

Modelling catchment hydrological responses in a Himalayan Lake as a function of changing land use and land cover

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In this paper, we evaluate the impact of changing land use/land cover (LULC) on the hydrological processes in Dal lake catchment of Kashmir Himalayas by integrating remote sensing, simulation modelling and extensive field observations. Over the years, various anthropogenic pressures in the lake catchment have significantly altered the land system, impairing, *inter-alia*, sustained biotic communities and water quality of the lake. The primary objective of this paper was to help a better understanding of the LULC change, its driving forces and the overall impact on the hydrological response patterns. Multi-sensor and multi-temporal satellite data for 1992 and 2005 was used for determining the spatio-temporal dynamics of the lake catchment. Geographic Information System (GIS) based simulation model namely Generalized Watershed Loading Function (GWLF) was used to model the hydrological processes under the LULC conditions. We discuss spatio-temporal variations in LULC and identify factors contributing to these variations and analyze the corresponding impacts of the change on the hydrological processes like runoff, erosion and sedimentation. The simulated results on the hydrological responses reveal that depletion of the vegetation cover in the study area and increase in impervious and bare surface cover due to anthropogenic interventions are the primary reasons for the increased runoff, erosion and sediment discharges in the Dal lake catchment. This study concludes that LULC change in the catchment is a major concern that has disrupted the ecological stability and functioning of the Dal lake ecosystem.

1. Introduction

The valley of Kashmir located in the northern Indian Himalayas, is represented by breathtaking lakes, mountains, snow and spring-fed streams, finest meadows and alpine forests. One of the striking features of the Valley is the chain of lakes categorized into glacial, pine-forest and valley lakes based on their origin, altitudinal situation and nature of biota they contain (Zutshi *et al.* 1972; Kaul 1977; Zutshi and Khan 1978; Pandit 1996, 1999). In Kashmir valley, eutrophication and dwindling of lake ecosystems is a very recent event of the

past 10–30 years, coinciding with a marked civilization evolution in the lake drainage basins (Pandit 1998). Since, there has not been much industrial development in the Kashmir valley, the main contributors towards the degradation of these water bodies are land-use changes, unplanned urbanization, increased soil erosion and reckless use of pesticides for agro-horticultural practices in the catchment areas (Badar and Romshoo 2007a, b). Consequently, most of the lakes in the Kashmir valley exhibit eutrophication (Kaul 1979; Khan 2008) characterized by excessive macrophytic vegetation growth, anoxic deep waters, with high nutrient

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concentrations in their waters (Koul *et al.* 1990; Khan 2000; Jeelani and Shah 2006).

Dal lake, a cradle of Kashmiri civilization has strong linkages with socio-economics of the state of Jammu and Kashmir in India. Since ages, the lake has been a source of livelihood to a large number of people through various activities ranging from tourism, farming and fisheries. With its multi-faceted ecosystem and grandeur, this lake has been a centre of attraction for national and international tourists for centuries. Other than the tourist trade, the lake is considered to be a goldmine for inhabitants as it provides livelihood to thousands of people who draw benefits from it through a series of trade activities ranging from farming to fish production. During the last few decades, anthropogenic interventions in the catchment like unplanned urbanization, deforestation, intensive grazing, stone quarrying, etc. have exerted tremendous pressure on the world famous freshwater ecosystem. Stone quarrying in certain parts of the catchment although banned now has resulted in largely degraded and defaced mountains that have placed a serious threat of soil erosion and landslides. Increased runoff, erosion and subsequent sedimentation in the catchment have resulted in increased turbidity, decreased light penetration, transparency and the depth of lake (AHEC 2000). Contaminants enter the lake through direct point sources, diffuse agricultural sources and diffuse urban sources. With the increase in the tourist influx, a large number of residential buildings, restaurants and hotels have come up along the lake front at an alarming rate. As a result, these activities are suffocating the lake and contaminating its water mass (Solim and Wanganeo 2008). The gradual reclamation of the lake to provide building and vegetable growing land and the increase in the area of floating gardens combined with natural processes reduced the area of open water within the lake area. As per DANIDA (1990), the Dal lake spread over an area of 22 km² till 1940. The present investigations reveal that now the open water extent of the lake barely covers 11.5 km² (Badar and Romshoo 2007a, b). A sizeable (20%) portion of the lake is covered by floating gardens reducing the open water area to 59% of the total Dal lake area (Khan 2000).

Hydrological response in the form of runoff is an integrated indicator of catchment conditions and significant changes in the LULC may affect the overall health and function of a catchment, as it modifies and alters many other inter-related processes. It has been observed that the changes in the land cover types in a catchment substantially affect the hydrological response including surface runoff (Thanapakpawin *et al.* 2007; Hejazi and Moglen 2008; Breuer and Huisman 2009). Such changes

in runoff patterns in turn result in severe environmental implications like increased erosion, sedimentation and nutrient loadings which ultimately find their way into the water bodies particularly fresh water ecosystems and disrupt their ecological stability and functioning. Studies suggest that agriculture, grazing, and urban development can significantly increase sediment yields into adjacent waterways (Heathwaite *et al.* 1990). Modelling has become an important tool for understanding physical and hydrological processes and impacts (Bronstert 1999). Recent developments of decision support systems based on GIS and distributed hydrological models have provided practical and useful tools to achieve this goal (Fohrer *et al.* 2001). Geospatial models are excellent tools that allow us to predict the hydrological and other land surface processes and phenomena at different spatial and temporal scales (Young *et al.* 1987; Shamsi 1996; Zollweg *et al.* 1996; Frankenberger *et al.* 1999; Olivera and Maidment 1999; Romshoo 2003; Yuksel *et al.* 2008). Impact of LULC is assessed by comparing model responses to the incorporation of different scenarios of land cover (Mosier *et al.* 1997).

Various research studies regarding the Kashmir Himalayan lakes have been centered on their hydrochemical and hydrobiological characteristics (Pandit 1998; Jeelani and Shah 2006; Saini *et al.* 2008). Very few studies, if at all, have dealt with modelling of different catchment scale processes (Badar and Romshoo 2007a, b; Muslim *et al.* 2008; Romshoo and Muslim 2011). Most of the Dal lake research conducted earlier has been mostly of conventional/routine nature without any serious attempt to model the effect of any catchment scale processes on the health of the Dal lake ecosystem (Amin and Romshoo 2007; Badar and Romshoo 2007a, b).

The major goals of this study have been to determine the LULC change in Dal lake catchment from 1992–2005 and its driving forces, identify the different critical source areas and simulate the hydrological response patterns under the changed land system scenarios.

2. Study area

The Dal lake catchment (figure 1) is located in Kashmir Himalayas, India between the geographical coordinates of 34°02'–34°13'N latitude and 74°50'–75°09'E longitude. The lake catchment is not only highly diverse but also covers a huge area of 337 km² which is nearly 18 times more than the lake area. The general relief of the catchment is a basin which comprises the Dal lake situated at an altitude of approximately 1580 m and a steep

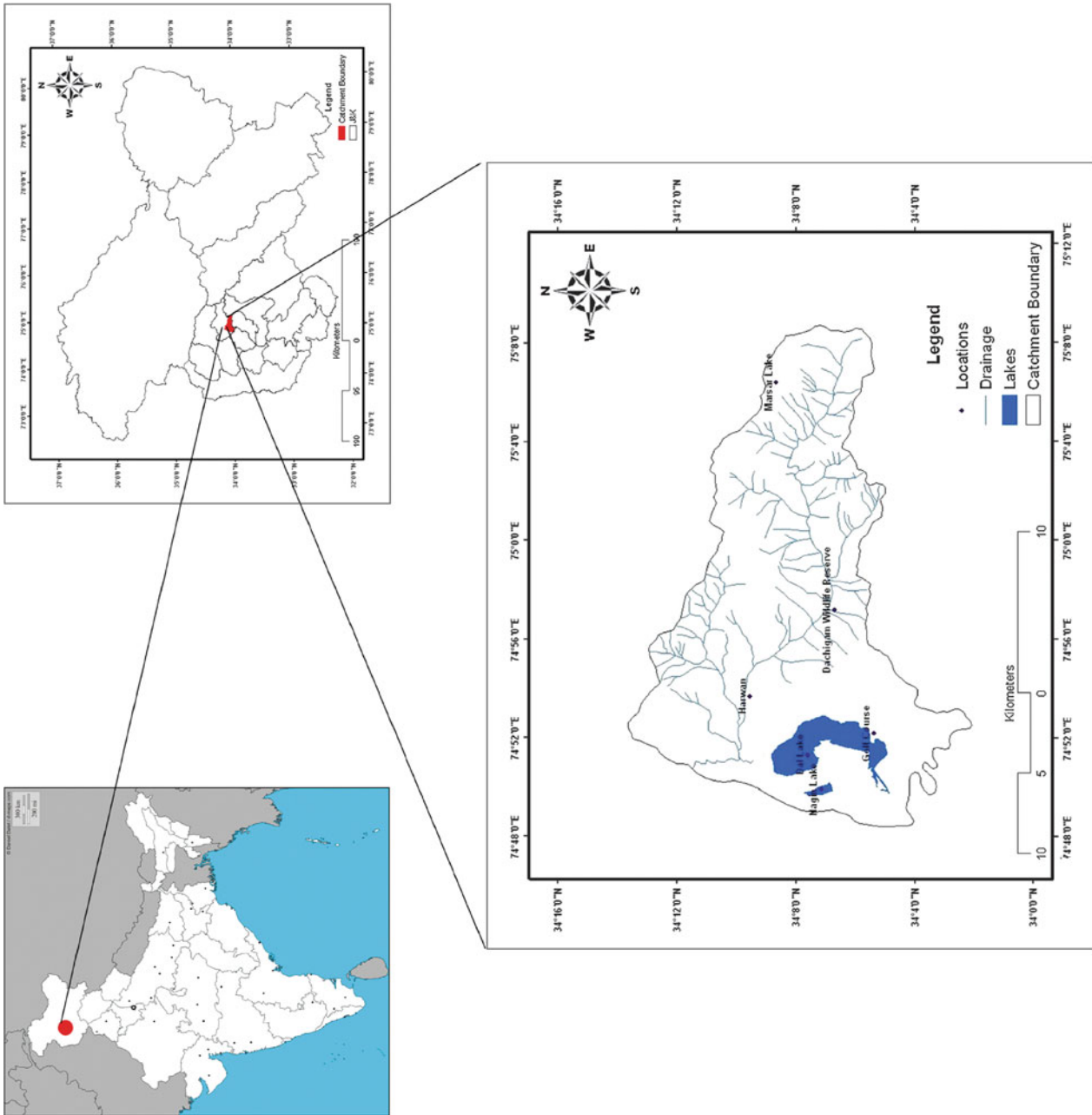


Figure 1. Location of the study area.

escarpment at an elevation of 4390 m located along eastern watershed. The flat areas of the catchment are mostly used as cropland, horticulture and built-up where human activities have intensified during the last few decades. The mountainous areas are mostly covered by forest, grassland, scrub lands, and the hilly regions consist of natural vegetation and barren land, respectively. Most of the surface runoff carrying the eroded soil and sediments originate from these mountainous and hilly areas of the catchment. The geological formations of the catchment area are dominated by alluvium, Panjal traps and agglomerate slates (Wadia 1971; Varadan 1977; Data 1983; Bhat 1989).

Dal lake is a shallow, multi-basin lake with inflow and outflow water channels. The drainage pattern in the study area is a combination of trellis and dendritic patterns with the general flow direction being from east to southwest. The lake is fed by a number of underground springs and streams but the main feeding channel is the Dachigam Creek, originating from the Alpine Marsar lake that enters into the lake on the northern side after draining the Dachigam Wildlife Reserve en-route.

The Dal lake catchment belongs to a sub-Mediterranean type climate with four seasons based on mean temperature and precipitation (Bagnolus and Meher-Homji 1959). The catchment receives an average annual rainfall of 650 mm at Srinagar station and 870 mm at Dachigam station. March, April and May are the wettest months of the year. The entire Dal Lake catchment remains covered with snow during winter months of December through March with minimum temperatures reeling below zero. The temperature varies between a monthly mean maximum of 31°C in July and a minimum of -4°C in January with an average of 11°C.

3. Materials and method

During the present study, a multitude of datasets were used in order to accomplish the research goals. For performing the change detection in land use and land cover, multi-date and multi-sensor satellite data in the form of Landsat Thematic Mapper (TM) and Indian Remote Sensing satellite data [IRS 1D, Linear Imaging Self Scanning (LISS-III)] was used. Landsat TM image of October 1992 with a spatial resolution of 30 m and band combination of 4:3:2 (IR:R:G) was used in the research that served as reference base map. Similarly, IRS-ID (LISS-III) of 5 October, 2005 with a spatial resolution of 23.5 m and spectral resolution of 0.52–0.86 μ was used in the study (NRSA 2003). Digital Elevation Model (DEM) from Shuttle Radar Topographic Mission (SRTM), with a spatial resolution

of 1 arc-sec was used for generating the topographic variables of the catchment for use in the geospatial model (Rodriguez *et al.* 2006). A soil map of the study area was generated by using remotely sensed classified data aided with extensive laboratory analysis of the soil samples followed by detailed ground truthing. A time series of hydro-meteorological data from the nearest observation station was used as input to the geospatial model. Ancillary data related to the sediment loadings was also used in this study.

3.1 Geospatial modelling approach

For simulating the hydrological responses under changed land system conditions, a distributed/lumped parameter watershed model GWLF was used (Haith and Shoemaker 1987). The model simulates runoff, erosion and sediment loads from a watershed given variable-size source areas on a continuous basis and uses daily time steps for weather data and water balance calculations (Haith *et al.* 1992; Lee *et al.* 2001; Evans *et al.* 2008). Monthly calculations are made based on the daily water balance accumulated to monthly values. For the surface loading, the approach adopted is distributed in the sense that it allows multiple LULC scenarios, but each area is assumed to be homogenous with regard to various attributes considered by the model. The model does not spatially distribute the source areas but simply aggregates the loads from each area into a watershed total. For sub-surface loading, the model acts as a lumped parameter model using a water balance approach. The model is particularly useful for application in regions where environmental data of all types is not available to assess the point and non-point source pollution from watershed (Evans *et al.* 2002; Strobe 2002). The overall schematic flow of the methodology is given in figure 2.

3.1.1 Model structure and mechanism

The GWLF model computes the runoff by using the Soil Conservation Service (SCS) curve number equation. Erosion is computed using the Universal Soil Loss Equation (USLE) and the sediment yield is the product of erosion and sediment delivery ratio (SDR). The yield in any month is proportional to the total transport capacity of daily runoff during the month.

The direct runoff is estimated from daily weather data using SCS curve number equation given by equation (1):

$$Q_{kt} = \frac{(R_t + M_t - 0.2DS_{kt})^2}{R_t + M_t + 0.8DS_{kt}}. \quad (1)$$

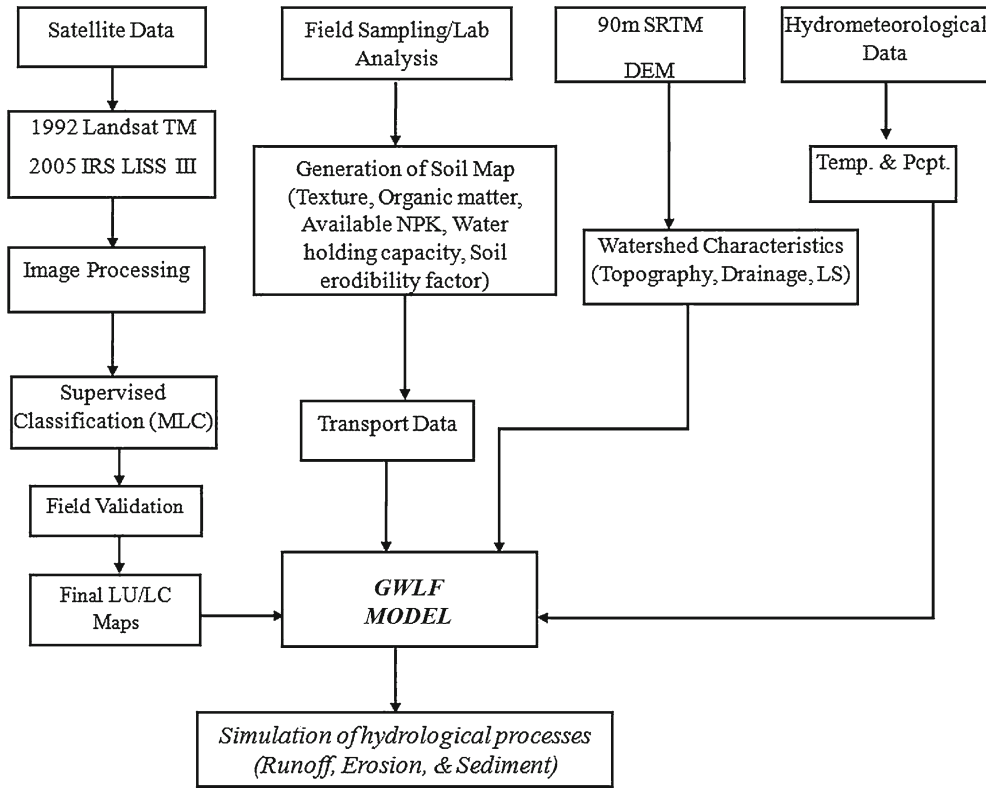


Figure 2. Methodology adopted.

Rainfall R_t (cm) and snowmelt M_t (cm of water) on the day t (cm), are estimated from daily precipitation and temperature data. DS_{kt} is the catchment's storage. Catchment storage is estimated for each source area using CN values with the equation (2) given below

$$DS_{kt} = \frac{2540}{CN_{kt}} - 25.4 \quad (2)$$

where CN_{kt} is the CN value for source area k , at time t .

Stream flow consists of runoff and discharge from groundwater. The latter is obtained from a lumped parameter watershed water balance (Haan 1972). Daily water balances are calculated for unsaturated and shallow saturated zones. Infiltration to the unsaturated and shallow saturated zones equals the excess, if any, of rainfall and snowmelt runoff. Percolation occurs when unsaturated zone water exceeds field capacity. The shallow saturated zone is modelled as linear ground water reservoir. Daily evapotranspiration is given by the product of a cover factor and potential evapotranspiration (Hamon 1961). The latter is estimated as a function of daily light hours, saturated water vapour pressure and daily temperature.

Erosion is computed using the USLE and the sediment yield is the product of erosion and SDR. The yield in any month is proportional to the total capacity of daily runoff during the month.

Erosion from source area (k) at time t , X_{kt} is estimated using the following equation:

$$X_{kt} = 0.132 * RE_t * K_k * (LS)_k * C_k * P_k * R_k \quad (3)$$

where $K_k * (LS)_k * C_k * P_k$ are the soil erodibility, topography, cover and management and supporting practice factor as specified by the USLE (Wischmeier and Smith 1978). RE_t is the rainfall erosivity on day t (MJ – mm/ha-h).

Soil loss from stream bank erosion is based upon the familiar sediment transport function having the form

$$LER = aQ^{0.6} \quad (4)$$

where LER is the lateral erosion rate in m/month which refers to the total distance that soil is eroded away from both banks along the entire length of a stream during a specified period of time, a is an empirically-derived erosion potential factor, and Q is mean monthly stream flow in m^3/s . In this case, the value of 0.6 is used based on a global review of stream bank erosion studies (Van Sickle and Beschta 1983; Lemke 1991; Rutherford 2000).

3.1.2 Preparation of input data

A variety of input parameters are required to run the GIS based GWLF model for simulating different hydrological processes at catchment scale which include the land use/land cover data, digital

topographic data, hydrometeorological data, transport parameter data (hydrologic and sediment) and nutrient parameter data. All these datasets were prepared with the procedures given below.

Land use and land cover data: Land use and land cover data are very important for determining the nature and mechanism of different hydrological responses. For identifying the change that has taken place in the land system and its subsequent effect on the hydrological response patterns in the catchment, multi-date satellite imageries were used. In order to derive the change, supervised classification using maximum likelihood classifier was performed on both the images. This procedure is most often used for the quantitative analysis of remote sensing data and allows the analyst to take charge of the pixel categorization process by specifying to the computer algorithm, the brightness values that will represent one category of land use/land cover in each band of the digital image. Different training sets were developed after analysis of various visual (colour, tone, texture, shape, size, association, convergence of evidence, etc.) and statistical (mean, standard deviation, etc.) characteristics of the data. The training sets were taken from homogeneous cover types as the validity estimate of sample depends upon size and the representativeness of the sample. This was followed by the extensive field verification and ground truthing of the identified land use classes. Accuracy assessment was carried out by using randomly selected points that were collected during the field survey to determine the accuracy of the land use/land cover classification.

Hydrometeorological data: Daily precipitation and temperature data are required for the simulation of hydrological processes by the GWLF

model. The daily hydrometeorological data from the India Meteorological Department (IMD) comprising of daily precipitation and daily temperature (minimum and maximum), with a time step of 28 years was prepared as an input to the model. In addition, mean daylight hours for the catchment with latitude 34°N were obtained from literature (Haith *et al.* 1992; Evans *et al.* 2008). The study area receives an average rainfall of about 650 mm with most of its precipitation between the months of March and May. January (−0.6°C) is the coldest month while as July (31.37°C) is the hottest month. Maximum daylight is recorded for the month of June (14.3 h) and July (14.1 h) and the minimum daylight is received in the months of December (9.7 h) and January (9.9 h).

Transport parameters: Transport parameters including hydrologic, erosion and sediment of the catchment are those aspects that influence the movement of the runoff and sediments from any given unit in the catchment down to the lake. Transport parameters calculated for different source areas in the catchment are given in table 1, with the complete procedures for generating each of these are explained as below.

Hydrological parameters: The evapotranspiration (ET) cover coefficient is the ratio of the water lost by evapotranspiration from the ground and plants compared to what would be lost by evaporation from an equal area of standing water (Thuman *et al.* 2003). The ET cover coefficients depend upon the type of land use and time period within the growing season of a given field crop (FAO 1980; Haith 1987). Typical ET values ranged from 0.3 to 1.00 for plantations depending upon the development stage. Values observed for the bare areas,

Table 1. Transport parameters used for different source areas in GWLF model for Dal Lake catchment.

Source areas	Hydrological conditions	LS	C	P	K	WCN	WDET	WGET	ET coefficient
Agriculture	Fair	2.609	0.42	0.52	0.169	82	0.3	1.0	0.4
Horticulture	Fair	3.206	0.05	0.1	0.186	87	0.3	1.0	0.6
Forest	Fair	46.33	1	1	0.226	68	0.3	1.0	0.7
Hay/pasture	Fair	59.38	0.03	0.74	0.255	63	0.3	1.0	0.5
Built up	N/A	0.488	0.08	0.2	0.13	94	1	1.0	0.1
Bare land	Poor	42.66	0.8	0.8	0.15	89	1.0	0.3	0.1

Note: Good hydrological condition refers to the areas that are protected from grazing and cultivation so that the litter and shrubs cover the soil; fair conditions refer to intermediate conditions, i.e., areas not fully protected from grazing and the poor hydrological conditions refer to areas that are heavily grazed or regularly cultivated so that the litter, wild woody plants and bushes are destroyed.

LS: slope length and steepness factor, C: cover factor, P: management factor, K: soil erodibility value, WCN: weighted curve number values, WDET: weighted average dormant season evapotranspiration, WGET: weighted average growing season evapotranspiration, ET: evapotranspiration coefficient.

urban surfaces, ploughed lands were 0.1 and 0.4 for agriculture and grasslands.

The SCS curve number is a parameter that determines the amount of precipitation that infiltrates into the ground or enters surface waters as runoff after adjusting it to accommodate the antecedent soil moisture conditions based on total precipitation for the preceding 5 days (EPA 2003a). A combination of factors such as land use/land cover, soil hydrological group, hydrological conditions, soil moisture conditions and management are used to determine the curve numbers (Arhonditsis *et al.* 2002). In GWLF model, the CN value is used to determine for each land use, the amount of precipitation that is assigned to the unsaturated zone where it may be lost through evapotranspiration and/or percolation to the shallow saturated zone if storage in the unsaturated zone exceeds soil water capacity. In percolation, the shallow saturated zone is considered to be a linear reservoir that discharges to stream or losses to deep seepage, at a rate estimated by the product of zone's moisture storage and a constant rate coefficient (SCS 1986). The soil parameters of the catchment were determined by carrying out a comprehensive analysis of the soil samples in the laboratory. A total of 50 composite soil samples, well distributed over various land use and land cover categories were collected from the lake catchment. For the field sampling, similar soil units were delineated using the satellite imagery (Khan and Romshoo 2008). This was followed by laboratory analysis of the samples for

parameters like texture, organic matter and water holding capacity. Soil texture was determined by the International Pippeting Method (Piper 1966), field capacity of the samples was determined by Veihmeyer and Hendricjson (1931) and the soil organic matter/organic carbon was determined by the rapid titration method (Walkley and Black 1934). Using the field and lab observations of the soil samples, soil texture was determined using the soil textural triangle (Toogood 1958). The spatial soil texture map (figure 3) and the soil organic matter map (figure 4), were developed by stochastic interpolation method in GIS environment (Burrough 1986). The soil hydrological groups for all the soil units in the catchment were derived from the soil texture and permeability properties (figure 5; table 2).

Sediment yield parameters: Several soil and topographic parameters are required for simulating the soil erosion using the GWLF model. The LS factor used as a combination of slope length and slope steepness parameters determines the effect of topography on soil erosion and was derived from the DEM of the study area (Arhonditsis *et al.* 2002). The soil erodibility factor (K) of the catchment was generated from the soil texture and soil organic matter content maps were prepared as described above (Steward *et al.* 1975). The rainfall erosivity factor (RE) was estimated from the product of the storm energy (E) and the maximum

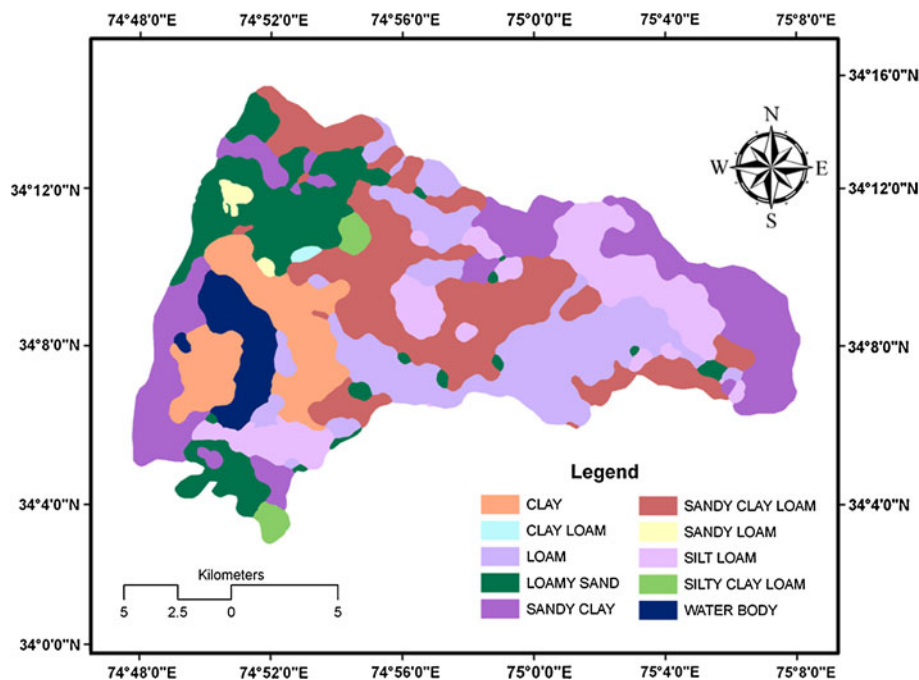


Figure 3. Soil texture map of Dal lake catchment.

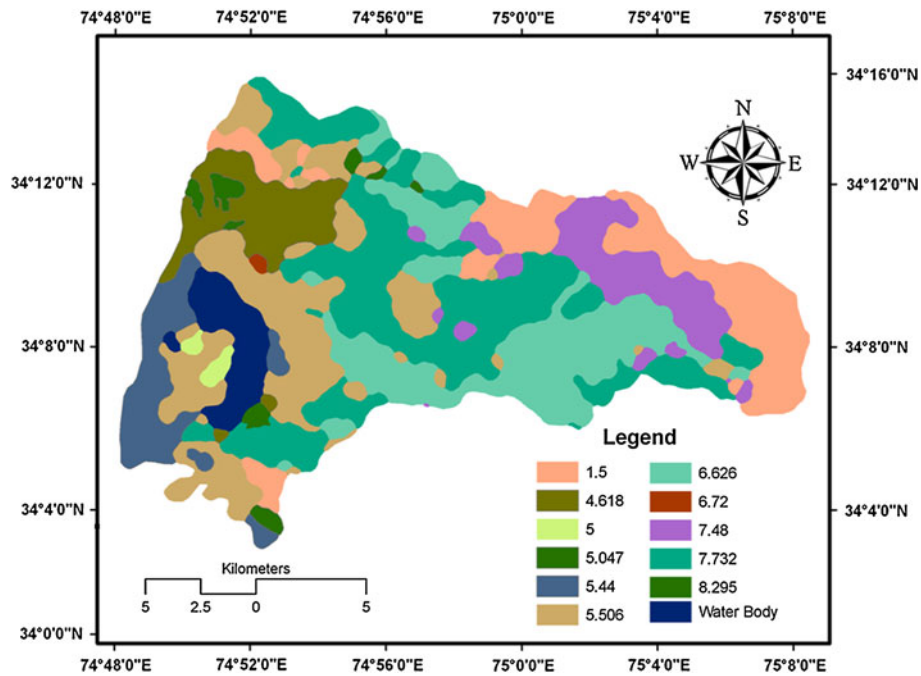


Figure 4. Soil organic matter in Dal lake catchment.

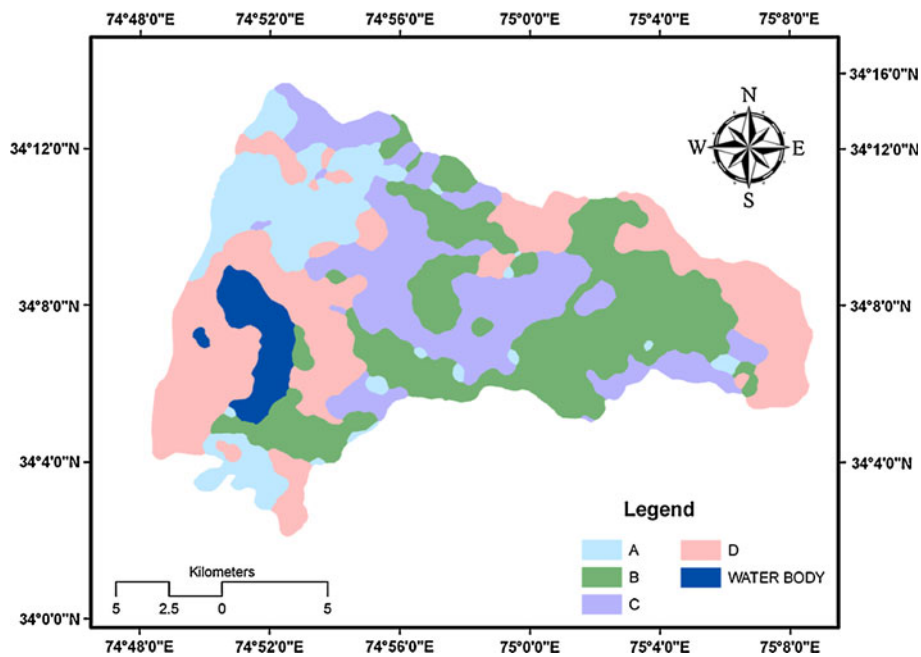


Figure 5. Dominant soil hydrological groups in Dal lake catchment.

30-minute rainfall intensity (I_{30}) data collected for that period. Erosivity coefficient for the dry season (May–September) was estimated to be 0.01 and coefficient for wet season was estimated to be 0.034 (Montanarella *et al.* 2000). The crop management factor (C) related to soil protection cover (Wischmeier and Smith 1978) and the conservation practice factor (P) that reflects soil conservation

measures (Pavanelli and Bigi 2004) were determined from the land use and land cover characteristics (Haith *et al.* 1992; EPA 2003b). The GWLF model estimates the sediment yield by multiplying SDR with the estimated erosion. Use of the logarithmic graph based on the catchment area (Vanoni 1975; Haith *et al.* 1992; Evans *et al.* 2008) was made for determining the SDR.

Table 2. Dominant soil hydrological groups used in the GWLF model.

Dominant hydrological group	Soil texture	Soil runoff potential and permeability properties
A	Sand, loamy sand, sandy loam	Low surface runoff potential
B	Silt loam, loam	Moderately coarse soils with intermediate rates of water transmission
C	Sandy clay loam	Moderately fine texture soils with slow rates of water transmission
D	Clay loam, silty clay loam, sandy clay, silty clay, clay	High surface runoff potential

4. Results

4.1 Land use/land cover change detection

The classification of the satellite imagery for the two study periods provided the spatial distribution of land use/land cover categories. Figures 6 and 7 show the spatial distribution of land use/land cover in 1992 and 2005 respectively, with the statistics and change in area is given in table 3. Both the years were classified into 16 land use/land cover classes namely coniferous forest, deciduous

forest, sparse forest, grasslands, scrub lands, plantation, agriculture, horticulture, agriculture fallow, aquatic vegetation, snow, water, water channel area, bare land, bare exposed rocks and built up. However, for the year 2005, an extra class in the form of golf course was identified, as it was not present for the earlier year of 1992. It was observed that for 1992, deciduous forest was the most dominant class in the study area covering 76.49 km² (22.69%) followed by coniferous forest 51.87 km² (15.39%), plantation 47.9 km² (14.21%) and grasslands 33.31 km² (9.88%). Snow 1.05 km² (0.31%), aquatic vegetation 1.03 km² (0.30%) and fallow 0.08 km² (0.023%) were the least dominant classes. The statistics for 2005 revealed that the deciduous forest again dominated the land use/land cover area covering 74.69 km² (22.16%) followed by coniferous forest 46.2 km² (13.70%), plantation km² (10.38%), grasslands 25.42 km² (7.54%). The least representative of the classes was golf course/turf 0.51 km² (0.51%), water channel area 1.3 km² (0.38%) and fallow 0.004 km² (0.001%).

The change detection from 1992–2005 revealed significant changes in the Dal lake catchment particularly for agriculture, horticulture, built up, bare lands, grasslands, scrub lands and forests. The built up class comprised of the areas of settlements, residential, commercial, industrial establishments and recorded an increase of 12.08 km² from 1992–2005. Agriculture comprising the cumulative land under different crops decreased by 1.84 km², while as horticulture that included fruit crops decreased

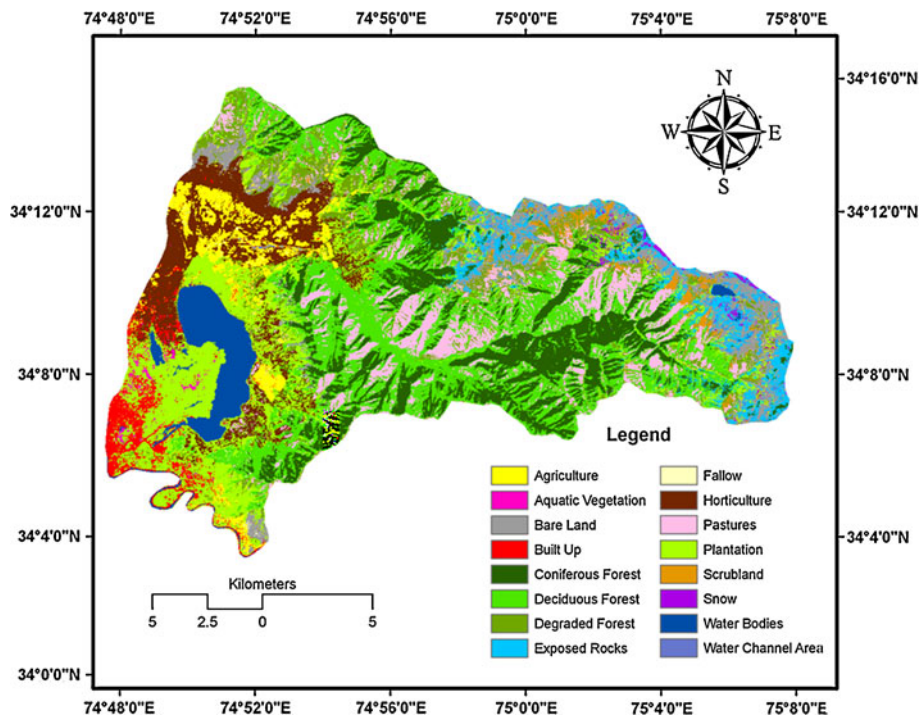


Figure 6. Spatial distribution of land use/land cover for Dal lake catchment in 1992.

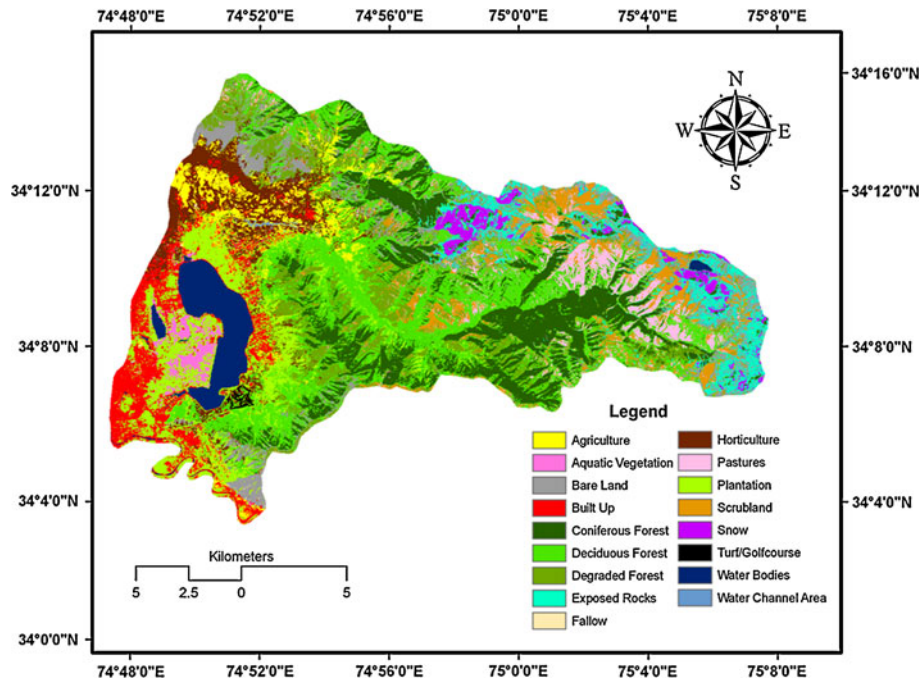


Figure 7. Spatial distribution of land use/land cover for Dal lake catchment in 2005.

Table 3. Change in the land use/land cover pattern of Dal lake catchment (1992–2005).

Sl. no.	Class name	Area (km ²)		Area change (km ²)	% change
		1992	2005		
1	Built up	9.31	21.39	+12.08	3.58
2	Agriculture	14.71	12.87	-1.84	0.54
3	Agriculture fallow	0.08	0.004	-0.076	0.02
4	Horticulture	26.91	19.34	-7.57	2.24
5	Coniferous forest	51.87	46.2	-5.67	1.68
6	Deciduous forest	76.49	74.69	-1.8	0.53
7	Sparse forest	19.76	18.8	-0.96	0.28
8	Grasslands	33.31	25.42	-7.89	2.34
9	Scrub land	3.68	15.65	+11.97	3.55
10	Plantation	47.9	35.00	-12.9	3.82
11	Aquatic vegetation	1.03	4.50	+3.47	1.02
12	Bare land	20.82	25.26	+4.44	1.31
13	Bare exposed rocks	14.09	15.7	+1.61	0.47
14	Water bodies	14.8	13.89	-0.91	0.27
15	Water channel area	1.24	1.30	+0.06	0.01
16	Snow	1.05	6.50	+5.45	1.61
17	Golf course/turf	0.00	0.51	+0.51	15.37
Total		337	337		

by 7.57 km². Overall forest cover of the study area showed a declining trend with 5.67 km², 1.8 km², 0.96 km² losses in coniferous, deciduous and sparse forest, respectively. Plantation cover also declined by 12.9 km². Large scale decrease in grassland area (-7.89 km²) and increased scrub lands (+11.97 km²) was also observed during the study. Bare lands included the land parcels

devoid of any vegetation cover and increased by 4.44 km². Other land classes also showed changes, viz., aquatic vegetation (+3.47 km²), bare exposed rocks (+1.61 km²), water bodies (-0.91 km²), water channel area (+0.06 km²), snow (+5.45 km²) and golf course/turf (+0.51 km²).

Table 4 shows the accuracy assessment matrix of the 2005 classified map. The overall accuracy of

Table 4. Classification accuracy of the land use and land cover of the study area.

Class name	Reference totals	Classified totals	Number correct	Producer's accuracy (%)	Users accuracy (%)	Kappa statistics
Built up	10	9	8	80	88.90	0.8851
Agriculture	5	6	5	100	83.33	0.8305
Horticulture	10	9	9	90	100.00	1
Coniferous forest	24	24	22	91.67	91.67	0.9094
Deciduous forest	32	33	28	87.5	84.85	0.8304
Sparse forest	10	9	8	80.00	88.89	0.8851
Grasslands	14	12	12	85.71	100.00	1
Scrub land	5	6	5	100	83.33	0.8305
Plantation	14	15	12	85.71	80.00	0.7902
Aquatic vegetation	2	3	2	100	66.67	0.6644
Barren	14	12	11	78.57	91.67	0.9126
Bare exposed rocks	5	6	4	80.00	66.67	0.6610
Water	6	6	6	100.00	100.00	1
Snow	2	3	2	100.00	66.67	0.6644
Total	300	300	281			0.91314

Overall accuracy = 93.67%.

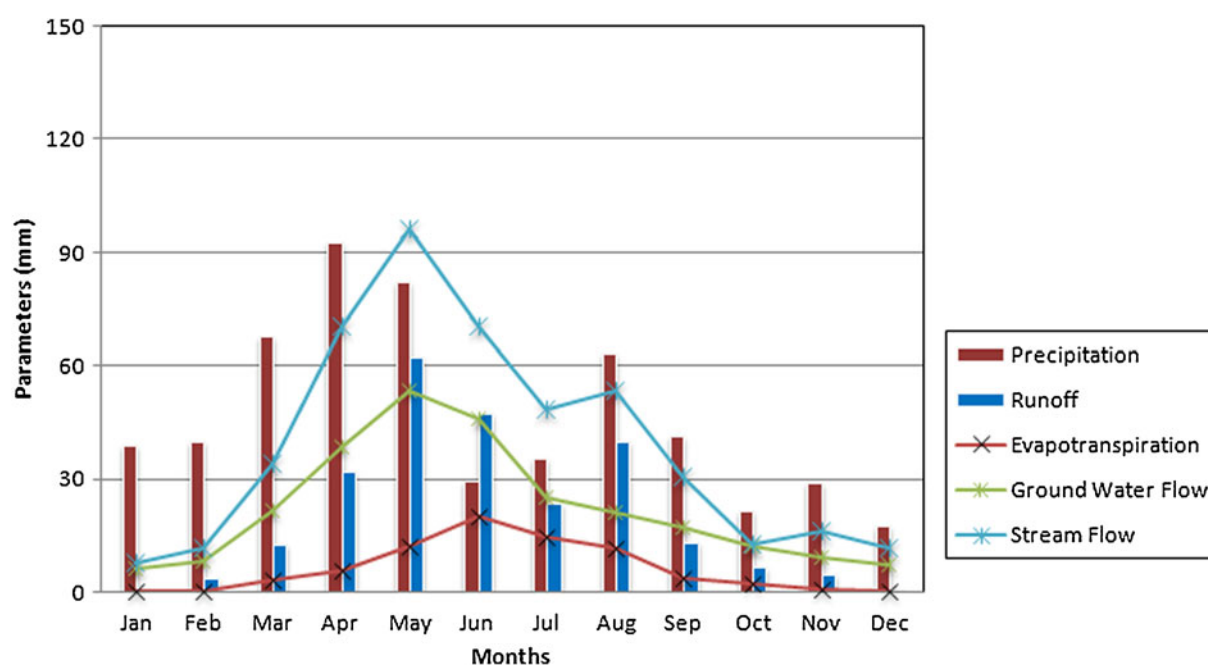


Figure 8. Mean monthly simulated water balance of Dal lake catchment (1981–2008).

the classification was found to be 93% with overall Kappa statistics equal to 0.91.

4.2 Simulated water balance of Dal Lake catchment

Figure 8 shows the mean monthly simulated water balance of Dal Lake catchment for 28 years (1981–2008). It is evident that October, November and December are the driest months with all the stream flow being made up of base flow. Since the runoff

at this time of the year is very small, most of the nutrients and sediment loading reaching the Dal Lake from its catchment are transported through stream flow and sub-surface flow. Further, it is observed that the maximum rainfall is received in the months of March, April and May of a particular year. During this period, surface runoff, stream flow and ground water flow are substantially high and the peak flows for all the parameters occur in the month of May. As a result, it is expected that

Table 5. Average rainfall-runoff relationships in Dal lake catchment (1981–2008).

Month	Precipitation total (mm)		Precipitation average (mm)	Runoff (mm)		Change (mm)
	1992	2005	1992–2005	1992	2005	
January	92	86	39.24	2.28	3	0.72
February	37	189	40.15	6.05	7.02	0.97
March	206	105	68	19.47	21.05	1.5
April	89	48	92.57	44.97	46.82	1.85
May	91	64	82.12	60.95	62.45	1.58
June	39	8	29.78	59.38	60.86	1.48
July	53	115	35.58	29.25	30.76	1.51
August	72	16	63.51	50.34	51.44	1.1
September	116	17	41.56	17.19	17.94	0.75
October	21	19	21.82	9.59	9.93	0.34
November	18	14	28.86	7.71	8.02	0.31
December	47	0	17.47	1.89	2.04	0.15
Total	881	681	560.66	309.07	321.33	12.26

Table 6. Source area contributions to the runoff under changed land use/land cover scenarios.

Class names	Runoff (mm)		Change (mm)
	1992	2005	
Pasture/scrub land	203.9	219.98	16.08
Forest	181.67	188.86	7.19
Agriculture	363.93	373.95	10.02
Horticulture	252.94	256.79	3.85
Bare land	409.95	422.82	12.87
Built up	441.97	465.52	23.55
Total	309.06	321.32	12.26

the sediment loadings from the catchment to the Dal lake will also reach maximum levels during this time of the year (Johnes 1999).

4.3 Catchment hydrological simulations

4.3.1 Rainfall–runoff patterns

Table 5 shows the total precipitation for the year 1992 and 2005 and the average rainfall-runoff relationships in Dal lake catchment for 28 years (1981–2008). It is observed that precipitation shows a decreasing trend while comparing the total amount received for 1992 and 2005. A total of 881 mm of precipitation was recorded for 1992 whereas, 681 mm was received in 2005. The statistics for the average rainfall-runoff relations reveal that out of the 560.66 mm of average rainfall received annually, 309.07 mm were lost to runoff under 1992 LU/LC. Under the 2005 LU/LC, 321.33 mm runoff was recorded, thus, showing an increase by 12.26 mm runoff during the 15 years. It was further observed

Table 7. Contribution of different source areas to erosion and sediment loads under the changed land system.

Class names	Runoff (mm)	Erosion (Tons/yr)	Sediment (Tons/yr)
Pasture/scrub land	12.87	23.25	19.58
Forest	7.19	2.72	7.34
Agriculture	10.02	46.14	22.99
Horticulture	3.85	0.02	0.01
Bare land	16.08	578.9	30.61
Built up	23.55	0.27	0.02

that under both the LU/LC conditions, the highest runoff was recorded in the month of May, followed by June, whereas, the lowest was recorded in the month of December.

4.3.2 Source area contributions

The source area contributions to the runoff generation are given in table 6 which shows that built up, bare land, agriculture and pasture/scrub land areas contributed highest to the runoff with an upward trend from the 1992 values. Built-up contributed the highest with 441.97 mm runoff under 1992 LU/LC and 465.52 mm under 2005 LU/LC, thus, recording an increase of 23.55 mm. An increase of 16.08 mm of runoff was observed for scrub lands. Bare lands also contributed significantly under both the LU/LC conditions and recorded an increase by 12.87 mm. Agricultural lands also recorded higher values of runoff with an increase of 10.22 mm. Lowest values were observed for forests and pasture lands during the study period.

Table 8. Comparison of the model predictions and observations for dissolved solids.

Year 2007	Sediment (mg/l)	
	Predicted	Observed
January	90	84
February	133.5	127
March	276.3	242
April	280	245
May	341.8	333
June	245.7	233
July	199.1	192
August	179.3	177
September	130.4	127
October	102.3	106
November	132	125
December	85.7	72

Natsh–Sutcliffe (R^2) coefficient = 0.91

Table 7 shows the contribution of different source areas to erosion and sediment loads under the changed land system. It was observed that bare land, agricultural areas and pasture/scrub land are the major contributors to both erosion and sediment loads. Barelands recorded an average annual load of 578.9 tons of erosion and 30.61 tons of sediment followed by agriculture with 46.14 tons of erosion and 22.99 tons of sediment and pasture/scrub lands with 23.25 tons of erosion and 19.58 of sediment, respectively. Forests contributed 2.72 tons of erosion and 7.34 tons of sediment. The least contributors were horticulture and urban classes.

4.3.3 Validation study

For the validation of the GWLF model results, sediment data for the Dal lake was compiled from January to December 2007. The main purpose of this part of the study was to statistically evaluate the observed and predicted mean annual sediment loads. The Nash–Sutcliffe statistical measure by ASCE (1993) for hydrological studies was used to assess the correlation, or ‘goodness-of-fit’, between observed and predicted values for mean annual sediment loads. The observations are given in table 8, depicting very good estimates (coefficient of determination $R^2 = 0.91$) for the sediment loads.

5. Discussion

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. The present study on the land use/land cover change analysis in the Dal lake catchment using satellite data for the 15-year time period (1992–2005) revealed significant changes which can be largely attributable to the activities of man as land use/land cover which is among the most evident impacts of human activities on natural resources (Lundqvist 1998). Agriculture and horticulture classes showed a decline by 1.84 and 7.57 km² respectively in the catchment area mostly because of the increased population in the catchment. Increased population and congestion in the Old Srinagar city have resulted in the conversion of large peripheral areas that were essentially used for agro-horticultural purposes into built up mostly residential areas. As a result, an increase of 12.08 km² in the built up area was observed during the study period. Accelerated nutrient enrichment of the Dal lake due to incoming effluents from the catchment results in the proficient and luxuriant growth of macrophytes, thereby resulting in an increase of 3.47 km² in the area of aquatic vegetation (Khan 2000; Solim and Wanganeo 2008). This causes the surface water to remain covered by the decomposed thick mats of such vegetation, hence disrupting the ecological balance of the lake. Large scale decline in grassland area (−7.89 km²) reveals the tremendous pressure on this ecologically and socio-economically important land cover. Biotic interference in and around the Dachigam National Park including clearing of the grasslands at the low altitudes for cultivation, exploitation for medicinal plants has been identified as the main reason for this decline. Several decades of grazing and that too beyond the carrying capacity has resulted in the creation of denuded and semi-denuded patches in these grasslands. This observation is similar to those made by Bhat *et al.* (2002) in relation to the human interfered temperate and Alpine pasturelands of Dachigam National Park. Increase in bare lands (+4.44 km²) at both higher and lower elevations of the Dal lake catchment was observed. It was found that the overgrazed grasslands have paved the way for creation of barren area (Shah and Bhat 2004). Also deforested areas of the Dal lake catchment have resulted in the creation of bare lands that is very much vulnerable to increased erosion and sediment yields as well as increased runoff. Increase in scrub land area during the 15-year study period by 11.97 km² is another significant change observed in the land use/land cover analysis. This increase in area may be attributed to the dwindling grasslands as well as the sparse forests in the catchment. Decline in the overall forest cover of the study area is mostly attributed to the large scale deforestation, both within the Dachigam National Park as well as

outside it, particularly along the higher reaches (Bhat *et al.* 2002).

The type and distribution of land use/land cover substantially affects a number of hydrological processes that have a profound effect on lake ecosystems (Matheussen *et al.* 2000; Fohrer *et al.* 2001; Quilbe *et al.* 2008). The results of model simulations for the hydrological processes showed a significant increase against the changing land use/land cover conditions. The source area contributions to the runoff generation as given in table 6 reveal that built up and bare land contributed highest to the runoff with an upward trend from the 1992 values. This is due to the large scale dwindling of the vegetation and increased impervious surface cover in the catchment that impedes the percolation of incident rainfall into the ground, thereby, resulting in higher runoff flows (Tucker and Bras 1998). Agricultural lands because of their loose soils and non-vegetative nature also recorded higher values of runoff (Stoate *et al.* 2001; Van Rompaey *et al.* 2001). Because of their vegetated nature, forests and pasture lands recorded lowest values during the study period (Hansen *et al.* 2004).

The major contribution to the erosion and sediment loadings were found to be highest for bare lands, agriculture areas and scrub lands as the type of land use in a catchment can affect the soil erodibility and sediment source as well as the amount of sediments generated by soil erosion (Woodward and Foster 1997). Observations during the present study suggest that it is primarily the sparsely vegetated or underpressure land use/land cover classes that are more erodible than the vegetated areas and generate higher runoff. Vegetation changes are often the result of anthropogenic pressures (Rishi 1982; Guerra *et al.* 1998; Janetos and Justice 2000). Soil erosion potential is increased if the soil has no or very little vegetative cover as is the case with the major contributing classes in this study (Elwell and Stocking 1976; Wischmeier and Smith 1978). Agricultural lands also reported high rates of soil and sediment loss (Dunne *et al.* 1978; Singh and Prakash 1985; Kilwe 1985). In general, as the protective canopy of land cover increases, the erosion hazard decreases (Snelder and Bryan 1995; Mkhonta 2000), hence, forests contribute less as compared to the other classes and the loads, if any, are mainly from the degraded forests. Stress on vegetation manifested due to biotic interferences such as overgrazing of grasslands beyond the carrying capacity, clearing of forest areas for construction and agricultural purposes has led to the creation of denuded patches that result in erosion in Dal catchment (Bhat *et al.* 2002). Moreover, increase in the barren and scrub land areas during the said period has also contributed largely to runoff without much infiltration capacity. As the

intensity of land use change increases, infiltration and the ability to recharge ground water decreases, consequently increasing the runoff and leading to increased water pollution and physical damage to aquatic systems (Miller and Mc Cormick 2001). Stone quarrying in certain areas of the Dal catchment, although banned now, has resulted in largely degraded and defaced mountains that has placed a serious threat of soil erosion and landslides. The subsequent sediment loss, that is carried through the streams downslope pollutes the waters of Dal lake (Shah and Bhat 2004). The sediment/silt generated from various land use/land cover classes in the catchment finally flows into the lake largely through the Telbal stream and have caused reduction of water depth and water volume and impacted thermal stability of the Dal lake (Zutshi and Yousuf 2000). With the increased sedimentation and silt accumulation, the lake ages, maximum depth lessens and volume of deep water diminishes more strikingly (Kurta and Kira 1990; Deevery 1995).

5.1 Conservation and management measures

The results of the current study have established that the Dal lake represents a case of threatened ecosystem in dire need of management with land use/land cover changes and subsequent hydrological changes like increased runoff, erosion and sedimentation in its catchment as the major pressures/threats to its existence. For addressing these issues, implementation of a watershed approach with the incorporation of best management practices (BMPs) is expected to play a major role in restoration of the lake. The BMPs can be implemented to start with the impaired watersheds utilizing both the natural landscape as well as artificial structural options. The best management practices particularly related to the urban and the agriculture areas can be very valuable in controlling/checking the inflow of nutrients and sediments into the lake. Agricultural BMPs such as cover crops, strip/contour farming, terrace farming and grazing land management should be promoted in the catchment keeping in view their efficacy in controlling the erosion and sediment loadings. It is also suggested to use various soil binding plant species like Acacia (*Robinia pseudoacacia*), Willow (*Salix* sp.), and Poplar (*Populus* sp.) to help control erosion and soil loss. Urban BMPs such as the detention basins and constructed wetlands can prove to be very effective for the temporary capture and storage of surface runoff during high rainfall events and shall be very useful in checking the amount of sediments and nutrients before the water is released downstream.

6. Conclusions

This study presents the LULC change in the Dal lake catchment of Kashmir Himalayas, its driving forces and the influence it has on various hydrological processes. The results clearly reveal that the changing land system strongly affects the response of hydrological patterns like runoff, erosion and sediment loadings. Increased anthropogenic interventions, unplanned urbanization, deforestation in the catchment were identified as the driving forces that led to the land use/cover change in the catchment. Remotely sensed data coupled with GIS simulation modelling has been observed to have a potential scientific value for the study of human–environment interactions, and has, therefore, been identified as a useful tool to aid such processes in case of lake ecosystems. This integrated approach used for this study provided reliable estimates over variable critical source areas in the lake catchment. Built up, bare lands, agriculture and scrub lands were the major critical source areas and contributed the maximum to runoff, erosion and sediment yields. All the studied hydrological parameters recorded higher values during the wet periods as against the drier periods. This revealed that precipitation has a significant influence on such processes and affects their transport from the catchment to the lake inlet. The research methodology established during the present study should help in the effective conservation and management of other threatened lacustrine ecosystems of Kashmir Himalaya.

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