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Rainfall, runoff and sediment transport from a forested Lesser Himalayan watershed in Himachal Pradesh

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ABSTRACT
Sediment transfer from continents to oceans via rivers is one of the most important processes. The amount of sediment transported from a watershed system is an indicator of the rate of erosion or the soil loss. In the present study, the long-term annual, seasonal, monthly and diurnal variations in sediment transport have been studied at the outlet (concentration point) of Tirthan watershed using the monitored data during 1981-2004. The sediment transport at the outlet of watershed is a function of rainfall and runoff occurring over the watershed area. A temporal and spatial variation in the amount of rainfall and runoff clearly exhibits annual, seasonal, monthly and diurnal variation in the sediment generation response behaviour. The higher concentration of rainfall depths exceeding 5 mm or more with significant variability could result in generation of more sediment fluxes. Both sediment concentration and load have been found to be the highest in the month of July followed by August and nearly 67% of the total sediment load has been transported in these two months. The peak of sediment load in July and August indicates that materials weathered during the dry season get mobilized during this period. Sediment load for the entire study period is computed as 454 t km^{-2} yr^{-1}. Sediment yield from the watershed was lower as compared to the average sedimentation rate of the north Indian reservoirs. Availability of good forest cover (56%) within the watershed system may be attributed to low sediment transport rates from this watershed. The lower sedimentation rate from the watershed will enhance the operational efficiency of hydro-power projects to be built or already constructed in the Tirthan watershed system.

INTRODUCTION

Sediment transfer from continents to oceans via rivers is one of the most important processes affecting riverbank stabilization, soil formation, uplift rates, biogeochemical cycling of elements, crust evolution and many other earth related processes (Krishnaswamy *et al.*, 2001; Chakrapani, 2005; Ali and Boer, 2006; Vanacker *et al.*, 2007; Singh *et al.*, 2008). The amount of sediment transported from the watershed is an indicator of the rate of erosion or soil loss. Presently, rivers contribute 95% of sediments entering the world oceans (Vorosmarty *et al.* 1997; Syvitski, 2003; Lu *et al.*, 2003; Zhang *et al.*, 2006). Recent estimation budgets have demonstrated that about 18×10^9 t of sediments are transported from rivers to oceans annually. Further, it is estimated that about 65% of water and 80% of the sediments globally delivered to oceans each year come from Southern Asian, Oceania and north-eastern South American rivers (Syvitski *et al.*, 2003; Le *et al.*, 2006). Amongst these, the Himalayan rivers are the major contributors, contributing up to 50% of the total world river sediment flux (Stoddart, 1969). Therefore, research interests pertaining to sediment transport in the Himalayan river systems have attracted much attention in recent times (Rawat and Rai, 1997; Singh *et al.*, 2003, 2005; Sharma and Rai, 2004; Haritashya *et al.*, 2006; Singh, 2007; Bhattacharya *et al.*, 2008). In Table 1 the data on sediment yields of different Himalayan rivers has been presented.

Sediment load and the transport rate govern the geomorphological, hydrological, sedimentological and ecological processes of river basins. This information at basin scale is useful for planning, design, installation and operation of hydro-power projects, including management of reservoirs. Small basins have very high rate of sediment transportation in comparison to larger basins (Ritter *et al.*, 2002; Singh, 2007). However, hardly any study exists pertaining to the transportation and quantification of sediment fluxes from the small Lesser Himalayan watersheds, which are currently being developed for various hydro-power projects. Hence, in view of this research gap, the present study has been undertaken.

Table 1. Annual sediment yields in Indian Himalayan catchments at different locations.

Basin	State	Station	Sediment yield (t km^{-2} yr^{-1})	Source
Spiti	HP	Khab	1334	Sharma *et al.* (1991)
Satluj	HP	Khab	192	Sharma *et al.* (1991)
Kinnaur	HP	Wangtu	1597	Sharma *et al.* (1991)
Giri	HP	Dadahu	957	Chaudhary and Sharma (1999)
Chenab	HP	Tandi	371	Rao *et al.* (1997)
Chenab	J&K	Benzwar	1597	Rao *et al.* (1997)
Chenab	J&K	Premnagar	1363	Rao *et al.* (1997)
Chenab	J&K	Dhamkund	1900	Rao *et al.* (1997)
Chenab	J&K	Ghousal	513	Rao *et al.* (1997)
Chenab	J&K	Tillar	373	Rao *et al.* (1997)
Chenab	J&K	Sirshi	939	Rao *et al.* (1997)
Chenab	J&K	Kuriya	878	Rao *et al.* (1997)
Nubra	J&K	Siachin Glacier Snout	707	Bhutiyani (2000)
Bhagirathi	UA	Tehri	1946	Singh and Gupta (1982)
Bhagirathi	UA	Dokarni glacier Snout	2800	Singh *et al.* (2003)
Gaula	UA	Kathgodam	3703	Valdiya and Bartarya (1989)
Nana Kosi	UA	Nana Kosi	200	Rawat and Rawat (1994)
Khulgad	UA	Khulgad	186	Rawat and Rai (1997)
Dhauliganga	UA	Markura	461	Kumar (1987)
Dhauliganga	UA	Reni	418	Kumar (1987)
Dhauliganga	UA	Tapoban	670	Kumar (1987)
Dhauliganga	UA	Rishiganga	419	Kumar (1987)
Mamlay	SKM	Rinjikhola	616	Rai and Sharma (1998)
Ganga	UA	Haridwar	178	Abbas and Subramanian (1984)
Ganga	UP	Kannauj	91	Abbas and Subramanian (1984)
Ganga	UP	Allahabad	718	Abbas and Subramanian (1984)
Ganga	WB	Farakka	1235	Abbas and Subramanian (1984)
Ramganga	UA	Kalagarh	424	Abbas and Subramanian (1984)
Yamuna	HR	Tajewala	2178	Jha *et al.* (1988)
Yamuna	DLI	Delhi	1075	Jha *et al.* (1988)
Yamuna	UP	Allahabad	308	Jha *et al.* (1988)

HP-Himachal Pradesh J&K-Jammu and Kashmir UA-Uttarakhand
SKM-Sikkim UP-Uttar Pradesh WB-West Bengal
HR-Haryana DLI-Delhi

STUDY AREA

Tirthan watershed falls under the left bank of Upper Beas river system in the Lesser Himalayan alpine zone. The area of the watershed is 687 km^2 and extends between latitudes 31°30′25" and 31°44′02" north and longitudes 77°13′03" and 77°41′14" east (Fig. 1). The watershed presents a typical mosaic of moderate to high rugged topography with numerous mountain peaks over 4000 m above mean sea level. More than 71% area of the watershed lies between 1800-3600 m altitudes. There is no area above 5400 m in the watershed. Topography has been fairly dissected by several streams, rivers, gullies and nallahs. Landslides occur very frequently during the rainy season. The average slope of the watershed is 40.04° along with the mean elevation of 2826 m above mean sea level. The rock materials in the basin mainly comprise of colluvium, alluvium, and glacial deposits, in which debris has been derived from phyllite, slate, quartzites, dolomites, sandstone, schist and granites. Soils are podsolic in nature, texture varying from sandy loam to loam with average organic matter content of around 70%, very shallow to moderately deep in depth and pale yellow, yellowish brown and dark brown in colour.

The climate is warm temperate with an annual rainfall of 1000 mm of which more than 50% of it being received during the south-west monsoon (June-

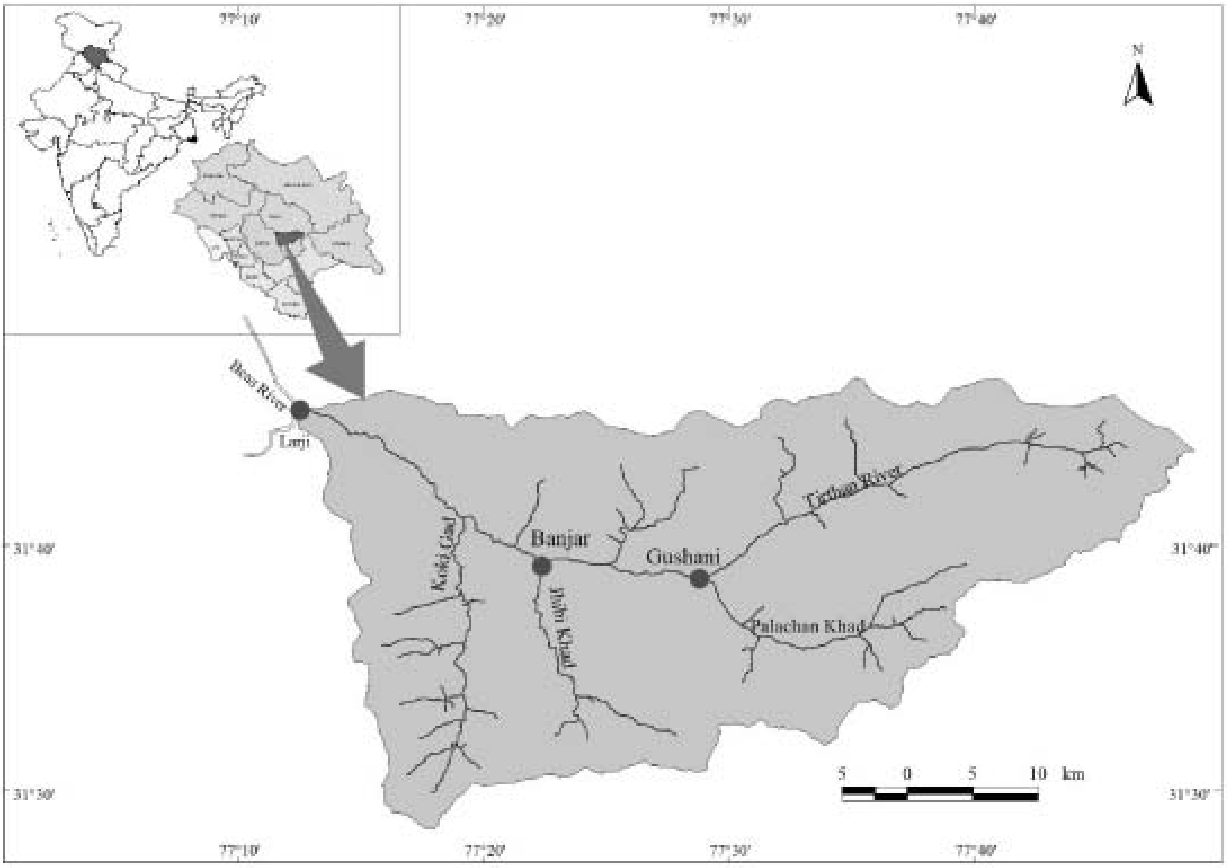

Figure 1. Delineated map of the Tirthan watershed in Lesser Himalayan region with natural drainage network.

September). Average annual snowfall in the region is 345 mm during the winter season (October-March), which is confined mostly to upper reaches. The mean monthly temperatures recorded at Larji (the outlet or the concentration point of the study watershed) ranged from a minimum of 8.7^{0}C during January to the maximum of 26.3^{0}C during June. The minimum and maximum relative humidity are recorded in the months of May (63.3%) and August (78.7%) respectively. Evaporation is minimum in the months of December (36.1 mm) and January (38.7 mm), the coldest months of the year, and maximum during June (165.0 mm), the warmest month of the year.

METHODOLOGY

The study watershed (Tirthan) was delineated from the topological information of the watershed using the Watershed Morphology Estimation Tool (WMET) interface (Sarangi *et al.,* 2004). The land cover map of the watershed was generated using the Survey of India topographical maps and False Colour Composite (FCC) images captured on December 5, 1999 by Indian Remote Sensing (IRS-1C) satellite. While generating the land cover maps, the ground truth information in conjunction with land cover visual interpretation techniques were used. The FCC generated land cover map of the watershed was scanned, digitized and projected to real world co-ordinate systems using the Auto Cad ® and Arc Info ® GIS softwares and their areal extent under different land cover conditions were estimated. The forested area was maximum 56.2% (385.5 km^2) followed by rocky outcrops 17.6% (120.6 km^2) in the watershed. Snow bound area was 7.1% (48.5 km^2) while the agricultural land was only 16.9% (115.8 km^2) of basin area. The area covered by glaciers was only 1.1% (7.8 km^2) in the watershed.

Data on rainfall, runoff and suspended sediment transport in the Lesser Himalayan region are limited due to remoteness, ruggedness and inaccessibility. In the present study, daily rainfall, runoff and suspended sediment flux data for a period of 24 years (1981-2004) measured at the outlet of Tirthan watershed along with the calibrated segments at Larji gauging station were obtained from Bhakra Beas Management Board (BBMB). The suspended sediment samples were collected daily from three transects across the stream with the help of depth integrating samplers. The samples were then passed separately through a 100-mesh sieve and the fraction retained was dried and weighed to estimate the suspended sediment concentration (BBMB, 1997). It has been reported by the BBMB that similar procedure of daily sample collection was carried out during the entire study period (1981-2004).

The rainfall events for the Tirthan watershed were analyzed to obtain mean monthly, mean seasonal and mean annual rainfall depths along with their standard deviations (SD). These rain events have also been classified into frequency classes and percentage of rainfall depths in each class. Similarly, daily runoff data measured along the calibrated segments of the watershed at Larji for the above mentioned period was analyzed for mean monthly, seasonal and annual runoff along with their coefficient of variability (CV) and SD. The flow depths acquired from stage level recorders were converted to the discharge rate using the developed stage discharge rating curves for the respective gauging sites (BBMB, 1997; Singh *et al.*, 2008). The suspended sediment load flux from the Tirthan watershed was derived by multiplying the daily discharge rate at the gauging station with the ratio of suspended sediment concentration and the discharge rate. Further, the seasonal and annual runoff and the total sediment flux were estimated by using the standard accounting procedures spanning through the days, months, seasons and years (Singh, 2007; Singh *et al.*, 2008).

RESULTS AND DISCUSSION

Variations in rainfall

Variation in rainfall was observed along the length of the Tirthan watershed which could be attributed to the orientation of the mountains and the topographical conditions of the watershed (Table 2). The long period (1981-2004) average rainfall was observed to be 1015 mm with 17.8% CV. The wettest year was 1988 (1314 mm), while driest year was 1981 (628 mm). A pronounced seasonal variability in rainfall distribution has also been observed across the watershed. Monsoon accounts for about 50% of the annual rainfall, followed by rain in winter season, which accounts for another 30% of the annual rainfall. Large-scale inter-seasonal variability of rainfall, maximum during the post-monsoon season (> 100%) and minimum during the winter and monsoon season has been observed. Monthly rainfall shows a triple peaked distribution in July, August and March. Moreover, maximum number of rain events has also been observed during July and August. Nearly 60% of the annual rainfall occurs in rain events of more than 50 mm, indicating that rainfall is mostly experienced as heavy downpours with very high intensity. The higher occurrence of rainfall depths exceeding 5 mm or more with significant variability could result in generation of more sediment fluxes (Schwab *et al.*, 1981).

Variations in runoff and sediment flux

The mean annual runoff was observed to be $9.6\times10^3 \pm 1.3\times10^3$ m^3/s in the watershed. The annual runoff records showed a lesser degree of variation with CV as low as 14%, which indicated the undisturbed nature and dependability of annual runoff from the watershed (Table 3). The seasonal fluctuations in runoff showed that the summer-monsoon season (April-September) produced about 80% of the total annual flow for different years. The higher contribution to the annual flow during April-September is primarily attributed to the combination of rain, snow and glacier melting at the higher reaches. It was also observed that the runoff during winter months of December through February were the lowest despite occurrence of high precipitation depths. A peak flow of 518.3 m^3/s occurred thrice in the Tirthan watershed on July 11, 1993, September 5, 1995 and August 3, 1997. All these peak flows have been the result of unprecedented

Table 2. Mean monthly and annual rainfall (mm) distribution for different stations in Tirthan watershed.

Water-shed	Station	Years of data	No. of years	Elevation (m)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Annual
Tirthan	Banjar	1981-2004	24	1400	75.9	80.6	105.5	73.6	90.1	83.2	178.8	164.0	82.8	28.0	18.0	34.2	1014.7
	Deotha chanon	1992-1996	5	2000	104.5	85.1	98.5	70.4	88.5	66.5	194.8	177.0	124.7	14.4	10.3	11.6	1046.5
	Palach	1995-1999	5	1600	28.8	168.1	266.5	49.6	58.5	49.8	115.4	87.1	73.8	17.8	3.0	111.3	1029.7
	Panjai	1982-1992	11	2300	25.8	57.7	103.4	93.5	184.2	82.8	187.9	155.0	72.8	45.2	30.3	31.4	1070.1

Source: Bhakra Beas Management Board, Pandoh and Forest Department, Himachal Pradesh.

Table 3. The yearly values of rainfall, runoff and suspended sediment load in the Tirthan watershed at Larji station.

Year	Rainfall (mm)	Runoff (m^3/s)	Suspended load (10^3 t)	3 year mean (10^3 t)	Specific sediment yield (t km^{-2})	3 year mean
1981	628.4	8118.4	36.8	-	53.6	-
1982	753.2	11470.3	89.8	-	130.7	-
1983	1115.2	11242.1	115.7	80.8	168.4	117.6
1984	653.6	7796.3	84.6	96.7	123.2	140.8
1985	991.5	10168.3	235.5	145.3	342.8	211.5
1986	878.2	10006.8	94.1	138.1	137.0	201.0
1987	826.7	8867.7	74.9	134.8	109.0	196.3
1988	1314.0	11481.2	1063.4	410.8	1547.8	598.0
1989	970.9	7365.5	123.4	420.5	179.6	612.2
1990	1256.7	10787.4	134.8	440.5	196.2	641.2
1991	908.7	7648.8	49.3	102.5	71.7	149.2
1992	1129.3	9740.0	152.2	112.1	221.5	163.1
1993	1079.1	9258.5	1333.8	511.7	1941.4	744.9
1994	1226.6	9894.6	155.9	547.3	226.9	796.6
1995	1114.2	10190.0	961.1	816.9	1398.9	1189.2
1996	1028.0	8231.0	113.6	410.2	165.3	597.0
1997	1242.3	9992.9	421.1	498.6	612.9	725.7
1998	1153.7	12534.5	415.6	316.8	605.0	461.1
1999	1062.9	8223.7	445.1	427.3	647.9	622.0
2000	1070.1	9534.2	431.8	430.8	628.5	627.2
2001	865.9	9664.0	361.8	412.9	526.6	601.0
2002	998.6	8527.9	178.9	324.2	260.5	471.9
2003	1015.0	9737.6	188.4	243.0	274.2	353.8
2004	1070.6	8974.2	223.1	196.8	324.7	286.5
Mean	**1014.7**	**9560.7**	**311.9**	-	**453.9**	-
SD	180.4	1336.0	341.2	-	-	-
CV	17.8	14.0	109.4	-	-	-

rainfall that occurred in the watershed. Moreover, 4-5 peak flows as a result of storm rainfall have been recorded during different years in Tirthan watershed. Again, sediment fluxes were directly related to the rainfall and resultant outflow rate from the watershed.

Variations in suspended sediment concentration

The average annual suspended sediment concentration (SSC) in Tirthan watershed varied from 29-179 mg l^{-1} (Table 4). The SSC levels for a particular year cannot be taken as a general rule as there is considerable variation between the same months for different years. Highest SSC from the Tirthan watershed usually occurs on some days during June-September months in a year (Fig. 2). It was observed that SSC are relatively very high at the onset of floods during monsoon in a year, presumably due to flushing activity from the watershed system. Moreover, SSC levels were also observed highest in the month of March and October during the year 1991 and 1998, respectively.

The concentration level during monsoon period (June-September) has assumed alarming proportions (60-70 times higher than the desirable level of 200-250 mg l^{-1}) in Tirthan watershed. Unusual concentrations from this watershed may probably be due to bed erosion, occurrence of rain, large amounts of debris generated through different kinds of mass wasting phenomena along the watercourses and within the watershed. Ramsay (1985) has found such mass-wasting phenomenon to be responsible for 90% sediment

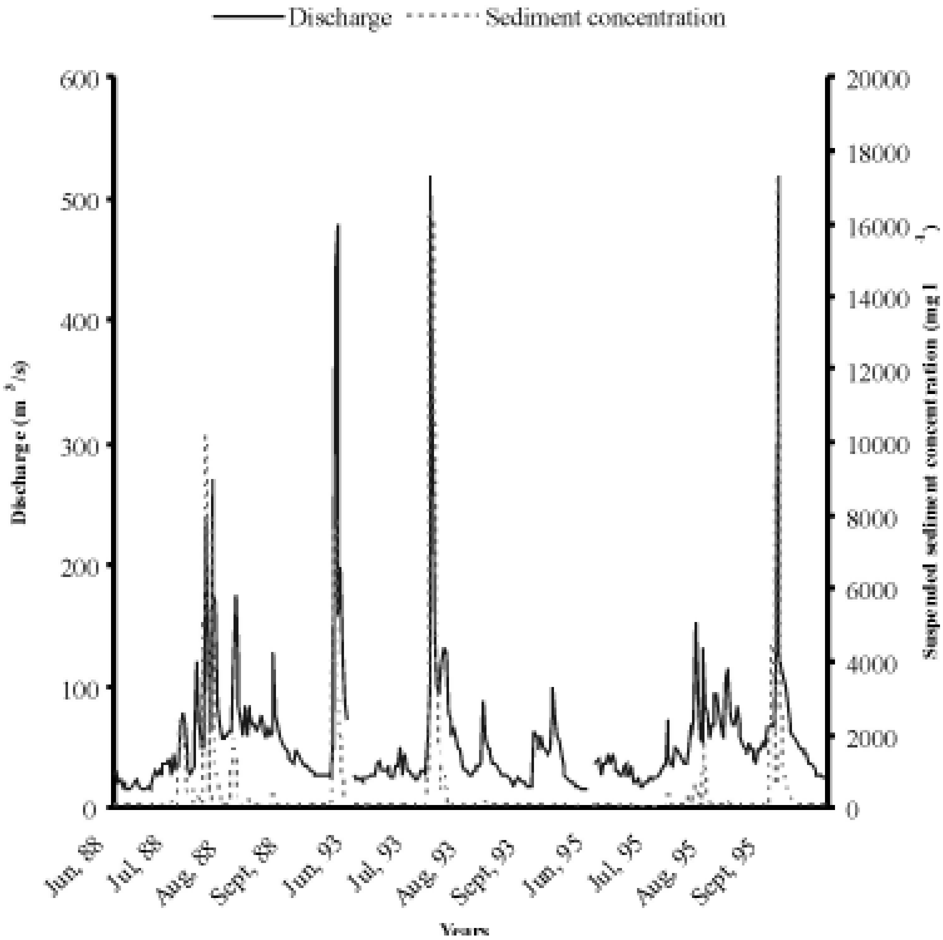

Figure 2: Discharge and suspended sediment concentration regimes at Larji in Tirthan watershed.

deposition in the Phewa Tal watershed in middle hills of west central Nepal. Higher concentrations of sediment are not always attributed to high runoff during monsoons but also due to transportation of loosened material and loss of topsoil during a moderate rainfall event. During post-monsoon and winter the sediment concentrations are fairly low because of low rainfall. It was further observed that average SSC is more erratic during the monsoon with a wide range of 53 to 479 mg l^{-1} (Fig. 3). During summers, average values have been varying between 20 to124 mg l^{-1} in the watershed. Sediment concentration was uniform for rest of the two seasons barring 1998 in the watershed, which can be attributed to unprecedented rains during the October month in entire region.

The mean monthly SSC for the Tirthan watershed at Larji for the months of June, July, August and September were found to be 106, 310, 274 and 154 mg l^{-1}, respectively, with CV's ranging from 75% to 154%. The mean SSC during October month was observed to be highly variable in the watershed. The highest SSC pertains to the month of July, followed by August; and together accounting 55% of the total SSC. This was three times higher than in the month of June, and nearly twice of this in September. Maximum daily SSC values (1981-2004) for June, July, August and September are 5,727, 16,517, 6,600 and 17,222 mg l^{-1} respectively. Similarly, maximum daily mean SSC values of 283, 1,504, 770 and 1,112 mg l^{-1} were obtained in June, July, August and September months. The highest percentage of discharge and SSC has been observed for the month of August in the watershed (Fig. 4). This strong increase in monthly SSC with discharge is attributed to the transportation of loosened materials into the channel, produced mainly by several processes of erosion like mass wasting; rain splash and sheet wash (Sharma *et al.*, 1991; Chaudhary and Sharma, 1999; Singh *et al.*, 2003, 2005).

The mean daily SSC for monsoon season has been computed to be 212.5 mg l^{-1} for the Tirthan watershed.

A plot of daily SSC and discharge versus time for the Tirthan watershed has been demonstrated in Fig. 5. Daily suspended sediment concentration in the watershed varied from 9 to 17,222 mgl^{-1} during 1981-2004 (Table 4). The daily suspended sediment concentration almost followed the pattern of daily discharge in the watershed. The suspended sediment concentration begins to increase in the watershed in response to increase in discharge from April onward. It remains low during April and May and increases substantially at the beginning of June. It remains at quite high levels until the middle of September and

Table 4. Yearly v ariations in maximum, minimum and average suspended sediment concentration (SSC) and their date of occurrence at Larji in the Tirthan watershed (1981 -2004).

Year		1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992
SSC (mg l^{-1})	Max.	316.1	4645.6	2639.2	5726.9	2137.6	886.6	3088.9	10196.7	3541.3	1529.2	589.4	2409.6
	Min.	8.5	8.5	8.7	8.7	8.7	8.2	8.7	8.5	8.9	8.9	8.7	8.8
	Avg.	29.2	44.6	47.2	44.9	72.4	53.1	51.6	169.6	59.0	69.3	49.1	70.8
Date of occurrence	Max.	July 29	June 12	August 19	June 17	July 16	June 22	July 25	July 19	August 28	July 10	March 5	July 12
	Min	Dec 20-27	Jan 1 -3	Dec 26	Dec 10	Jan 13	Feb 10	Dec 3	Feb 5	Feb 16	Dec 4	Jan 15	Dec 15

Table 4 . Yearly v ariations in maximum, minimum and average suspended sediment concentration (SSC) and their date of occurrence at Larji in the Tirthan watershed (1981 -2004).

Year		1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
SSC (mg l^{-1})	Max.	16517.1	1204.6	17222.0	822.6	3916.0	3492.0	6600.8	1862.4	4292.2	1424.4	798.6	1713.2
	Min.	8.6	8.7	8.9	8.7	12.5	9.3	9.5	9.9	9.4	9.4	9.7	9.8
	Avg.	153.0	65.1	126.9	75.2	98.3	143.9	132.5	179.2	106.9	101.2	113.5	128.5
Date of occurrence	Max.	Jul 11	Aug 1	Sept 5	Jun 24	Aug 3	Oct 18	Aug 10	Jul 31	Aug14	Aug 14	Jul 27	Aug 1
	Min	Dec 18	Jan 1,5,9	Dec 25,26, 29	Jan 11	Jan 2	Feb 12	Feb 6	Feb 23	Feb 14	Nov 25	Dec 9	Feb 16

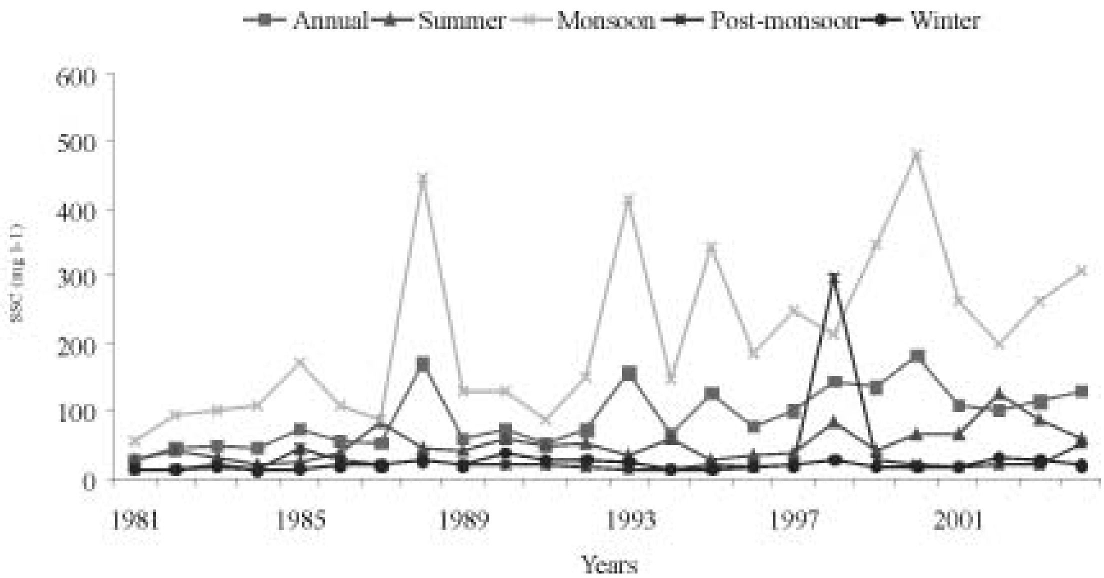

Figure 3. Seasonal distribution of suspended sediment concentration in the Tirthan watershed (1981-2004).

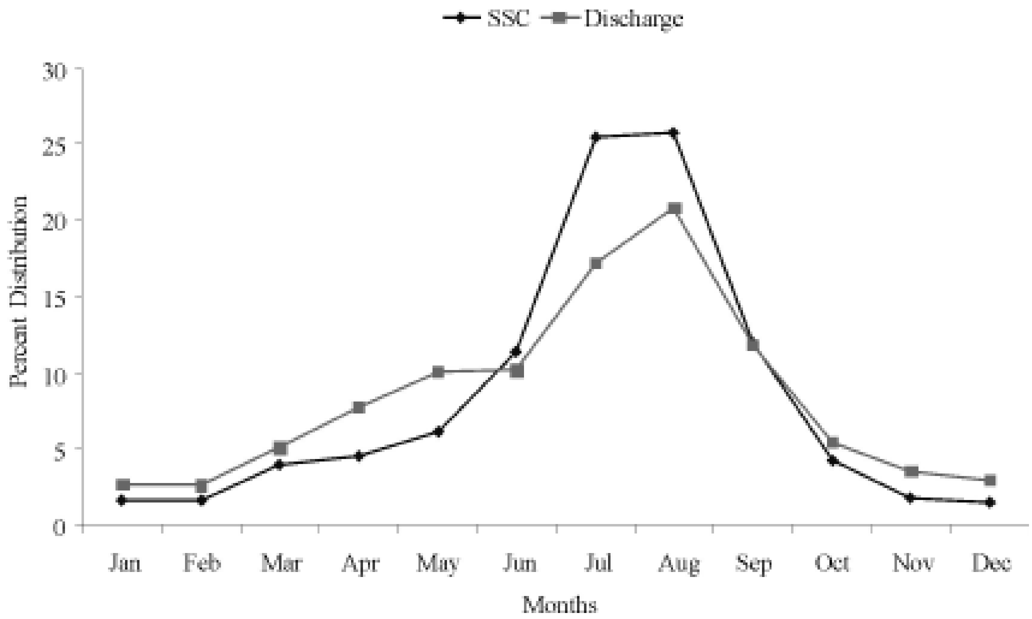

Figure 4. Monthly average discharge and SSC (%) during 1981-2004 at Larji in the Tirthan watershed

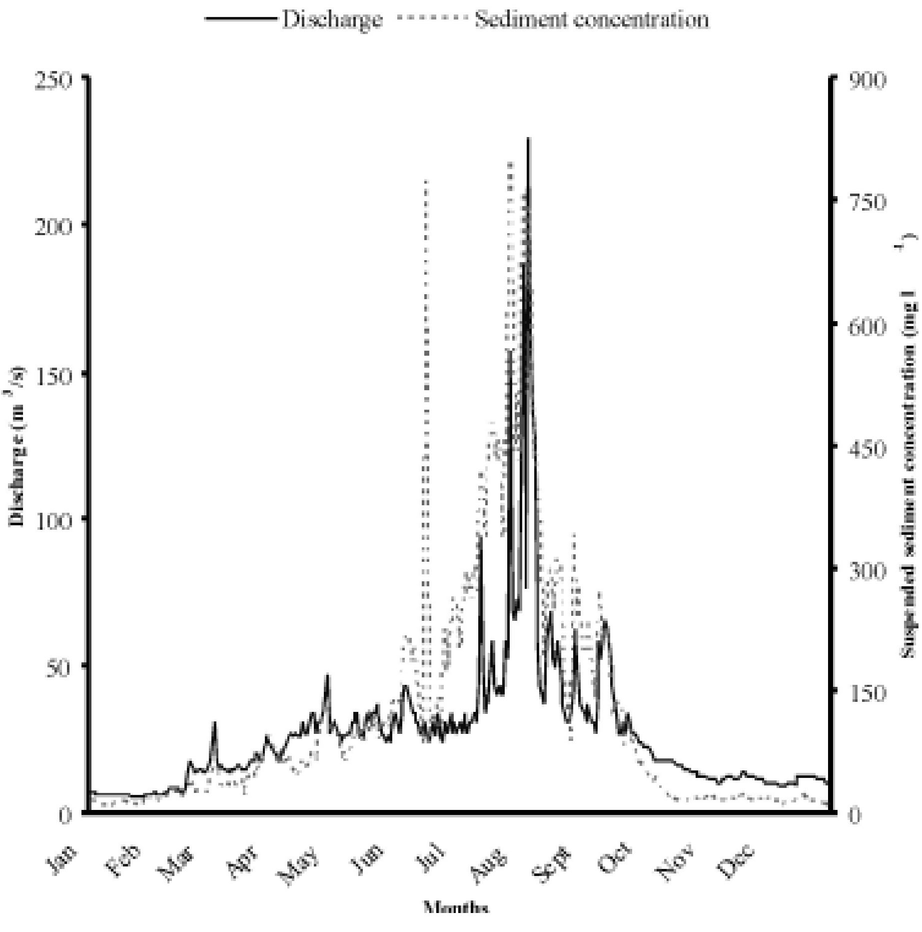

Figure 5. Daily discharge and suspended sediment concentration regimes in the Tirthan during 2003.

thereafter it begins to fall. By the end of September, the concentration turns very low, and between November and March it reaches to its minimum level. The similar variation in concentration has also been reported by Sharma *et al.* (1991) for Satluj river flowing through the high Himalayas, Chaudhary and Sharma (1999) for Giri river flowing through Shimla hills in the state of Himachal Pradesh, Singh *et al.* (2003, 2005) in Dokriani and Gangotri glaciers and Haritashya *et al.* (2006) in Gangotri glaciers melt waters in the Garhwal Himalayas.

Variations in suspended sediment load

The annual sediment flux in the Tirthan watershed varied from 36.85×10^3 to $1,333.8\times10^3$ t with a mean value of 311.9×10^3 t with a CV of 109.4 % (Fig. 6). The suspended load has touched an all time high value of $1,333.76\times10^3$ t during 1993 when unprecedented rains for continuous 7 days and subsequently high stream flow (518 m^3/s) have been experienced in the watershed. Therefore, annual trend of sediment load does not conform to the yearly total discharge from the watershed. During 1981 and 1990 sediment load is minimum and it follows the rainfall pattern in the watershed. The increasing suspended sediment load with runoff is only episodic and it is not necessary that high annual rainfall and runoff will lead to high suspended sediment load in the watershed and vice versa. The rate of sediment flux for the entire watershed was in the order of 45.4×10^3 t 100 km^{-2} or 453.9 t km^{-2}. The iso-erosion rate map of India shows that mean annual erosion rates in India vary from 350 to 2,500 t $km^{-2}yr^{-1}$ (Garde and Kothyari, 1987). Thus, the sediment yield is well within the limits in comparison to reported data. The lower sedimentation rate from Tirthan watershed will enhance the operational efficiency of hydro-power to be built (5) or already constructed (2) in the region. Permissible limit of sediment yield for the watershed can be attributed to good forest cover, which is 56% of watershed area. It may also be pointed out here that sediment yield for the study watershed have been computed using suspended sediment concentration data collected only once a day and could be improved upon using higher frequency observations. Of the annual sediment of 43×10^5 m^3 transported in the Pandoh reservoir (verbal communication with SDO, Dam and Reservoir), about 5% was transported from the Tirthan watershed. Moreover, the long-term average of annual sediment yield was found to be 4.5 t ha^{-1} yr^{-1} for the watershed which is quite disturbing in the light of permissible limit of sediment yield at 1.8 t ha^{-1} yr^{-1} for sustained productivity of lands (Singh et al., 1992).

The suspended sediment yield response of

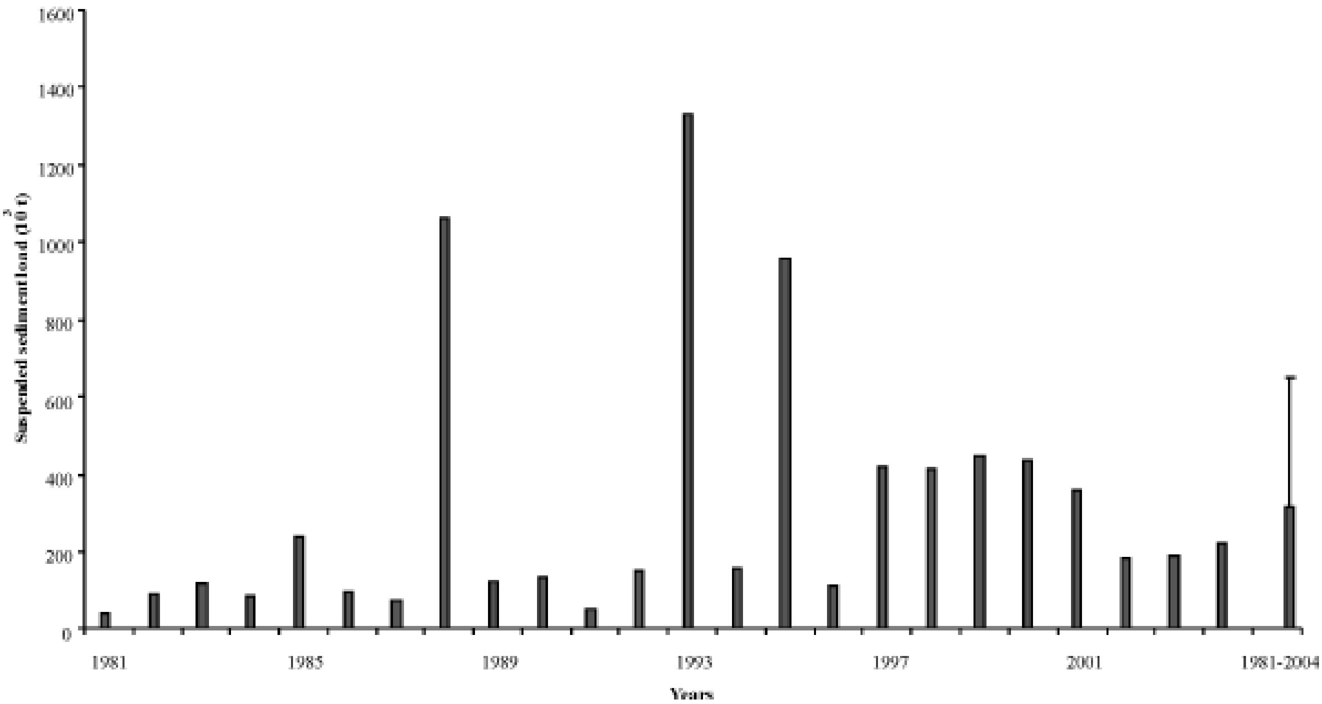

Figure 6. Annual sediment flux in the Tirthan watershed (1981-2004).

Himalayan watersheds is different from other basins in the rest of India. Sediment yield characteristics in the Tirthan watershed differ depending on the season (Fig. 7). During the post-monsoon (October-November) and winter (December-March) season, the suspended sediment yield is at its minimal and is < 5 % of the annual sediment yield. During pre-monsoon season (April-May), the seasonal snow cover melts in the intermediate and upper reaches of the watershed. The lower reaches (< 1,500 m approximately) receive rain and the intermediate reaches experiences rain-on-snow (sleet) causing high discharge and reasonable suspended sediment yield is received during the pre-monsoon season. During the monsoon season (June-September) rainfall contribution to flows is very high in the lower reaches and gradually tapers at elevations of about 4,000 m (Singh *et al.,* 1995). Therefore, rainfall may have little to do with the sediment yield in the upper reaches of the watershed. The monsoon season contributed to 88.0% of annual sediment yield in the Tirthan watershed. Some other reasons besides rainfall and snowmelt may be attributed to the prevailing geologic and soil conditions. The maximum sediment transport in the other Himalayan rivers is also reported to be during the summer-monsoon period either due to more rains or snowmelt (Holeman, 1968; Tejwani, 1987; Sharma *et al.,* 1991). The sediment transport in the Bhagirathi river during June-September has constituted 92-99% of the annual suspended sediment load (Singh and Gupta, 1982). The average total suspended sediment load for this season was computed to be 72,385 t (88%) for Tirthan watershed.

The bulk of the sediment flux in the Tirthan watersheds occurs in the months of June, July, August and September (Fig. 8) when there are monsoonal rains in the entire Lesser Himalayan region. The average sediment load transported during the months of June, July, August and September are 12,465, 1,21,839, 84,120 and 71,116 t, respectively for the Tirthan watershed. The sediment load during this period together constituted 49-99 % (average 88 %) of the annual sediment transport. The contribution of June, July, August and September months towards annual sediment load is to the tune of 9, 29.4, 37.4 and 12.2 %, respectively in the watershed. The maximum sedimentation in the watershed has occurred during the month of August, followed by July

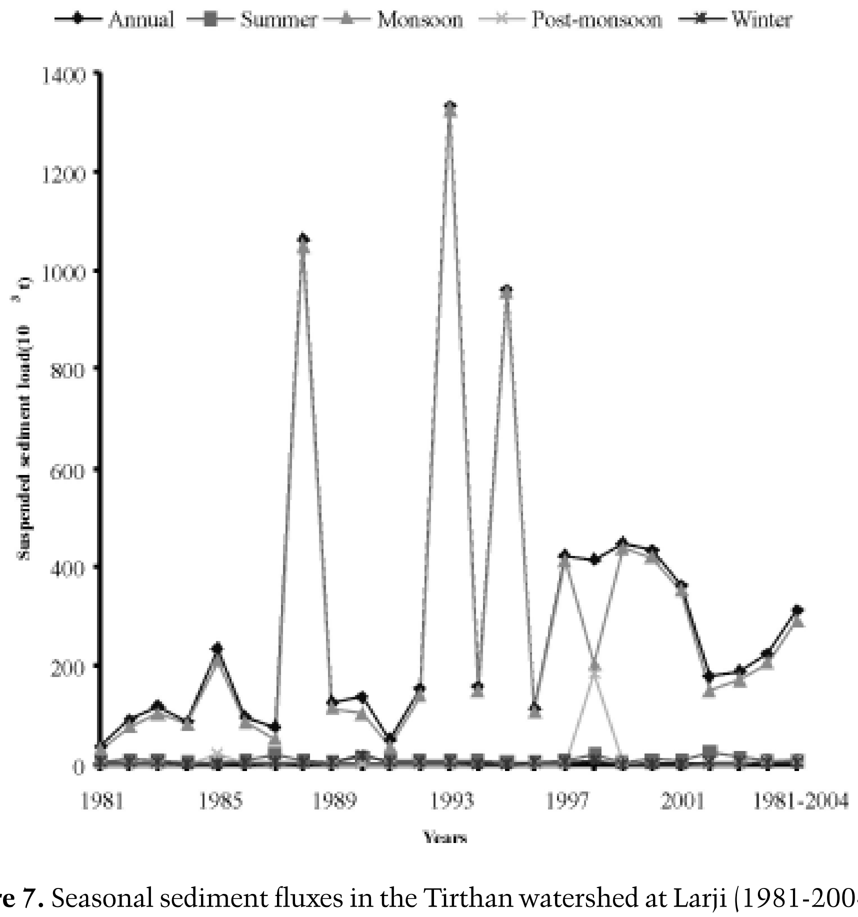

Figure 7. Seasonal sediment fluxes in the Tirthan watershed at Larji (1981-2004).

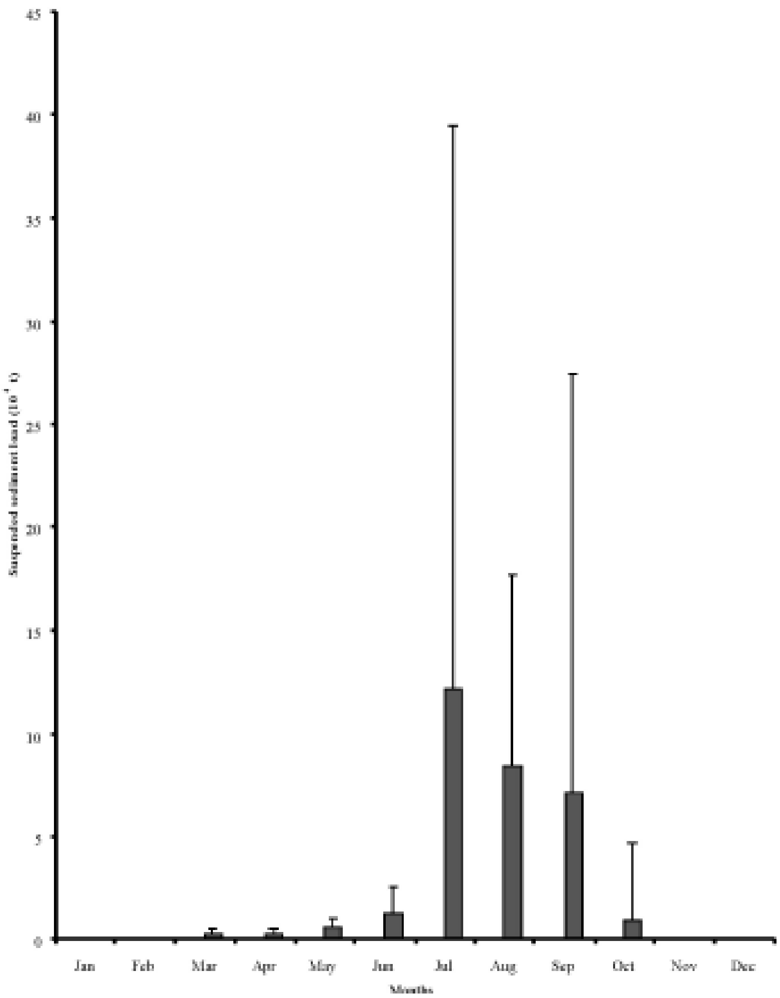

Figure 8. Mean monthly sediment flux with standard deviation from Tirthan watershed (1981-2004).

on the basis of average percentage share. However, on the basis of average absolute total sediment load, maximum sediment load from the watershed occurred in the month of July, followed by August. Prominent peaks in the sediment flux from the Tirthan watershed are associated anomalously with higher water discharge because of maximum rainfall for the entire study period (1981-2004) occurred in July, followed by August and maximum runoff contributed in August, followed by July in the watershed. Sediment flux during other months showed almost negligible share. The reason of sediment flux increase in the month of August could be attributed to the high rainfall intensity and surface runoff, relatively saturated slopes and subsequent mass wasting process in the watershed. It was also visualized from the monthly analysis that the maximum monthly sediment load has not occurred in the same month for all the 24 years. Out of 24 years, maximum suspended sediment load values have been obtained once in June and October, twice in September, seven times in July and thirteen times in August. During the non-monsoon months, October has transported more than 0.1×10^6 t of suspended sediment load during 1998 in the watershed. In addition, the sediment load of more than 0.1×10^6 t has been observed thrice in September and five times each in July and August in the watershed.

Daily suspended sediment flux ranges between 4 and 7,71,155 t in the Tirthan watershed at the Larji gauging site (Table 5), with several peaks of suspended sediment load during different years. A rainfall storm of 40 mm in a day during winters did not generate high sediment load but the same rainfall storm produced enormous amount of sediment load during the monsoon season. This difference in sediment load is attributed to high rainfall intensity and wide spread rains during monsoon season. It was revealed from the analysis that unprecedented rains and stream flows have occurred on July 11, 1993 in the watershed, which led to 88% suspended sediment load transportation on July 11 and 12, 1993 in the

Table 5. Yearly variations in sediment load flux at Larji in the Tirthan watershed (1981 -2004).

Year		1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992
Sediment load (t)	Max.	2467	37806	41200	30828	28735	8797	21238	298927	51644	21515	3354	37616
	Min.	4.7	5.7	6.3	5.4	5.7	5.9	6.0	5.1	7.3	5.6	5.3	5.4
	Max/Min	520	6610	6562	5680	5075	1483	3548	58510	7084	3870	630	6915
Date of occurrence	Max.	Jul 29	Jun 12	Aug 19	Jun 17	Jul 18	Jul 27	Jul 25	Sept 24	Aug 28	Jul 10	Aug 22	Jul 21
	Min	Jan 23	Feb 9	Dec 26	Jan 28	Feb 14	Feb 10	Dec 29	Feb 16	Feb 16	Feb 6	Feb 1	Jan 5
Half load	(% time)	5.5	0.6	0.8	0.6	1.6	2.7	2.2	0.8	0.6	3.0	9.0	1.9

Table 5. Yearly variations in sediment load flux at Larji in the Tirthan watershed (1981 -2004).

Year		1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
Sediment load (t)	Max	739591	15297	771154	6173	175348	47421	146006	22785	143882	33285	14773	18235
	Min.	4.7	4.7	5.7	4.7	7.6	5.5	5.3	5.5	4.1	5.2	4.8	6.5
	Max/min	157931	3267	136246	1318.0	23147	8684	27679	4150	34754	6374	3113	2814
Date of occurrence	Max.	Jul 11	Aug 1	Sept 5	Aug 22	Aug 3	Oct 18	Aug 10	Jul 31	Aug 14	Aug 14	Aug 5	Aug 1
	Min	Dec 20	Jan 1, 5, 6, 9	Dec 25, 26, 29	Jan 11	Jan 14	Feb 12	Jan 13	Jan 3	Feb 14	Dec 16	Jan 27	Jan 17
Half load	(% time)	0.3	2.2	0.3	4.7	0.6	1.9	0.8	3.6	0.6	2.2	5.2	3.3

watershed. The highest daily suspended sediment load (7,71,155 t) from the watersheds has been observed on September 5, 1995, the day with the highest rainfall (55.1 mm) and 80% of total suspended sediment load is transported only on this single day from the watershed. During high rainfall events, greatly enhanced suspended sediment concentration and load are possible from soil available on the steep sidewalls of the valley, loosened topsoil material, presence of sediment material like boulders, landslides, rock avalanches and debris flows in the watershed. Similarly, Balasan River in the Sikkim Himalaya, during the flood event of September 1991 has transported about 64% of the annual suspended load in two days (Starkel *et al.*, 1998). The daily maximum suspended sediment load has crossed 0.1×10^6 t, which was six times in the watershed. Moreover, half of the sediment load was transported in a very short time (*i.e.* 14 days or 0.16% of time) during 24 years period in the Tirthan watershed. The daily extremes of sediment flux did not exhibit significant change, presumably because of high variability of rainfall events in the watershed. Similarly, Sarma (1986) and Kale (2002) while working on the Burhi Dihing in Assam and Tapi river in Peninsular India observed that 50% of the total load was carried in less than 7% of the time. Sarma (2005) while studying Brahmaputra river have reported 50% of sediment transport in 29% and 35% of time during the year 1978 and 1979, respectively.

CONCLUSIONS

The present study deals with the analysis of rainfall, runoff, suspended sediment concentrations, loads and yields, and erosion rates for the Tirthan watershed during 1981-2004. The frequency of rainfall events exceeding or equal to 5 mm was observed to be 56% in Tirthan watershed. Besides this the annual rainfall variability was 18% in the watershed. This study has shown a temporal variability of sediment flux, more particularly during the monsoon (wet) period on an annual basis in the Tirthan watershed. The occurrences of large short-term pulses of sediment are mostly associated with short-term increase in stream discharge resulting from rainstorms. Both sediment concentration and load are found to be the highest in July followed by August and about 67% of the total sediment load has been transported in these two months from the Tirthan watershed. The peak of sediment load in July and August months indicate that materials weathered during the dry season (summer) get mobilized during this period; hence there is an increase in suspended sediment load and a decrease during the subsequent period. Suspended sediment load for the entire study period was computed to be about 454 t $km^{-2}yr^{-1}$ from the watershed. This sediment yield transport from the watershed has been found to be within the permissible limits and it is presumably attributed to good forest cover available within the watershed system.

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