controlled by rainfall and snow glacial melt. The decrease in the discharge is the result of increased temperature which leads to the retreat of glaciers over the years and decreases in rainfall, and hence decreased river discharge (Mushtaq and Lala 2016a, b).

A time series analysis of temperature (1979–2013) and river discharge data (1990–2012) of Madhumati and Erin was analysed to examine the hydrological processes as a function of climatic variability. The analysis indicated that the maximum and minimum annual average temperature point towards an increasing trend of 0.05 and 0.02 °C, respectively (Fig. 8). The analysis of the discharge data of Madhumati and Erin stream evidently indicates the decreasing tendency of river discharge (Fig. 8). The study area falls under the HSG "A" and HSG "B" which clearly indicates that the water transmission capacity of the soils is high to moderate which will result in low to moderate runoff potential. Although there is an increase in the barren land in the watershed which could lead to high runoff, the majority of the area in the watershed, i.e. approximately

**Table 8** Area in (%) of soil erosion risk classes on land use types

| Land use type | 1992 | | | | | 2004 | | | | | 2013 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Least | Low | Moderate | High | Extreme | Least | Low | Moderate | High | Extreme | Least | Low | Moderate | High | Extreme |
| Built-up | 0.33 | 0.07 | 0.00 | 0.00 | 0.00 | 0.53 | 0.10 | 0.00 | 0.00 | 0.00 | 2.04 | 0.91 | 0.14 | 0.06 | 0.02 |
| Agriculture | 4.67 | 0.54 | 0.01 | 0.00 | 0.00 | 4.81 | 0.59 | 0.01 | 0.00 | 0.00 | 3.65 | 1.40 | 0.04 | 0.00 | 0.00 |
| Forest | 42.16 | 1.60 | 0.00 | 0.00 | 0.00 | 36.36 | 0.81 | 0.00 | 0.00 | 0.00 | 32.72 | 0.68 | 0.00 | 0.00 | 0.00 |
| Plantation | 3.27 | 0.56 | 0.00 | 0.00 | 0.00 | 3.48 | 0.55 | 0.00 | 0.00 | 0.00 | 3.35 | 0.98 | 0.02 | 0.00 | 0.00 |
| Scrub | 27.48 | 0.00 | 0.00 | 0.00 | 0.00 | 30.88 | 0.00 | 0.00 | 0.00 | 0.00 | 17.51 | 0.00 | 0.00 | 0.00 | 0.00 |
| Barren | 0.00 | 0.15 | 0.34 | 0.33 | 0.26 | 0.02 | 0.59 | 0.68 | 0.67 | 0.35 | 0.98 | 7.67 | 5.02 | 5.19 | 4.36 |
| Waterbody | 0.67 | 0.00 | 0.00 | 0.00 | 0.00 | 0.71 | 0.00 | 0.00 | 0.00 | 0.00 | 0.60 | 0.00 | 0.00 | 0.00 | 0.00 |
| Snow | 17.55 | 0.00 | 0.00 | 0.00 | 0.00 | 18.85 | 0.00 | 0.00 | 0.00 | 0.00 | 12.68 | 0.00 | 0.00 | 0.00 | 0.00 |

60%, is under vegetation cover. The total precipitation recorded in the year 1992 was 988.2 mm, whereas 200.7 mm was recorded in 2004 and 417.4 mm in the year 2013. The results obtained depict that in the year 1992, out of the 988.2 mm of rainfall recorded, 725.5 mm was lost to runoff. In the year 2004, 44.7 mm runoff was observed, thus depicting a decrease by 680.8 mm runoff during the 12 years. In the year 2013, 203.4 mm runoff was observed exhibiting an increase by 158.7 mm runoff in the course of last 9 years.

## Catchment hydrological response

Land use/land cover is one of the most critical sources of information that needs to be assessed for better understanding of different catchment scale processes. It has been revealed that the LULC in upper catchment of Wular Lake has considerably changed in past few decades due to anthropogenic influences. The change analysis for the period 1992–2013 indicates significant changes in the upper catchments of Wular Lake particularly for barren, built-up, scrub, snow, and forest. It can be discerned that the expansion of built-up area from 300 ha to 2200 ha in the year 1992 to 2013 and decrease in forest cover (− 22.93%) and scrub land (− 36.73%) leads to the increased amount of soil loss in upper catchment of lake. In addition, the major contribution to the erosion and sediment loadings was found to be highest for barren lands which increased by 158 $km^2$ (5266.67%). Economic benefit in the horticulture crops resulted in significant increase in plantation 3 $km^2$ (10.71%); this leads to increased application of pesticides and other chemicals, which finally leach into the lake water, leading to the deterioration of water quality (Mushtaq et al. 2015; Mushtaq and Lala 2016a, b). In addition, the increase in plantation and built-up in the catchment hastens the nutrient enrichment of the Wular Lake, thus leading to increased aquatic vegetation (Mushtaq and Pandey 2014). It was observed that the area covered by the snow and glaciers also decreased by -35 $km^2$ (− 27.78%) which leads to the decrease in the discharge in the major rivers flowing into the Wular Lake because the discharge of these rivers is primarily controlled by snow glacial melt and rainfall. The reduction in the discharge is due to the increase in temperature which resulted in the retreat of glaciers over the years and decrease in rainfall, hence affecting the water extent of the lake (Mushtaq and Lala 2016a, b).

The analysis carried out for soil erosion, sediment yield, and runoff in the present study indicates that the soil erosion and sediment yield have increased in the watershed from past 21 years, but the runoff has been decreased in the watershed from the past 35 years (Table 11). It was found that there exist a difference among the soil loss and

**Table 9** Difference in the amount of soil loss in each land use

| Land use type | Soil loss ( t $ha^{-1}$ $year^{-1}$) | | | |
|---|---|---|---|---|
| | 1992 | 2004 | 2013 | Change |
| Built-up | 290.00 | 450.00 | 2254.00 | 1964.00 |
| Agriculture | 3714.00 | 3855.00 | 3626.00 | − 88.00 |
| Forest | 31,163.00 | 26,465.00 | 23,782.00 | − 7381.00 |
| Plantation | 2724.00 | 2872.00 | 3094.00 | 370.00 |
| Scrub | 19,566.00 | 21,990.00 | 12,464.00 | − 7102.00 |
| Barren | 771.00 | 1638.00 | 16,526.00 | 15,755.00 |
| Waterbody | 479.00 | 507.00 | 428.00 | − 51.00 |
| Snow | 12,493.00 | 13,400.00 | 9026.00 | − 3467.00 |

runoff generated in the watershed and no correlation was found in both the parameters. It was observed from the present study that the main factors leading to the increased soil erosion in the watershed are mainly due to the change in the LULC by the human activities. The major contribution to the erosion and sediment loadings was found to be highest for barren lands. Increase in barren lands in upper catchment (161 $Km^2$) of Wular Lake was observed that it is very much vulnerable to increased erosion and sediment yields. The other important factor which is contributing to the soil loss in the watershed is the slope. Increased erosion and sediment yield for the period of 21 years from 1992 to 2013 clearly indicate the deteriorating condition of the watershed. The increase in soil loss and sediment yield in the upper catchment leads to the siltation and sedimentation of the waterbody downstream, thus leading to the decrease in the water holding capacity of the lake day by day. Increased siltation and sedimentation over the years result in the presence of high TSS and turbidity in lake water (Mushtaq and Lala 2016a, b).

The runoff showed a good relationship with rainfall. The decrease in rainfall from the last 35 years in the study area has led to the decline in runoff. In addition to the decrease in rainfall, the other factors which lead to the decrease in runoff in major tributaries of Wular Lake are due to the reduction in snow cover area (− 27.78%). The reduction in runoff from major tributaries of Wular Lake over the last decades resulted in the decrease in lake water extent of (13 $km^2$) (Mushtaq and Lala 2016a, b). In addition, to the decrease in rainfall and runoff, the other factors like increase in temperature (0.05 °C) and the increasing pollution from anthropogenic factors are also responsible for the deteriorating condition of lake (Mushtaq and Pandey 2014; Mushtaq et al. 2015; Mushtaq and Lala 2016a, b). The results of the present study indicate that the Wular Lake characterizes a case of vulnerable ecosystem due to the changes in LULC and consequent hydrological changes like decreased runoff and increased erosion and sedimentation in its catchment.

## Conclusion

This study is an attempt to assess the hydrological response of the upper catchment of Wular Lake in terms of LULC change, soil erosion, sediment yield, and runoff in order to identify the relationship and effect of various hydrological processes on the lake ecosystem. The results clearly reveal that significant changes have taken place in LULC classes in the upper catchment of Wular Lake. The changes in land system have intensely affected the responses of various processes like soil erosion, runoff, and sediment loading. The main impelling forces that led to the changes in land use/land cover in the catchment are mainly due to increased human activities like unplanned urbanization and deforestation. The LULC cover change ultimately leads to the increased erosional activities in the area leading to the generation of more sediment yield and thus the sedimentation of the Wular Lake. It was observed that 14.9% of the area of the watershed was under moderate to extreme risk of erosion in the year 2013. The barren land is the main perilous source area and contributes to the maximum erosion and sediment yields. The change analysis revealed that increase in the built-up, barren land and plantation led to more erosion from these types of land use as compared to previous years. An increase in built-up, barren land and decrease in forest cover and scrub land lead to the increased amount of soil loss in upper catchment of lake. In addition, increase in plantation and built-up leads to increased nutrient enrichment of the Wular Lake. The decrease in the snow and glaciers leads to the decrease in runoff which ultimately affected the water extent of the lake. The study indicates that the changes that have taken place in the LULC in past few decades resulted in the decrease in runoff and increase in erosional activities in the area, leading to the sedimentation and siltation, thus affecting the overall water holding capacity of the Wular Lake.

In addition, to the decline in glaciers, expansion of built-up the other factors like decrease in rainfall and increase in temperature is also responsible for the reduction in lake water extent. In addition to the LULC change, decreased level of precipitation, discharge, and increased temperature is aggravating the algae growth leading to eutrophication and therefore reducing lake water extent and depth. The study points towards that the decrease in the extent of in the lake leads to the decline in fish and waterbird diversity, shifting of vegetational belts and drastic loss in productivity of some economically important species. Depletion of the water body exhibits serious implications not only on

**Table 10** Total rainfall, actual direct runoff, and total runoff volume of the watersheds during the period from 1979 to 2013

| Year | Total rainfall (*P*, mm) | Actual direct runoff (*Q*, mm) | Total runoff volume ($m^3$) |
|---|---|---|---|
| 1979 | 438.9 | 221.4 | 157,632.8 |
| 1980 | 441.2 | 223.3 | 159,015.2 |
| 1981 | 620.6 | 381.2 | 271,424.8 |
| 1982 | 835.7 | 580.6 | 413,365.0 |
| 1983 | 673.1 | 429.1 | 305,548.7 |
| 1984 | 641.9 | 400.6 | 285,224.7 |
| 1985 | 361.9 | 158.3 | 112,696.5 |
| 1986 | 712.7 | 465.6 | 331,508.6 |
| 1987 | 512.5 | 284.7 | 202,735.6 |
| 1988 | 619.7 | 380.4 | 270,836.0 |
| 1989 | 631.0 | 390.6 | 278,099.4 |
| 1990 | 751.5 | 501.6 | 357,154.1 |
| 1991 | 638.8 | 397.7 | 283,155.9 |
| 1992 | 988.2 | 725.5 | 516,522.3 |
| 1993 | 625.7 | 385.8 | 274,682.2 |
| 1994 | 891.1 | 633.0 | 450,681.3 |
| 1995 | 754.4 | 504.3 | 359,063.1 |
| 1996 | 833.2 | 578.2 | 411,653.3 |
| 1997 | 446.6 | 227.9 | 162,299.2 |
| 1998 | 542.5 | 311.1 | 221,516.7 |
| 1999 | 257.1 | 80.4 | 57,230.8 |
| 2000 | 212.4 | 51.6 | 36,761.1 |
| 2001 | 16.2 | 17.0 | 12,098.2 |
| 2002 | 246.4 | 73.2 | 52,118.4 |
| 2003 | 625.2 | 385.4 | 274,379.7 |
| 2004 | 200.7 | 44.7 | 31,841.7 |
| 2005 | 500.5 | 274.3 | 195,289.3 |
| 2006 | 623.0 | 383.3 | 272,924.1 |
| 2007 | 282.3 | 98.0 | 69,750.0 |
| 2008 | 490.2 | 265.3 | 188,884.7 |
| 2009 | 409.1 | 196.6 | 139,947.3 |
| 2010 | 501.7 | 275.3 | 196,020.8 |
| 2011 | 443.7 | 225.5 | 160,535.0 |
| 2012 | 544.3 | 312.7 | 222,655.8 |
| 2013 | 417.4 | 203.4 | 144,822.5 |
| Average | 535.2 | 316.2 | 225,145.0 |

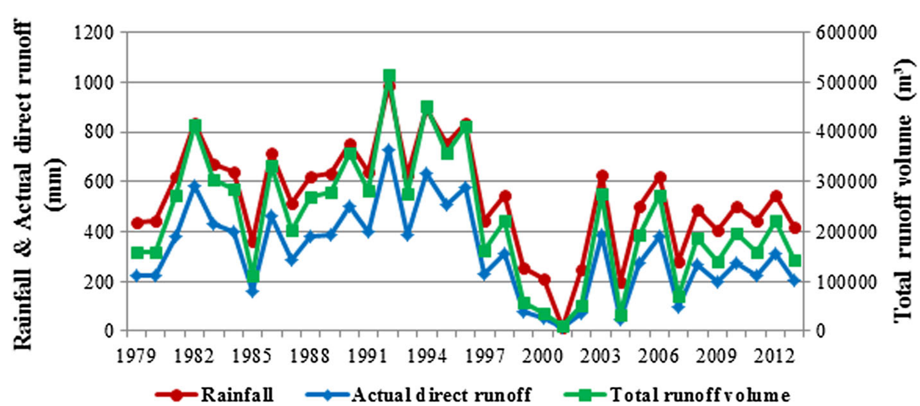


**Fig. 7** Graph displaying interrelationship between rainfall, actual direct rainfall, and total runoff volume

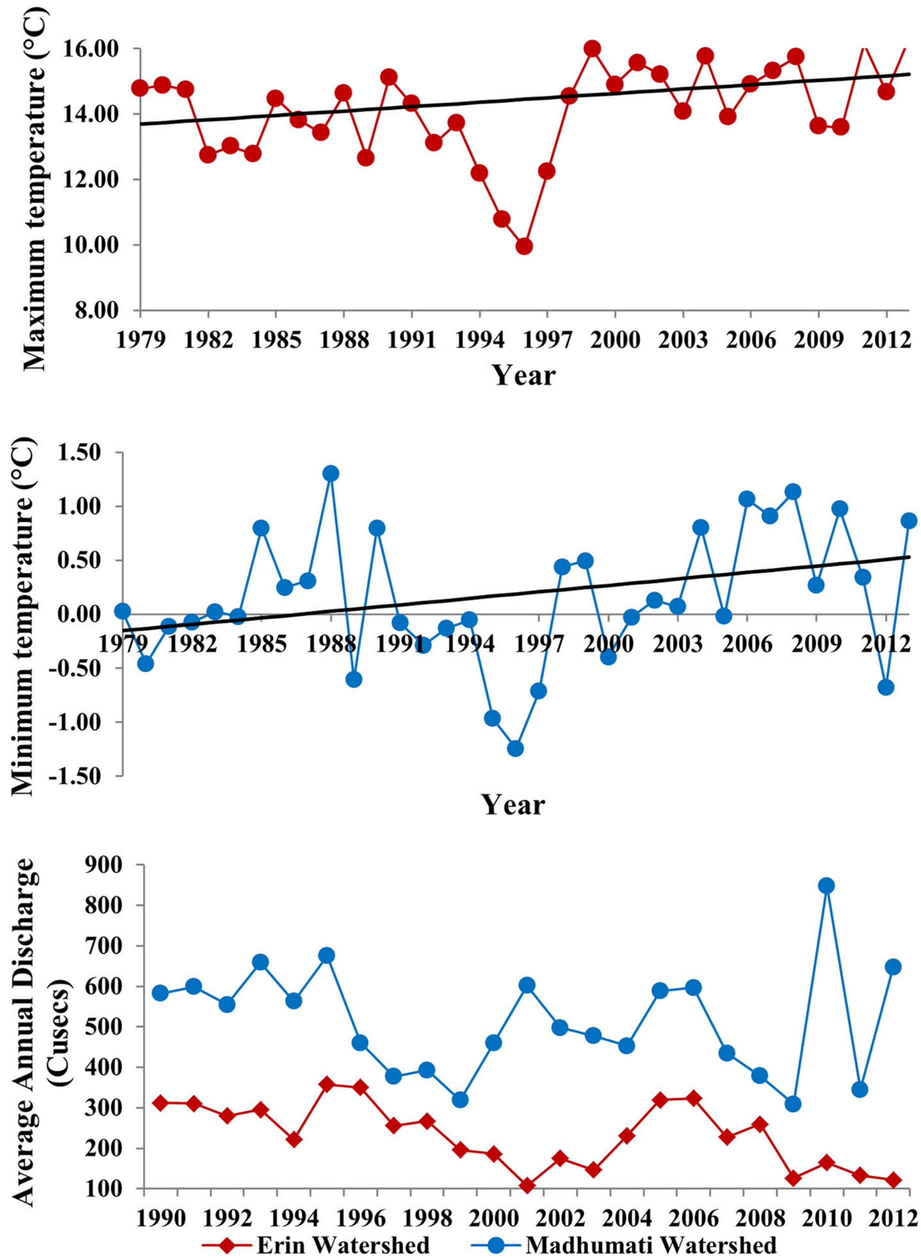


**Fig. 8** Average annual maximum, minimum temperature, and discharge of Madhumati and Erin stream

**Table 11** Estimated soil loss, sediment yield, and runoff of the watersheds

| Parameter | 1992 | 2004 | 2013 |
|---|---|---|---|
| Mean soil loss (t $ha^{-1}$ $year^{-1}$) | 123.23 | 140.31 | 942.52 |
| Mean sediment yield (t $ha^{-1}$ $year^{-1}$) | 30.52 | 34.75 | 233.39 |
| Runoff (mm) | 725.45 | 44.72 | 203.40 |

our flora and fauna but also on the livelihood of the people dependent on the service and goods provided by the lake.

The outcomes of the present study indicate that the Wular Lake characterizes a case of vulnerable ecosystem due to the changes in LULC and consequent hydrological changes like decreased runoff and increased erosion and sedimentation in its catchment. Due to the threat from key factors/forces, the lake is in crucial need of management for its survival. In order to assess the impact of climate change and LULC change on hydrology of Wular Lake, there is a need to use integrated hydrological simulation model with downscaled climate and land use projections.

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