Anthropogenic impacts on the sediment flux in two alpine watersheds of the Lesser Himalayas

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Water erosion caused by accelerated anthropogenic activities has been perceived as the major source of sediment flow in Himalayan catchments. Keeping this in view, the sediment flux data measured at the outlet of the Sainj and the Tirthan watersheds in the Lesser Himalayan region was analysed. Rainfall behaviour coupled with existing forest cover, snow bound and glaciated areas with rocky outcrops in the Sainj watershed could result in more sediment yields as compared to the Tirthan. It was observed that the sediment flux from the Sainj watershed was 1.5 times more than the Tirthan watershed. Also, the sediment transport from both watersheds showed an increasing trend in the monthly, seasonal and annual flux during the study period (1981–2004). This increase could be attributed to the intensification of anthropogenic activities related to land surface disturbance besides the rainfall and existing land use and land cover practices. The detected changes in sediment flux resulting from such human activities have significant implications which necessitate appropriate soil and water conservation measures in these watersheds.

Keywords. Anthropogenic activities, Lesser Himalayan region, rainfall variability, sediment flux, watershed.

THERE is a growing concern about the potential impact of human activities on hydrological processes – it can exacerbate the process of land degradation, aggravate the problem of floods, droughts and water pollution, and shorten the life span of reservoirs[1–7]. Research studies have revealed that large scale human activities like afforestation, deforestation, intensification of agriculture, hydropower development and urbanization would alter the basic components of the hydrological cycle and finally affect the sediment flux in rivers[8–12]. Afforestation, for example, may increase or reduce erosion through several mechanisms[13].

The profound disturbances to land surface such as land-use changes, livestock grazing and fodder extraction, fuel wood collection, timber harvesting, mining, reservoir and road constructions have been accentuated during the past four decades in the Himalayan region due to population pressure and socio-economic policies[14–17]. Infrastructure development activities might accelerate and intensify the watershed degradation process[8]. The Sainj and Tirthan watersheds in the Beas river catchment have also experienced a wide range of common human activities such as deforestation, development of hydropower projects and roads, and expansion of agricultural and horticultural activities. Sediment flux in relation to human interventions within alpine cascading systems is still poorly understood in the region. This study was aimed at elucidating the temporal changes of sediment flux in the Sainj and Tirthan watersheds during 1981–2004. It was also planned to study the possible impact of human activities on sediment flux in these alpine watersheds.

Study area

The study area was delineated into two distinct watersheds, viz. Sainj (741 km^2) and Tirthan (687 km^2). Both watersheds fall under the left bank of the Upper Beas river system in the Lesser Himalayan alpine zone. The area extends between lat. 31°30′28″N and 31°55′02″ N and long. 77°13′02″E and 77°45′57″E as shown in Figure 1. The watersheds present a typical mosaic of moderate to high rugged topography with numerous mountain peaks over 4000 m above mean sea level (amsl). The average slope of the Sainj and Tirthan watersheds are 38.12° and 40.04° with mean elevation of 3510 and 2826 m amsl respectively. The rock types are mainly colluvium, alluvium, glacial deposits, phyllite, slate, quartzites, dolomites, sandstone, schist and granites. The soil texture varies from sandy loam to loam with average organic matter content around 70%. Soils vary from very shallow to moderately deep in depth and pale yellow, yellowish brown and dark brown in colour.

The climate of the watersheds is mostly warm temperate and they receive an average annual rainfall of 1000 mm, more than 50% of which is received during the southwest monsoon (June–September). Average annual snowfall in

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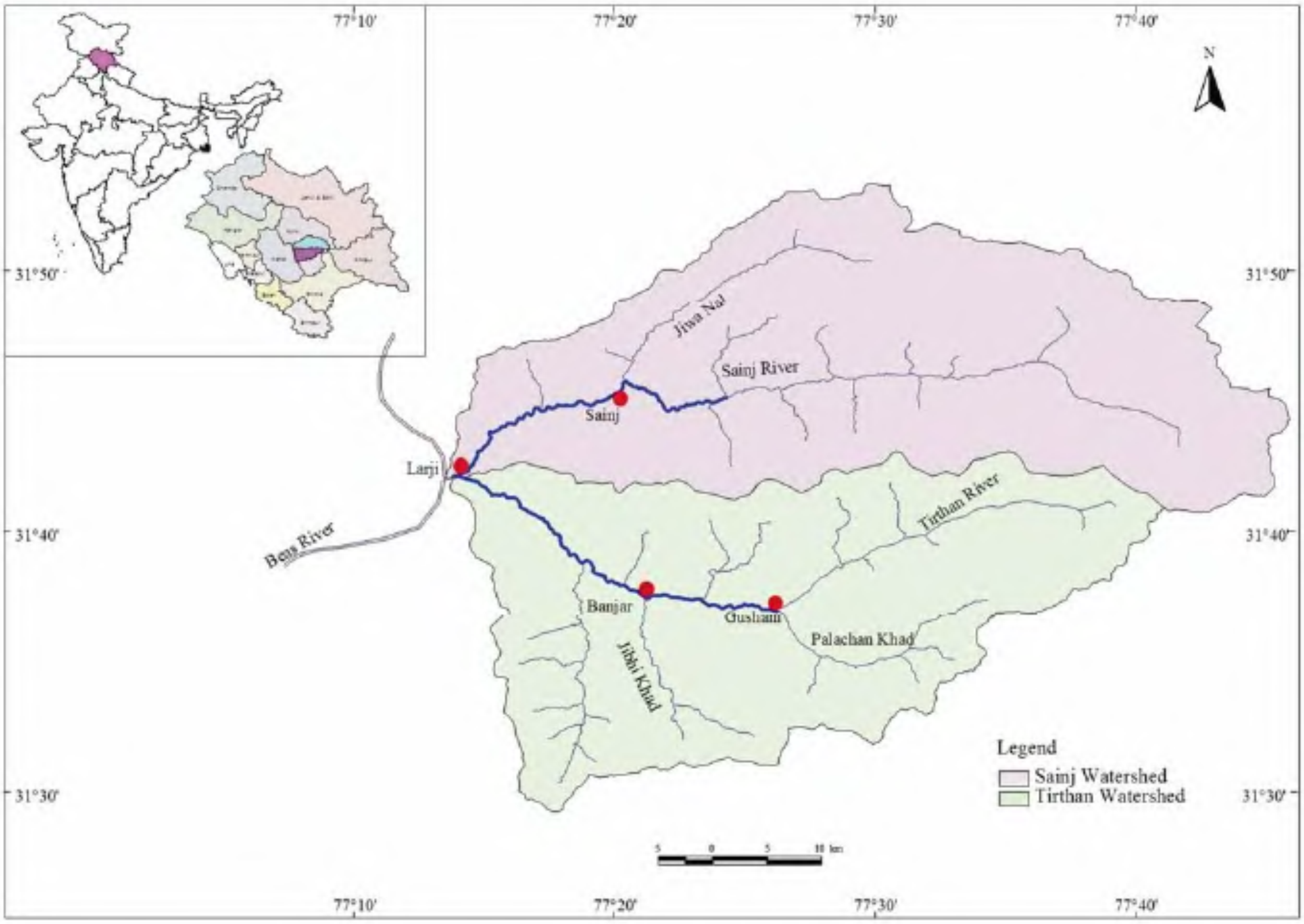

Figure 1. Location of Himachal Pradesh showing the Sainj and Tirthan watersheds.

the region is about 345 mm, which is confined to the upper reaches and occurs only during the winter season (October–March). The mean monthly temperature at Larji (the outlet of the watersheds) ranges from a minimum of 8.7°C during January to a maximum of 26.3°C during June. The minimum and maximum relative humidity are recorded in May (63.3%) and August (78.7%) respectively. Evaporation is observed to be minimum in 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.

Watersheds delineation and preparation of land-use map

The study watersheds (Sainj and Tirthan) were delineated from the topographical maps. The land-use maps of these watersheds were generated using the False Colour Composite (FCC) images captured by the Indian Remote Sensing (IRS-1C) satellite. Further, the land-use/land-cover maps were generated through visual image interpretation techniques and corroborated through primary survey and ground truthing. Major land uses like forests, degraded forests, scrub lands, agriculture, glacial movements and snow covered areas have been demarcated considering various image and terrain elements.

Acquisition of rainfall, runoff and sediment flux data

Data on rainfall, runoff and sediment transport in the Lesser Himalayan region is limited due to remoteness, ruggedness and inaccessibility. In the present study, daily rainfall, runoff and sediment flux data measured at the outlet of the Sainj and Tirthan watersheds along with calibrated segments at the Larji gauging station were obtained from the Bhakra Beas Management Board (BBMB). The acquired data was for a period of 24 years from 1981 to 2004. 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; the fraction retained is dried and weighed to estimate the suspended sediment concentration (SSC)[18]. A similar procedure was carried out for daily sample collection during the entire study period.

Moreover, information pertaining to human interventions (human and livestock population growth, road construction, deforestation and encroachments) was collected through personal interaction with the local population of the study watersheds and also from various governmental organizations in the state of Himachal Pradesh.

Analysis of rainfall, runoff and sediment flux data

Rainfall events for these watersheds were analysed to obtain mean monthly, mean seasonal and mean annual rainfall depths along with their standard deviations. 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 two watersheds at the Larji gauging station was analysed for mean monthly, seasonal and annual run-off along with their coefficient of variability and standard deviation. 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[18,19]. The sediment flux was derived by multiplying the daily discharge rate at the gauging station by the ratio of the SSC and the discharge rate. Further, the seasonal and annual run-off and total sediment flux were estimated by using standard accounting procedures spanning days, months, seasons and years[19]. A data screening procedure was undertaken, to remove extreme rainfall and subsequent runoff and sediment flux data, to ensure unbiased hydrological responses pertaining to generation of sediment flux from both the watersheds.

Estimation of trend in sediment flux

The data was split into two equal time intervals, i.e. 1981–1992 (period I) and 1993–2004 (period II) to ascertain temporal changes. Monthly and seasonal sediment flux scenarios were also developed and the following model was applied:

$$\text{Temporal change} = \left(\frac{Y_2 - Y_1}{Y_1}\right) \times 100, \qquad (1)$$

where Y_1 = average of period I; Y_2 = average of period II. The significance of temporal change was detected using paired 't' test on the monthly, seasonal and yearly averages.

Results and discussion

Rainfall frequency and variability

Analysis of rainfall records showed that the frequency of storms ≥ 5 mm accounted for 71% of the total rainy days in the Sainj and 56% in the Tirthan watersheds. A rainfall depth of ≥ 5 mm generally triggers soil erosivity leading to subsequent erodibility and transportation of sediment to downstream reservoirs[20]. Rainfall depths of 10–25 mm accounted for 31% in the Sainj and 25% in the Tirthan watersheds. Storms exceeding 25 mm in the Sainj (12%) were more than in the Tirthan watershed (9%). There are more large storms in the Sainj watershed than in the Tirthan (Table 1). Also, significant spatio-temporal variations in annual rainfall depths were observed, which could be attributed to the orientation of the mountains and the topographical conditions of the Sainj and Tirthan watersheds (Table 2). Rainfall records revealed that the wettest years were 1997 (Sainj, 2030 mm) and 1988 (Tirthan, 1314 mm), whereas lowest rainfall was recorded in 1984 (594 mm) and 1981 (628 mm) in the Sainj and Tirthan watersheds respectively. The standard deviation and coefficient of variability have been observed to be high in the Sainj watershed, which means that the rainfall variability in the Sainj is more pronounced than in the Tirthan (Table 3). The higher occurrence of rainfall depths of ≥ 5 mm in the Sainj watershed coupled with significant variability than that of the Tirthan watershed could result in generation of more sediment flux.

Runoff rate and sediment flux

The mean annual run-off was observed to be $13.1 \times 10^3 \pm 1.8 \times 10^3$ m^3/s and $9.6 \times 10^3 \pm 1.3 \times 10^3$ m^3/s in the Sainj and Tirthan watersheds respectively. The annual run-off records showed a low degree of variation with coefficients of variance as low as 14%, which indicate the undisturbed nature and dependability of annual runoff from these watersheds. The seasonal fluctuations in run-off showed that the summer–monsoon season (April–September) produced about 80% of the total annual flow in both the watersheds 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 in these watersheds. It was also observed that the runoff during the winter months of December through February was lowest despite the occurrence of high precipitation depths. Moreover, the occurrence of peak flows in these watersheds followed almost the same date and month, which is attributed to their proximity and affinity. The sediment flux was directly related to the outflow rate from these watersheds.

Annual sediment flux

The annual sediment flux varied from 93.2×10^3 to 1734.3×10^3 t with a mean value of 533.6×10^3 t in the Sainj watershed; for the Tirthan watershed it varied from

Table 1. Rainfall frequency in the Sainj and Tirthan watersheds during 1981–2004

	Sainj		Tirthan	
Rainfall frequency (mm)	No. of days	Days (%)	No. of days	Days (%)
0–5	629	29.4	1091	44.7
6–10	592	27.7	514	21.1
11–25	655	30.6	613	25.1
26–50	220	10.3	189	7.7
51–100	44	2.1	32	1.3
101–200	1	0.1	3	0.1
Total	2141	100.0	2442	100.0

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

	Watershed							
	Sainj				Tirthan			
Station →	Larji	Sainj	Niharni	Swakandhadhar	Banjar	Deotha Chanon	Palach	Panjai
Years of data	1981–2004	1981–2004	1987–1998	1987–1998	1981–2004	1992–1996	1995–1999	1982–1992
No. of years	24	24	12	12	24	5	5	11
Elevation (m)	1000	1400	1800	3500	1400	2000	1600	2300
January	71.8	72.6	63.2	6.1	75.9	104.5	28.8	25.8
February	89.0	98.7	105.7	10.6	80.6	85.1	168.1	57.7
March	114.1	144.3	136.6	20.0	105.5	98.5	266.5	103.4
April	71.9	71.8	73.1	72.9	73.6	70.4	49.6	93.5
May	76.1	91.1	72.1	143.3	90.1	88.5	58.5	184.2
June	87.4	78.9	96.0	140.6	83.2	66.5	49.8	82.8
July	187.0	210.8	190.6	264.5	178.8	194.8	115.4	187.9
August	174.7	196.3	196.5	263.2	164.0	177.0	87.1	155.0
September	75.5	93.5	124.9	177.6	82.8	124.7	73.8	72.8
October	37.6	28.9	28.2	43.8	28.0	14.4	17.8	45.2
November	19.8	24.3	26.1	25.5	18.0	10.3	3.0	30.3
December	41.1	37.9	35.9	0.9	34.2	11.6	111.3	31.4
Annual	1045.8	1149.1	1148.9	1169.0	1014.7	1046.5	1034.8	1070.1

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

Table 3. Average annual and seasonal rainfall and their variations in the Sainj and Tirthan watersheds during 1981–2004

Watershed	Mean rainfall (mm)	Annual rainfall (%)	Standard deviation	Coefficient of variation (%)
Annual				
Sainj	1149.1	–	307.6	26.8
Tirthan	1014.0	–	180.4	17.8
Monsoon season				
Sainj	579.6	50.4	237.0	40.9
Tirthan	508.8	50.1	160.6	31.6
Winter season				
Sainj	353.4	30.8	124.6	35.3
Tirthan	296.3	29.2	95.1	32.1
Post-monsoon				
Sainj	53.2	4.6	68.8	129.5
Tirthan	46.0	4.5	46.6	101.5
Summer season				
Sainj	163.0	14.2	109.0	66.9
Tirthan	163.7	16.1	67.2	41.0

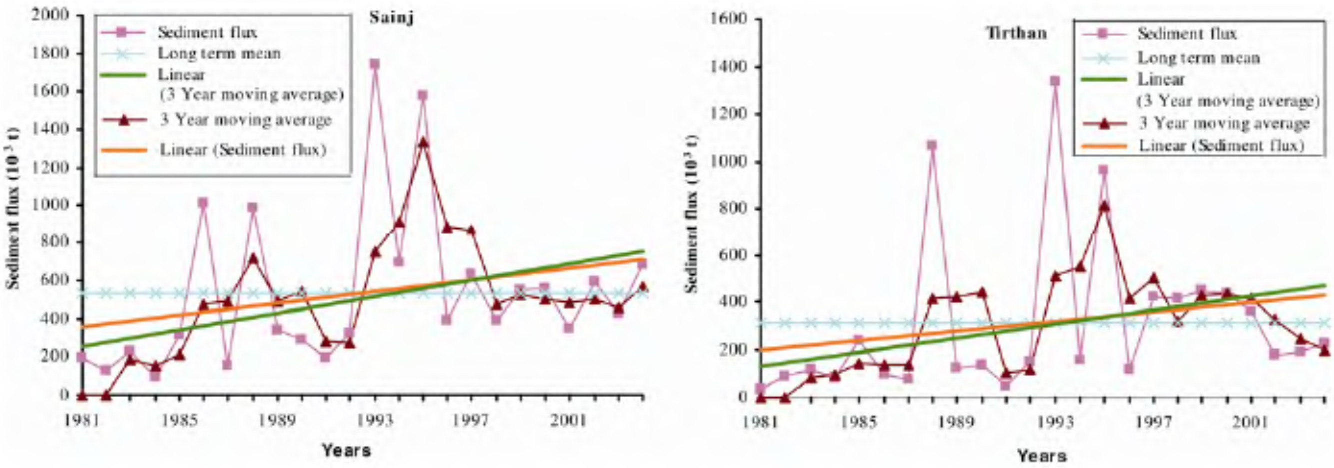

Figure 2. Annual sediment flux in the Sainj and Tirthan watersheds at Larji gauging station (1981–2004).

Table 4. Results of sediment flux trend analysis in the Sainj and Tirthan watersheds (1981–2004)

	Sainj			Tirthan		
	Decadal average (tonnes)		Decadal change (%)	Decadal average (tonnes)		Decadal change (%)
Months/season	1981–1992	1993–2004		1981–1992	1993–2004	
January	722.0	578.0	–20.0	353.3	349.6	–1.0
February	654.3	634.6	–3.0	354.1	363.3	2.6
March	2,533.3	1,664.2	–34.3	3,030.5	1,630.1	–46.2
April	3,499.7	4,215.7	20.5	2,986.3	3,298.1	10.4
May	8,971.3	15,493.1	72.7	4,982.7	6,401.4	28.5
June	71,041.5	44,148.3	–37.9	10,841.3	14,089.4	30.0
July	130,543.2	282,987.1	116.8	73,343.9	170,334.0	132.2
August	85,530.3	205,977.3	140.8*	41,314.3	126,925.2	207.2*
September	44,238.0	144,309.9	226.2	47,141.8	95,089.7	101.7
October	4,558.7	11,831.1	159.5	2,727.8	16,473.0	503.9
November	934.0	868.1	–7.0	459.3	511.0	11.2
December	685.7	577.3	–15.8	340.0	372.0	9.4
Summer	12,471.0	19,708.8	58.0	7,968.9	9,699.5	21.7
Monsoon	331,353.1	677,422.5	104.4*	172,641.3	406,438.2	135.4
Post-monsoon	5,492.7	12,699.1	131.2	3,187.1	16,983.9	432.9
Winter	4,595.2	3,454.0	–24.8	4,077.8	2,714.9	–33.4
Annual	353,911.9	713,284.5	101.5*	187,875.2	435,836.6	132.0

*Significant at 5% level.

36.85×10^3 to 1333.8×10^3 t with a mean value of 311.9×10^3 t (Figure 2). The variation in the annual sediment flux is depicted in the large values of coefficient of variability of –79.4% and 109.4% in the Sainj and Tirthan watersheds respectively. The long-term means of annual sediment yields were 7.2 t ha^{-1} yr^{-1} for the Sainj and 4.5 t ha^{-1} yr^{-1} for the Tirthan watersheds. The Sainj watershed sediment yield was almost 1.5 times higher than that of the Tirthan. The reasons for this could be attributed to the Sainj watershed having less area under forest, more construction activity related to road and hydropower generation and occurrence of high rainfall as compared to the Tirthan watershed. The data on spatio-temporal rainfall variability at eight rain gauge stations in these two watersheds are shown in Table 2. It is observed that the weighted average annual rainfall depth in the Sainj was 1128 mm as compared to 1042 mm in the Tirthan watershed. During a period of 12 years from 1993 to 2004, very few years had sediment flux lower than the long-term mean in both the watersheds. As to the overall trend, both watersheds showed an increasing trend of annual sediment load (Figure 2). According to the results of decadal change, the annual sediment flux had a positive trend at 0.05 significance level in the Sainj watershed. Positive decadal changes have been noticed in the annual sediment flux in the Tirthan watershed, but these were found to be non-significant at 0.05 level of significance (Table 4).

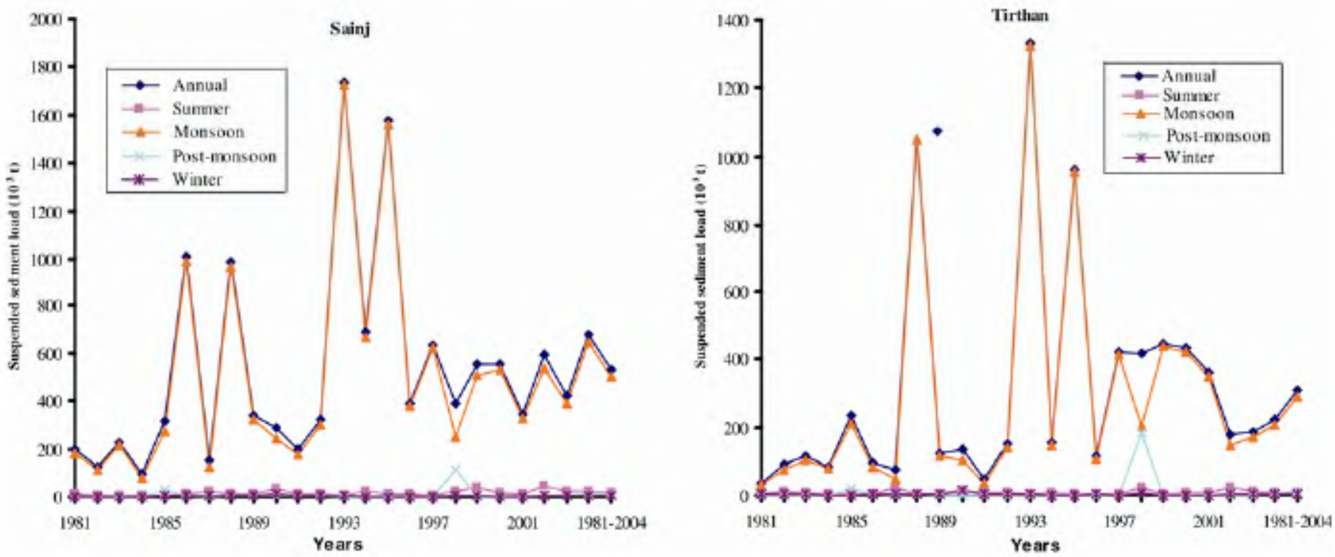

Figure 3. Seasonal sediment flux in the Sainj and Tirthan watersheds at Larji (1981–2004).

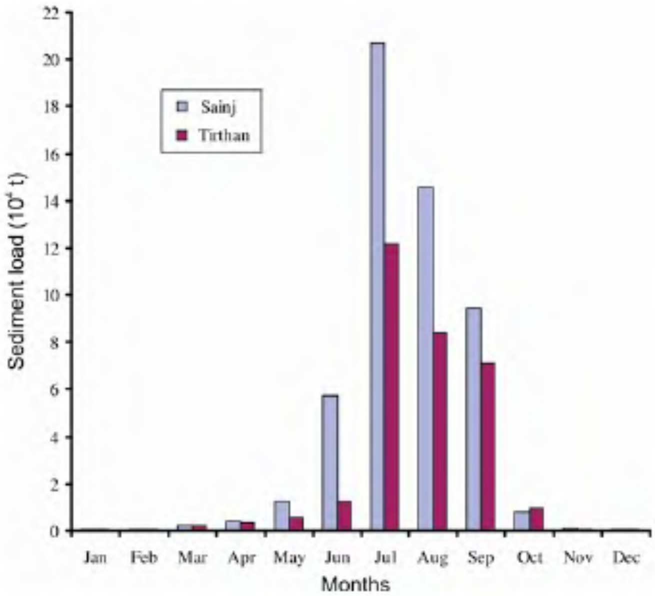

Figure 4. Mean monthly sediment flux in the Sainj and Tirthan watersheds (1981–2004).

Seasonal sediment flux

Sediment yield characteristics in the Sainj and Tirthan watersheds differ depending on the season (Figure 3). During the post-monsoon (October–November) and winter (December–March) seasons, the suspended sediment yield is at its minimal and is < 5% of the annual sediment yield in both the watersheds. The monsoon season (June–September) contributed about 91.8% and 88.0% of the annual sediment yield in the Sainj and Tirthan watersheds respectively. The average total suspended sediment load for this season was computed to be 126,097 and 72,385 t for the respective watersheds. The results of decadal change reveal that the summer, monsoon and post-monsoon seasons indicate positive trends in the sediment flux in both watersheds. It was observed from Figures 2 and 3 that the sediment outflow was less during periods of low annual discharge rate and when the sediment producing rainfall events occurring over the watersheds were minimum. Moreover, results also revealed an increase in the decadal sediment flux at 0.05 significance level in the Sainj watershed during the monsoon season (Table 4).

Monthly sediment flux

The bulk of the sediment flux in the watersheds occurs in the months from June to September (Figure 4) when there are monsoonal rains in the entire Lesser Himalayan region. The average sediment load transported during the June, July, August and September is 57,595; 206,765; 145,754 and 94,274 t for the Sainj and 12,465; 121,839; 84,120 and 71,116 t for the Tirthan watershed respectively. The sediment load during this period constituted 64–99% (average 92%) and 49–99% (average 88%) of the annual sediment transport in the Sainj and Tirthan watersheds respectively. The contribution of June–September towards the annual sediment load is to the tune of 11.5, 35.7, 33.5 and 11.1% in the Sainj and 9.0, 29.4, 37.4 and 12.2% in the Tirthan respectively. The maximum sedimentation in the watersheds has occurred during July followed by August in the Sainj watershed, and during August followed by July in the Tirthan, on the basis of average percentage share. However, on the basis of average absolute total sediment load, maximum sediment load in both watersheds occurs in July followed by August. Prominent peaks in the sediment flux are associated anomalously with higher water discharge, because the maximum rainfall percentage for the entire study period occurred in July followed by August and the maximum runoff percentage was contributed in August followed by July, in both the watersheds. Sediment flux during other months had an almost negligible share. But significant positive changes were observed in sediment flux during most of the months in both watersheds (Table 1). However, month of August experienced increasing trends of 140.8% and 207.2% in the Sainj and Tirthan respectively, significant at 0.05 significance level. The reason for the sediment flux increase in August could be attributed to the high rainfall intensity and surface runoff, relatively saturated slopes and subsequent mass wasting process in both the watersheds.

Daily sediment flux

Daily suspended sediment flux ranges between 9 and 1,218,716 t in the Sainj and 4 and 771,155 t in the Tirthan watersheds at the Larji gauging site (Table 5). The daily maximum suspended sediment load has crossed 0.1×10^6 t, which was eight times in the Sainj watershed and six times in the Tirthan. Moreover, half the sediment load was transported in a very short time, i.e. 0.72% (63 days) and 0.16% (14 days) of the time during the 24 year period in the Sainj and Tirthan watersheds respectively. The daily extremes of sediment flux did not exhibit significant change, presumably because of the high variability of rainfall events in these watersheds.

Evaluation of sediment flux from the watersheds

Annual sediment load from these two watersheds amounting to 43×10^5 m^3 was transported to the downstream Pandoh reservoir of the river Beas. It was observed that 14% of this sediment load in the Pandoh reservoir was from both the watersheds, with individual shares of 8.8% and 5.1% from the Sainj and the Tirthan respectively. Soil loss at the rate of 7.2 and 4.5 t ha^{-1} yr^{-1} respectively from the Sainj and the Tirthan watersheds is quite disturbing in the light of the permissible limit of 1.8 t ha^{-1} yr^{-1} for sustained productivity of lands[21]. Thus, higher-than-assumed sedimentation rates from the Sainj watershed will hamper the operational efficiency of hydropower projects to be built or already constructed in the region. This will also lead to shortening of the designed life span of the Pandoh reservoir downstream of both watersheds.

Impact of land surface disturbance on sediment flux

Land surface disturbance has been profound in both watersheds over the past few decades due to the rapid increase of population, inappropriate socio-economic policies and recently, rapid economic development. It was observed from the land-use maps of the Sainj and Tirthan watersheds that the forested area was maximum with 40% (283 km^2) and 56% (386 km^2) respectively. Forests were predominantly of open type and non-uniformly distributed throughout the watersheds, mostly confined to the high hills and interior valleys. The second major land use type was identified as rocky outcrops, which covered an area of 24% (176 km^2) in the Sainj and 18% (121 km^2) in the Tirthan watershed. Snow bound area was 23% (167 km^2) and 7% (49 km^2) in the Sainj and Tirthan watersheds respectively. Agricultural land was predominant in the Tirthan watershed with 17% (116 km^2) as compared to 5% (33 km^2) in the Sainj watershed. The areas covered by glaciers were 9% (70 km^2) and 1% (8 km^2) in the Sainj and Tirthan watersheds respectively (Figure 5). Degraded land in the Sainj watershed (24%) is more than that in the Tirthan (18%). It was observed that hydropower projects were under construction in the later phase of this study in the Sainj watershed. This may be one of the reasons for enhanced sediment outflow in the Sainj as compared to the Tirthan watershed. It was noted that the erosion rates are not directly related with the area under forest cover in the Sainj watershed. There exists a direct relationship between forest cover and erosion rates in the Tirthan watershed[19].

Besides changes in land use and land cover, a growth of 27% in human and 47% in livestock population was envisaged during 1981–2001 in these watersheds. Along with increase in the local population there was a large influx of migrated skilled and unskilled persons working in the hydropower projects. This resulted in an ever-increasing pressure on the finite land resources of the region. Also, 25–30% encroachment of agricultural activities into the forest land coupled with enhanced deforestation led to the removal of 119,438.4 m^3 of timber during 1987–2005. The construction of 55 km of roads during 1994–2002 in the watersheds resulted in excavation works amounting to 2.2–4.4 Mm^3 of debris accentuating the sediment load in the channels[22]. Further, there was a sharp increase in area under horticultural practices from 21.12 to 35.26 km^2 (67% increase) during 1993–2004 (Figure 6). This clearly depicted that these watersheds were under pronounced anthropogenic pressure. Due to this, there was an increasing trend of annual sediment outflow (Figures 2 and 3).

The amount of timber removed from the forests of the two watersheds during the deforestation process is presented in Table 6. It was revealed by 95% of the farmers surveyed during 2004–05 that deforestation has increased over the years. According to a household survey in the state of Himachal Pradesh, the annual fuel wood requirement per household is 4.45 t per year[23]. Taking 12,714 as the number of households in the study watersheds, the total fuel wood requirement of the area would be 56,578 t per year.

Table 5. Variations in sediment flux at Larji in the Sainj and Tirthan watersheds (1981–2004)

		Sainj				Tirthan			
Year	Sediment transport	Date	Sediment load (t)	Maximum/ minimum	Half-Sediment load (% time)	Date	Sediment load (t)	Maximum/ minimum	Half-sediment load (% time)
1981	Maximum	25 July	20,784.9	1,631.5	3.6	29 July	2,466.5	520.4	5.5
	Minimum	20 December	12.7			23 January	4.7		
1982	Maximum	20 July	22,479.0	1,991.1	4.4	12 June	37,806.4	6,609.5	0.6
	Minimum	17–18 December	11.3			9 February	5.7		
1983	Maximum	19 August	58,394.2	6,166.2	1.9	19 August	41,200.3	6,561.6	0.8
	Minimum	20 January	9.5			26 December	6.3		
1984	Maximum	19 July	4,661.4	363.0	7.7	17 June	30,828.3	5,679.5	0.6
	Minimum	2 February	12.8			28 January	5.4		
1985	Maximum	18 July	34,171.5	1,838.2	2.5	18 July	28,735.3	5,075.1	1.6
	Minimum	18 January	18.6			14 February	5.7		
1986	Maximum	23 June	309,272.8	32,936.4	0.8	27 July	8,796.5	1,483.4	2.7
	Minimum	7 February	9.4			10 February	5.9		
1987	Maximum	9 September	6,652.5	585.1	9.0	25 July	21,238.2	3,548.0	2.2
	Minimum	3 December	11.4			29 December	6.0		
1988	Maximum	25 September	216,459.8	23,052.0	0.8	24 September	298,927.2	58,510.0	0.8
	Minimum	8 February	9.4			16 February	5.1		
1989	Maximum	28 August	88,967.0	6,569.2	1.1	28 August	51,643.5	7,084.2	0.6
	Minimum	24 February	13.5			16 February	7.3		
1990	Maximum	10 July	34,089.8	2,735.9	6.9	10 July	21,514.9	3,869.6	3.0
	Minimum	14 January	12.5			6 February	5.6		
1991	Maximum	6 September	10,396.1	775.8	10.1	22 August	3,353.5	630.1	9.0
	Minimum	27 January	13.4			1 February	5.3		
1992	Maximum	21 July	50,335.8	4,102.3	3.0	21 July	37,616.0	6,914.7	1.9
	Minimum	25 December	12.3			5 January	5.4		
1993	Maximum	11 July	796,043.8	84,730.6	0.6	11 July	739,591.4	157,931.1	0.3
	Minimum	19 December	9.4			20 December	4.7		
1994	Maximum	20 July	127,053.3	13,417.8	2.7	1 August	15,297.4	3,266.6	2.2
	Minimum	5 January	9.5			1, 5, 6, 9 January	4.7		
1995	Maximum	5 September	1,218,716.0	126,488.0	0.3	5 September	771,154.0	136,246.3	0.3
	Minimum	30 December	9.6			25, 26, 29 December	5.7		
1996	Maximum	12 July	34,452.1	3,638.4	6.0	22 August	6,172.6	1,318.0	4.7
	Minimum	25 December	9.5			11 January	4.7		
1997	Maximum	3 August	221,554.5	24,346.6	0.8	3 August	175,348.0	23,147.0	0.6
	Minimum	1 January	9.3			14 January	7.6		
1998	Maximum	20 October	21,383.6	1,656.4	4.4	18 October	47,421.4	8,683.6	1.9
	Minimum	29 January	12.9			12 February	5.5		
1999	Maximum	10 August	86,035.1	7,973.6	2.5	10 August	146,006.0	27,678.9	0.8
	Minimum	9 February	10.8			13 January	5.3		
2000	Maximum	1 August	22,277.7	2,137.9	4.9	31 July	22,785.0	4,149.8	3.6
	Minimum	28 February	10.4			3 January	5.5		
2001	Maximum	14 August	84,505.1	8,051.2	2.5	14 August	143,882.3	34,754.2	0.6
	Minimum	14 February	10.5			14 February	4.1		
2002	Maximum	14 August	116,304.0	10,027.9	2.2	14 August	33,284.5	6,374.4	2.2
	Minimum	13 January	11.6			16 December	5.2		
2003	Maximum	5 August	40,191.0	3,699.5	8.0	5 August	14,773.4	3,112.8	5.2
	Minimum	19 January	10.9			27 January	4.8		
2004	Maximum	8 August	117,749.4	11,066.7	1.6	1 August	18,234.9	2,814.0	3.3
	Minimum	17 January	10.6			17 January	6.5		

Forest fires are an important ecological disaster in the watersheds. There have been 249 cases of forest fires involving 66.37 km^2 of forestland during 1967–2003 (Figure 7 *a* and *b*). These forest fires wipe out young regeneration completely and damage standing trees – that are either burnt out or eventually dry out or become susceptible to wind damage at a later stage. The fires leave the forest floor deprived of vegetative cover and render soils sterile, increasing the hazard of soil erosion and floods (Figure 8). However, there has been no immediate effect on sediment yield due to forest fires in the initial years due to delayed sediment delivery from the burnt areas.

Besides all these activities, many new roads were constructed to link remote areas in the watersheds. The road construction process resulted in large-scale instability and production of debris which ultimately finds its way into rivers and streams (Figure 9). It is estimated that 40,000–80,000 m^3 of debris is excavated for the construction of

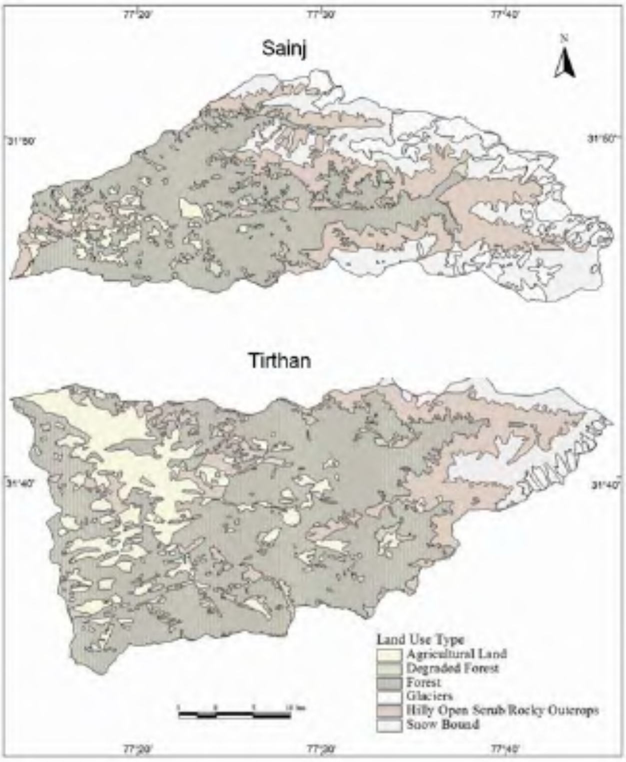

Figure 5. Distribution of land use/land cover in the Sainj and Tirthan watersheds using LISS-III-IRS-IC satellite data.

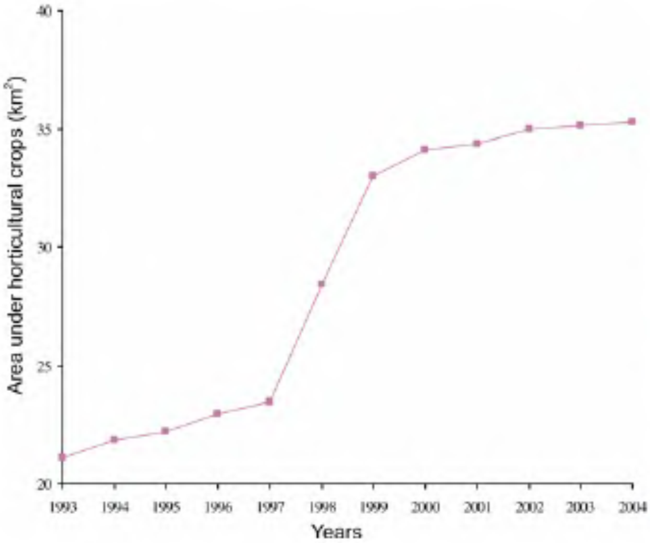

Figure 6. Exponential increase in area under horticultural practices in the watersheds during 1993–2004.

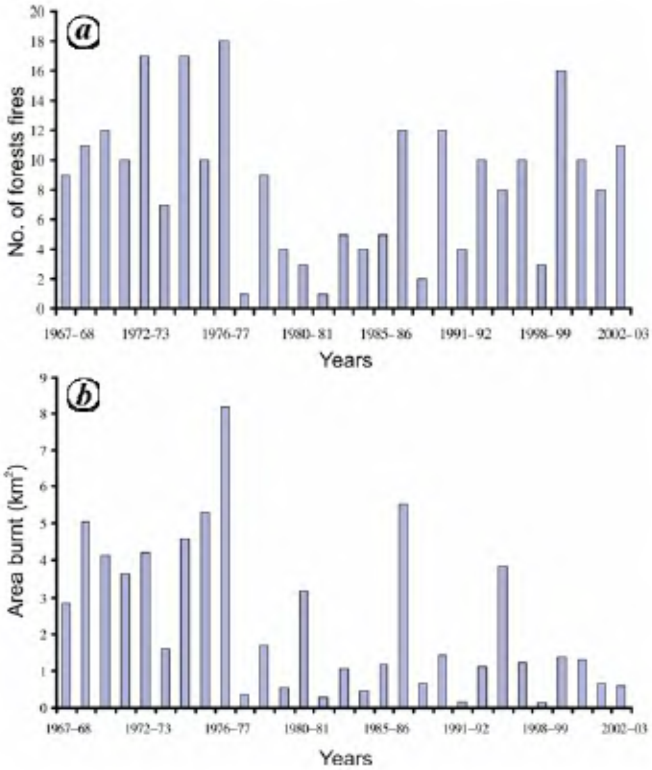

Figure 7. ***a***, Number of forest fires. ***b***, Forest area burnt in the Sainj and Tirthan watersheds.

Figure 8. Denuded land surface after forest fire, susceptible to sediment transport.

Table 6. Timber extracted from the Sainj and Tirthan watersheds

	Timber granted (m^3)					
Period/tree species	Deodar	Kail	Chil	Fir	Others	Total
1967–68 to 1986–87	116,728.8	99,443.6	2,372.3	58,105.1	3,030.3	279,680.1
1987–88 to 2004–05	46,182.1	25,647.3	6,691.5	34,837.5	6,080.0	119,438.4

Source: Annual Administration Report of Seraj Forest Division and Bali Chowki range.

Table 7. Livestock population in the Sainj and Tirthan watersheds

Year	Cattles and buffaloes	Sheep	Goat	Others	Total
1982	43,293 (30)	29,290 (21)	22,937 (16)	4,802 (3)	100,322 (70)
1992	40,218 (28)	27,869 (20)	20,629 (14)	5,075 (4)	9,3791 (66)
1997	55,958 (39)	38,137 (27)	29,121 (20)	5,215 (4)	128,431 (90)
2002	106,835 (75)	46,729 (33)	29,757 (21)	6,032 (4)	189,353 (133)

Source: Directorate of Animal Husbandry, Kullu. Figures in parentheses indicate animal load per square kilometer.

Figure 9. Road construction activities leading to down wearing (erosion) of hills and subsequently increasing sediment flux.

just a 1 km long road[24]. The construction of 55 km of roads during 1994–2002 in the watersheds resulted in excavation works amounting to 2.2–4.4 Mm^3 of debris, which accentuated the sediment loads in the channels[19,22]. The pastures in the watersheds are overgrazed and are presently suffering from a great deal of erosion-induced degradation due to heavy livestock grazing pressure (Table 7). Every year about 25,000–30,000 migratory animals (mainly sheep and goat) visit 175 thatches and pastures located in both the watersheds. The continuous grazing rakes up the soils and inhibits regeneration of biomass, accelerating the process of sediment flux. Also, the unscientific cultivation and mining activities taken up in the watersheds add to the sediment delivery at the watershed outlets.

Conclusion

The annual sediment flux in the Sainj and the Tirthan watersheds was observed to be 7.2 and 4.5 t ha^{-1} yr^{-1} respectively. This study has shown a temporal variability of sediment flux, more particularly during the monsoon (wet) period on an annual basis in these alpine watersheds. The frequency of rainfall depths > 5 mm was 1.3 times more in the Sainj watershed as compared to the Tirthan watershed. The detected changes in sediment flux may be due to land surface disturbance induced by human activities such as deforestation, development of hydropower projects and agricultural activities within the watersheds. Human activities are responsible for development of gullies and frequent slope failures in the watersheds. Unscientific dumping of material excavated during house building, road cutting and tunnel construction in hydropower projects increases the sediment load at watershed outlets. The land degradation, frequency of rainfall depths > 5 mm, road construction and other anthropogenic activities were more in the Sainj watershed as compared to the Tirthan watershed. This has resulted in a sediment flux 1.5 times more in the Sainj compared to that in the Tirthan watershed. The detected changes in sediment flux resulting from such human activities have significant implications for effective soil erosion control and agricultural water management activities in the watersheds.

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