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Temporal variations in runoff and soil loss in relation to soil conservation practices in catchments in Shiwaliks of lower Himalayas

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Abstract

The soil conservation strategies adopted in the catchments of Shiwaliks, the most fragile region in the Himalayan ecosystem, failed to serve their purpose after a few years of their execution. A study was carried out in four differentially-treated catchments to monitor the variation in runoff and soil loss. The treatments imposed during 1988 included fencing, planting native vegetation and engineering structures in catchment Ⅰ; planting native vegetation and fencing in catchment Ⅱ; fencing alone in catchment Ⅲ in addition to an untreated catchment Ⅳ. The soil loss during the initial years (1989 – 1995) of imposition of the treatments was lowest (25.2 t ha^{-1}) in catchment Ⅰ, treated to the maximum extent and highest (43.3 t ha^{-1}) in untreated catchment Ⅳ. During the later period (1996 – 2006) the trends reversed, i. e., catchment Ⅳ recorded the lowest (14.1 t ha^{-1}) soil loss whereas catchment Ⅰ recorded the highest (23.4 t ha^{-1}) soil loss despite the fact that there was no change in the status of soil conservation or the characteristics of the catchments. The runoff was 71% higher in untreated catchment than in treated catchments initially and this difference decreased to 27% during the later period.

Key Words: Catchment, Gully erosion, Sediment loss, Soil conservation

1 Introduction

The increased exploitation of land resources in the catchment areas of the Shwialiks belt (2.14 million ha, 30°10′–33°37′ N, 73°37′–77°39′ E, 415 AMSL), the most fragile region of the Himalayan ecosystem (Sidhu et al., 2000), has resulted in increased sediment yields in the runoff thereby reducing the capacity of reservoirs at the downstream end. The drying of vegetation during the months of April – June (due to extremely high temperatures and low relative humidity) and frequent forest fires creates a stage for soil erosion to take place at potentially high rates during the months of July – September when 80% of the annual rainfall occurs (Sur and Ghuman, 1994).

Gully erosion is the most serious form of soil erosion with catchments having a dense network of gullies in the Shiwaliks region of the lower Himalayas. The severity of gully erosion measured in terms of gully intensity (number of first-order gullies per unit area) varies from 254 – 768 km^{-2} and gully length (total length of gullies per unit area) from 8.7 – 16.3 km km^{-2} (Kukal and Singh, 2004). Recent studies (De Vente et al., 2005; Huon et al., 2005) indicate that gullies are often the main source of sediments from the catchments. Gullies are often blamed for enhanced drainage and accelerated aridification processes (Daba, 2003). In tropical NW Australia, about 80% of the sediments in the reservoirs come from gully erosion (Krause et al., 2003). Gullied catchments in NSW were observed to be at least one order of magnitude higher in sediment load than the catchments without gullies (Armstrong and Mackenzie, 2002). The impact of sediment trapping and grade stabilization works on sediment yield mainly depend on the activity of the gully being treated and the mobility of bed sediments. At the catchment

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scale, it is often the combination of widespread conservation measures in the gullies (plugging structures) as well as in the inter-gully zone that leads to a decrease in soil erosion rates (Nyssen et al., 2004 a, 2004 b). The frequent siltation of plugging structures (Kukal and Singh, 2004) or their collapse is due to the runoff volume and velocity (Nyssen et al., 2004a). The rainfall aggressiveness – ratio of highest monthly rainfall squared to the total annual rainfall, varies from 55.9 – 502.4 with an average annual value of 207.8±121.7 (Singh, 2000) in the region and is shown to be related to gully intensity and the sediment yield in the streams and rivers (Fournier, 1960). Studies in the region (Matharu et al., 2002) have shown that about 77% variation in annual sediment yield could be explained by rainfall aggressiveness.

Recently, the Shiwaliks region has started receiving attention for the management of runoff and soil loss on micro-watershed basis through various anti-erosion measures. However, it had been a common observation that the soil conservation measures, particularly the gully plugging structures, installed in the highest-order gullies, were successful in controlling the runoff and sediment losses from the catchments during the initial years, but after 3 – 4 years of their installation the soil erosion rates in treated catchments exceed from those in untreated ones (Kukal et al., 2002). The gully plugging structures installed in the catchment get silted up within no time leading to enhanced runoff and sediment losses from the catchment areas. This has baffled the soil conservation planners in the region. A study was thus initiated in 1989 to monitor the runoff and soil loss in relation to soil conservation practices at catchment scale.

2 Materials and methods

2.1 *Study site*

The study was conducted in the northwest part of Punjab in India, located in the Shiwaliks belt of lower Himalayas. The climate of the region is semi-arid sub-tropical with warm summers and cold winters. The mean annual summer and winter temperatures in the region vary from 15 – 22℃ and 5 – 6℃. The mean summer soil temperature varies from 29 – 32℃ and mean winter soil temperature varies from 8.4 – 15℃. The area receives an annual average rainfall of 950±291 mm of which about 80% is received during a short period of three months (July – September) with a high degree of coefficient of variation (Sur and Ghuman, 1994). Shallow soil depth and stoniness in the region generates rapid runoff due to low storage, low water holding capacity and low nutrient status. Stoniness covering 25% of the area is the main problem in severely eroded areas (Sidhu et al., 2000). Soils in the region are generally light textured, well drained and highly erodible (Kukal et al., 1991).

2.2 *Treatments*

Four catchments, varying in size from 3 – 16 ha and treated with a combination of different anti-erosion measures viz. afforestation, fencing and gully control structures were monitored for runoff and soil loss (Table 1). The catchment Ⅰ was fenced, planted with native vegetation with gully control structures installed in the highest-order gullies; catchment Ⅱ was fenced and planted with native vegetation; and catchment Ⅲ was fenced only. The catchment Ⅳ was kept untreated and was designated as control (C). The fencing was carried out with barbed galvanized iron wire fixed thrice all around the catchment using cemented (reinforced concrete cement) fixtures with the aim of preventing wild animals from grazing and deforestation by humans. The native vegetation mainly comprised of *Acacia catechu* trees and *Eulaliopsis binata* grass. The engineering structures for plugging the gullies were gabions and lose rock dams (made from the locally-available stones) installed as check dams in series at upper, middle and lower segments of the main (highest-order) gullies (Fig. 1 and Fig. 2).

Table 1 General catchment characteristics

Catchment	Area (ha)	Average relief	Lemniscate ratio
Ⅰ	11.8	0.19	0.66
Ⅱ	20.6	0.11	1.00
Ⅲ	8.75	0.19	0.60
Ⅳ	42.6	0.33	0.79

Note: Catchment Ⅰ – planted vegetation, fencing and engineering structures; catchment Ⅱ – planted vegetation and fencing; catchment Ⅲ – fencing alone and catchment Ⅳ – untreated.

2.3 *Observations*

Detailed ground surveys were carried out in all the catchments to mark the gullies up to the first-order. For

(a) (b)

Fig. 1 The loose rock dam structures (a and b) installed in a study catchment

(a) (b)

Fig. 2 The loose rock dam structures (as in Fig. 1) silted up

(a) downstream side and (b) upstream side

this purpose, each catchment was divided into grids of 50 m×50 m. Each gully line was sketched on the maps (at a scale of 1 : 1,000) by measuring the distance from the wooden pegs laid out in the grids. The catchment characteristics viz. relief and shape were recorded for each catchment.

2.4 *Runoff and soil loss measurement*

The runoff was gauged with stage level recorders installed at the outlet end of each catchment. The hydrographs so obtained were analyzed for determining total runoff volume and amount. The Coshocton wheel samplers, which mixed the sediments in the runoff in the storage tank, were used to collect runoff samples at different time intervals after the start of the rainfall. These runoff samples were then mixed together to get a composite sample for an individual rain event to measure sediment load.

2.5 *Statistical analysis*

The observations so obtained were analyzed statistically using analysis of variance (ANOVA) to obtain least significant difference among the treatments at the 5% level of significance (LSD 0.05) (Cochran and Cox, 1965). The LSD (0.05) was used to determine the significance of differences among various treatments.

3 Results and discussion

3.1 *Climatic variability*

The rainfall amount during the three months (JulyP – September) of the monsoon season was quite variable over different years (Fig. 3). It was 625 mm in 2003 compared to 1,600 mm in 1994. A comparison with long-term average rain amount in the region shows that the rainfall remained below-normal during 1989 – 1992 and 1999 – 2003, whereas it was above normal during 1993 – 1996. The rainfall in the region had a standard deviation of 335.4 mm and coefficient of variation of 30.4% during the last 20 years (Sur and Ghuman, 1994). In general the rains in the region have shown a decreasing trend during the last decade (Mukherjee et al., 2005).

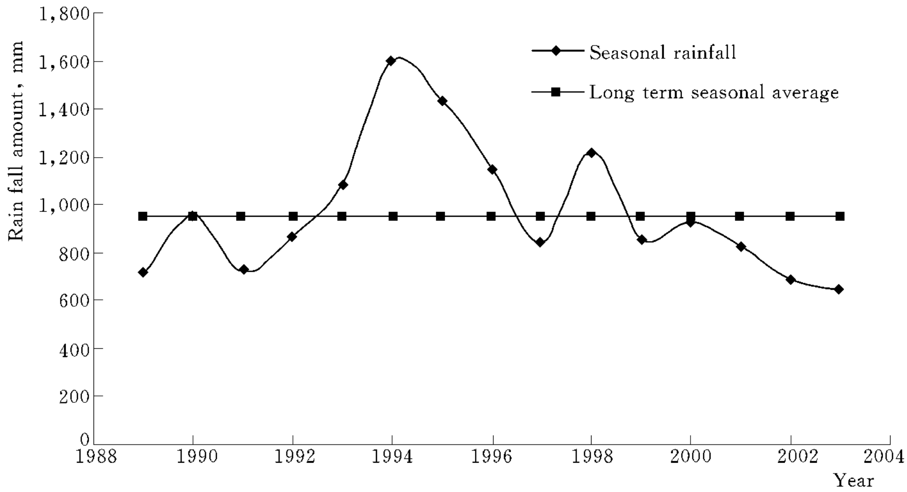

Fig. 3 Temporal variation in rainfall amount during July – September (Monsoon season)

3.2 *Catchment characteristics*

The shape index, lemniscate ratio (ratio of square of maximum length of the catchment to four times its area) (Morgan, 2005) of catchment Ⅲ had the lowest value (0.60) and catchment Ⅱ had the highest (1.00) (Table 1). A lower value of lemniscate ratio indicates a more compact shape of the catchment, which results in rapid generation of runoff and hence higher soil erosion. The average relief of the untreated catchment was highest (0.33), whereas in all other catchments, it was not much different. The average relief and shape of the catchments were in no way related to each other.

The intensity of gully erosion in the catchments expressed as gully intensity (number of first-order gullies per unit area) and gully length (length of all the gullies per unit area) is presented in Table 2. The gully intensity was highest ($750\ km^{-2}$) in catchment Ⅰ, closely followed by $722\ km^{-2}$ in catchment Ⅲ ($722\ km^{-2}$). It was lower in catchment Ⅱ (about $440\ km^{-2}$) and catchment Ⅳ (about $251\ km^{-2}$). The gully length was highest ($31.7\ km\ km^{-2}$) in catchment Ⅰ but least in catchment Ⅳ ($8.6\ km\ km^{-2}$). The gully length in catchment Ⅱ and Ⅲ was however, similar, but gully intensity differed significantly between the two catchments.

Table 2 Extent of gully erosion in the treated catchments

Catchment	Gully texture ($No.\ km^{-2}$)	Gully density ($km\ km^{-2}$)	1st order gullies (%)	
			Length	Number
Ⅰ	758.0	31.7	79.4	79.8
Ⅱ	439.9	15.5	89.0	85.0
Ⅲ	722.0	15.8	75.0	76.0
Ⅳ	251.2	8.6	59.6	58.8

Note: Catchment Ⅰ – planted vegetation, fencing and engineering structures; catchment Ⅱ – planted vegetation and fencing; catchment Ⅲ – fencing alone and catchment Ⅳ – untreated.

3.3 *Soil loss*

The mean soil loss during the study period (1989 – 2003) was statistically similar in the treated catchments (Table 3). It was, however, significantly higher in untreated catchment Ⅳ ($28.7\ t\ ha^{-1}$). The soil loss during the initial years (1989 – 1995) varied with the treatments imposed. The mean soil loss during 1989 – 1995 was highest ($43.3\ t\ ha^{-1}$) in untreated catchment Ⅳ followed by similar amounts in catchments Ⅲ (fenced only) and Ⅱ (fenced + planted vegetation) and lowest ($25.2\ t\ ha^{-1}$) in the catchment Ⅰ. The soil loss in fenced and vegetated catchment Ⅱ was not statistically different from that in catchment Ⅲ with fencing alone. It was significantly higher from that in catchment Ⅰ, where in addition to native vegetation and fencing gully plugging structures were installed in the highest order gully.

Table 3 **Soil loss and runoff in differentially treated catchments during different time periods**

Catchment	Soil loss(t ha^{-1})			Runoff(%)		
	1989 – 2003	1989 – 1995	1996 – 2003	1989 – 2003	1989 – 1995	1996 – 2003
Ⅰ	24. 3	25. 2	23. 4	18. 9	20. 7	17. 1
Ⅱ	25. 1	32. 3	18. 0	17. 8	21. 9	13. 5
Ⅲ	25. 3	33. 7	16. 8	15. 4	22. 0	8. 4
Ⅳ	28. 7	43. 3	14. 1	28. 7	35. 5	21. 9
LSD(0. 05)	2. 5	4. 3	3. 2	3. 7	2. 9	3. 9

Note: Catchment Ⅰ – planted vegetation, fencing and engineering structures; catchment Ⅱ – planted vegetation and fencing; catchment Ⅲ – fencing alone and catchment Ⅳ – untreated.

The trend in soil loss from different catchments, however, reversed during 1996 – 2003 (Table 3; Fig. 4). The catchment Ⅰ (planted vegetation+fencing+structures) experienced the highest soil loss during the period (23. 4 t ha^{-1}), whereas the soil loss in untreated catchment Ⅳ remained lowest (14. 1 t ha^{-1}) despite of its being untreated with soil conservation measures and being steeper than other catchments. The soil loss from catchments Ⅱ and Ⅲ did not vary significantly from each other as in 1989 – 1995 (Fig. 4). The magnitude of the soil loss in all the four catchments was lower during 1996 – 2003 compared to that in 1989 – 1995. It could be due to below normal rainfall during the period 1996 – 2003 (Fig. 3).

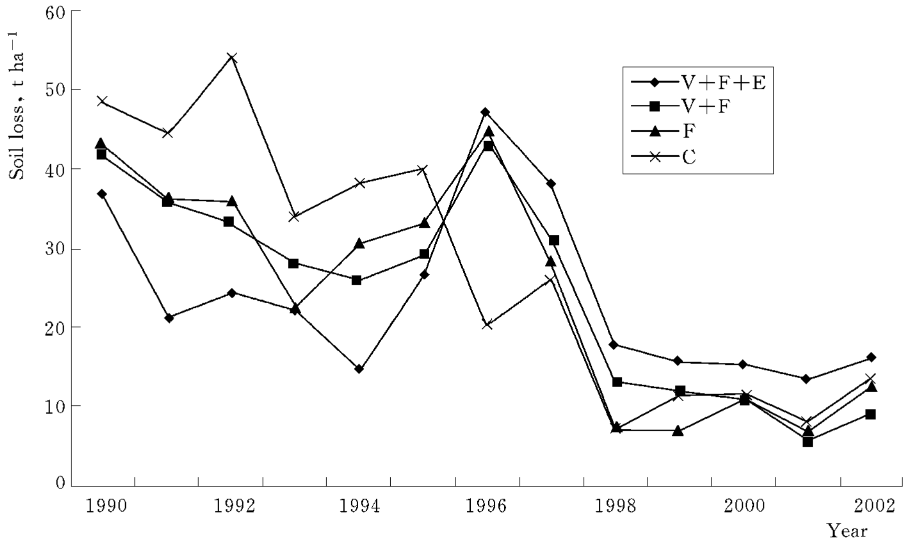

Fig. 4 Variation in soil loss over different years in treated and untreated catchments

(V+F+E indicates planted vegetation, fencing and engineering structures; V+F indicates planted vegetation and fencing; F indicates fencing alone and C indicates untreated catchment)

3. 4 *Runoff*

The mean runoff over the period (1989 – 2003) was highest (28. 7%) in the untreated catchment Ⅳ, compared to that in the treated catchments Ⅰ (18. 9%), Ⅱ (17. 8%) and Ⅲ (15. 4%) (Table 3; Fig. 5). It did not vary much among the treated catchments. The runoff during the period 1989 – 1995 followed a similar trend as during 1989 – 2003. However, it was 71% higher in catchment Ⅳ than in catchment Ⅰ during 1989 – 1995. However, this difference decreased to 27% during 1996 – 2003. The runoff from untreated catchment remained higher throughout the study period both due to the absence of soil conservation measures and its higher steepness. However, during the period 1996 – 2003, the differences narrowed down from 71% to 27%, though there was no change in its steepness or soil conservation status. It indicates higher runoff generation in this catchment during 1996 – 2003 compared to the other catchments.

The catchment characteristics viz., area, average relief and slope could not explain the variation in soil loss over time and space. The extent of the gully network and distribution of first-order gullies could also not explain the trend in soil loss variation among different catchments. However, number and length of first-order gullies were higher in catchment Ⅰ (treated to the maximum extent) than in catchment Ⅳ (untreated). The first-order gullies

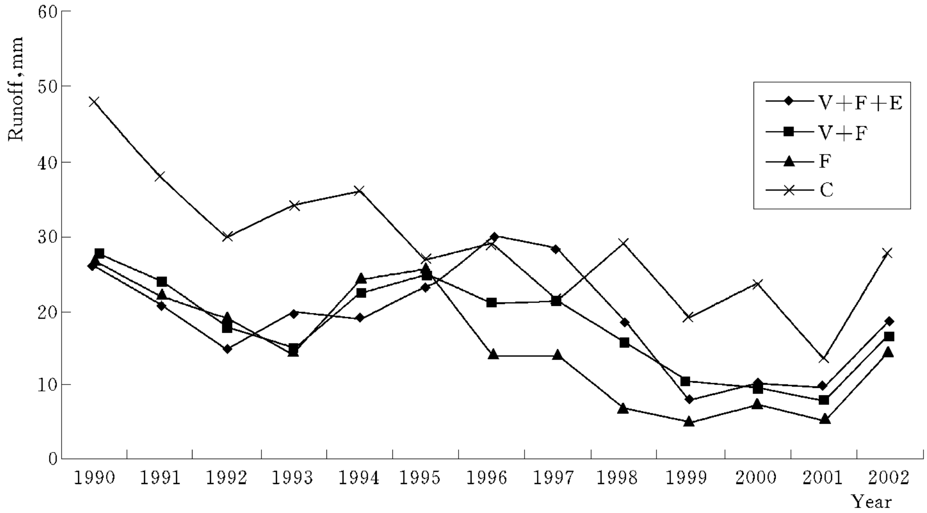

Fig. 5 Variation in runoff over different years in treated and untreated catchments

(V+F+E indicates planted vegetation, fencing and engineering structures; V+F indicates planted vegetation and fencing; F indicates fencing alone and C indicates untreated catchment)

collect runoff from each nook and corner of the catchment and pass it on to the 2nd, 3rd and ultimately the final-order gullies and constitute the fundamental energy cells of the drainage system (Strahler, 1964). The first order gullies constituting 60% – 80% of total gullies could have played a significant role in causing runoff and soil loss despite the catchments being fenced and vegetated (Daniels et al., 2008).

The soil loss in fenced and vegetated catchment Ⅱ was not statistically different from that in catchment Ⅲ (with fencing alone), which shows that fencing alone could ensure sufficient natural vegetation to get established and be effective in checking soil loss from the catchments. The menace of overgrazing and human interference in the catchments is the most important factor responsible for accelerated soil erosion in the region (Kukal et al., 2006).

The lowest soil loss in catchment Ⅰ during 1989 – 1995 could be simply due to the fact that the gully plugging structures filtered and retained the sediments carried by the runoff water on the upstream side. The periodic deposition of sediments resulted in complete siltation on the upstream side of the structures up to the crest level (Fig. 1). The runoff water then starts flowing over the crest of the structures carrying the deposited sediments along with it. The runoff water, which now falls over a greater height, becomes more erosive and causes soil erosion on the downstream end of the gully plugging structures. This runoff otherwise would have flown smoothly (being less erosive) in the absence of any gully plugging structure. The soil erosion caused by the runoff falling over the structures is reflected from the depressions formed at the downstream end of almost all the structures installed in catchment Ⅰ. This process could have resulted in increased soil loss from the catchment treated with gully plugging structures during the period 1996 – 2003. Kukal et al. (2006) observed that the siltation of the installed structures in the region is a common feature as these structures are generally installed in the highest-order gullies. The runoff build up in the gully network takes place as usual through the lower-order gullies, with sufficient sediments in it as is reflected from the amount of runoff which was not affected by treatments to the catchments. The gully plugging structures thus installed in the highest order gully are not effective in checking the amount of runoff generated in catchment Ⅰ, particularly during the later years (1996 – 2003) of their installation (Fig. 1) as these structures become silted up to the crest height (Fig. 2) and were not able to intercept runoff any more thereafter.

4 Conclusions

The long-term information on runoff and soil loss in catchments treated with soil conservation structures, especially gully plugging in the highest order gullies showed that the planted vegetation in Shiwaliks was not as effective vis-à-vis fencing, as the fencing itself has the potential to generate the natural vegetation. The gully plugging structures installed in the highest order gullies are effective only during the initial years and later on these cause greater soil erosion. These structures being installed in the highest-ordered gullies get silted up within a few years due to unabated runoff and soil loss in the gully network. It results in increased erosivity of the runoff water resulting in greater mass movement of soil from the catchments irrespective of the vegetation status. It is, therefore, important that to reduce the runoff volume and its sediment load, the lowest-order gullies be plugged with structures instead of the highest-order gullies.

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