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# Extreme rainfalls in Eastern Himalaya and southern slope of Meghalaya Plateau and their geomorphologic impacts

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## Abstract

This paper presents the detailed rainfall characteristics of 3 key areas located in the eastern monsoon India: the margin of Darjeeling Himalaya, the margin of Bhutanese Himalaya and the Cherrapunji region at the southern slope of Meghalaya Upland. All these areas are sensitive to changes but differ in annual rainfall totals (2000–4000 mm, 4000–6000 m and 6000–23,000 mm respectively) and in the frequency of extreme rainfalls. Therefore the response of geomorphic processes is different, also due to various human impact. In the Darjeeling Himalaya the thresholds may be passed 2–3 times in one century and the system may return to the former equilibrium. At the margin of western Bhutanese Himalaya in 1990s, the clustering of three events caused an acceleration in the transformation and formation of a new trend of evolution, especially in the piedmont zone. In the Cherrapunji of Meghalaya region in the natural conditions the effects of dozens of extreme rainfalls every year were checked by the dense vegetation cover. After deforestation and extensive land use the fertile soil was removed and either the exposed bedrock or armoured debris top layer protect the surface against degradation and facilitate only rapid overland flow. A new “sterile” system has been formed.

*Keywords:* Eastern India; Frequency of extreme rainfalls; Relaxation; Clustering; New equilibrium

## 1. Introduction

The aim of this paper is to present a detailed characterisation of rainfall in the monsoon Eastern India exemplified by three regions located at the mountain margins sensitive to changes, as well as a presentation of various tendencies in relief transformation connected with different frequency and totals of extreme rainfalls. In two of these areas, the Darjeeling Himalaya and Cherrapunji region (Fig. 1) detailed observations were carried out on the geomorphic effects of extreme rainfalls and also in particular sites the measurements of parameters of water circulation and geomorphic processes (Starkel, 1972a,b; Froehlich and Starkel, 1987; Starkel, 1989; Froehlich et al., 1990; Starkel and Basu, 2000; Starkel et al., 2002; Starkel and Singh, 2004). In the third one, at the margin of Bhutanese Himalaya, preliminary records were collected and research is continuing (Starkel and Sarkar, 2002).

These three selected regions (Table 1) have two common features: (a) they are located in the zone of monsoonal circulation with seasonal summer heavy rains and (b) they are located at the margin of uplifting mountains or a horst, separated by active tectonic lines from subsiding forelands. At the same time these areas have different substratum lithology and tectonics but the rocks are

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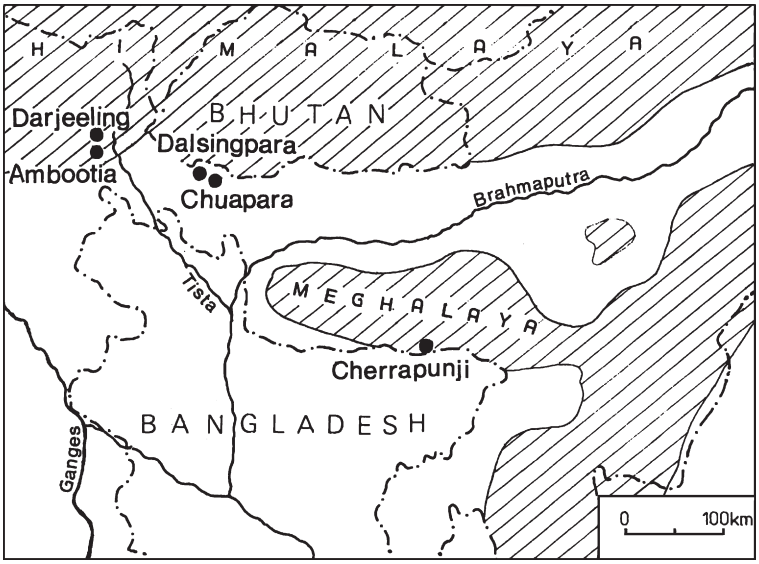

Fig. 1. Location of three research areas in Eastern India, mentioned in the text. The records are from 5 meteorological or rainfall stations: 1. Darjeeling, 2. Ambootia, 3. Dalsingpara, 4. Chuapara, 5. Cherrapunji.

generally of similar medium resistance. They are also characterised by different types and extents of human impact reflected in land use. The three regions also differ in the totals of annual rainfalls manifested in various frequency of extreme rainfalls (Fig. 2). Of the three areas the lowest annual rainfalls are registered in the marginal part of Darjeeling Himalaya to the west of the Tista river valley; they fluctuate between 2000 and 4000 mm, locally in exceptional years passing 5000 mm. The two-year recurrence interval in Darjeeling is calculated at 2735 mm and the 50-year recurrence interval at 4178 mm (Table 2). The second region occupies the western part of the Bhutanese Himalaya margin (between Chel and Jainti rivers) and their foreland. The annual rainfall totals fluctuate here between 4000 and 6000 mm (during some years reaching 7000–8000 mm; the 50-year rainfall at Chuapara reaches 7150 mm, Table 1). Finally the southern slope of the Meghalaya Plateau near Cherrapunji records 6300–23,700 mm of rainfall (mean annual rainfall 11,100 mm, a 50-year rainfall reaches 18,065 mm).

In this paper we examine how the various frequency and totals of extreme rainfalls influence the different rates and directions of the present-day transformation of relief, developing the thesis outlined in previous papers (Starkel, 2004a).

## 2. Methods and materials

The basic material for the comparison of three regions consists of rainfall records for selected stations. We tried

Table 1
Characteristics of environmental parameters of 3 selected uplifting highlands regions in NE-India

| Element | Darjeeling Himalaya | W part of Bhutanese Himalaya | Cherrapunji spur (S-Meghalaya) |
|---|---|---|---|
| Relief energy | Young relief 500–1500 m | Young relief 500–1500 m | Flat plateau 50–100 m dissected by canyons (to 1000 m deep) |
| Slope gradient | 15–45° | 15–45° | 5–15° (steep in canyons) |
| Lithology | Metamorphic rocks | Metamorphic rocks | Sandstones, siltstones |
| Tectonics | Folded, overthrusted | Folded, overthrusted | Horizontal bedding |
| Regolith–soils | Silty–sandy | Silty–sandy | Remains of lateritic cover, armoured surface |
| River channels in mountains | Incised or aggraded | Incised or aggraded | wide, rocky with waterfalls |
| River channels at foreland | Braided, aggraded | Braided, aggraded | – |
| Annual rainfall | 2000–4000 mm | 4000–6000 mm | 10,000–15,000 mm |
| Extreme rainfall, reccur.interval of 500–1000 mm in 2–3 days | 20–50 years | 2–5 years | Every year (1 to several events) |
| Dominant runoff | Subsurface runoff | Subsurface runoff | Overland flow |
| Vegetation/land use | 60–80% deforested (mainly tea gardens) | 20–40% deforested | >95% deforested (on the plateau) |

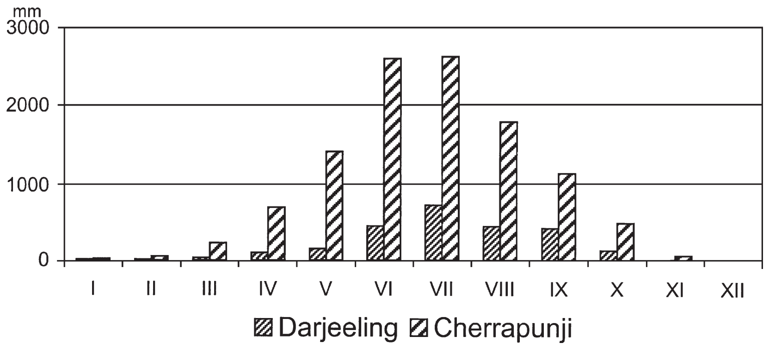

Fig. 2. The annual course of mean monthly rainfalls in Darjeeling (1901–1986) and Cherrapunji (1903–2001).

to select the same time units. It was not an easy task because there were several gaps in the records. For the Darjeeling Himalaya we got annual and monthly rainfall totals from Darjeeling station located in the hills (30 km from the margin) for the period 1868–1986; and from the Ambootia Tea Estate near the edge of mountains only for 1964–2001. For the margin of the Bhutanese Himalaya we gathered the longest annual records for the period 1926–2001 at the Chuapara TE and the Dalsingpara TE located in the plains 5–6 km from the mountain margin. We found that the rainfall totals were similar there to those at tea gardens located at the edge of mountains. The Cherrapunji meteorological station has continuous data from middle of the 19th century (Fig. 1).

For a more detailed characterisation of precipitation previously published data on totals of one-day and three-day extreme rainfalls in Darjeeling were used for the period 1949–1986 (Froehlich et al., 1990). In the case of the Bhutanese section and Cherrapunji we had for disposal rainfall records of 9 years between 1993 and 2001 (Fig. 3, Table 3). Therefore only for that period in all three regions the number of days with rainfall above 100 mm (and following hundreds of mm 200, 300 etc.), their mean annual and frequency of extremes as well as the number of successive days with totals above 100 mm were calculated.

To identify the extremes we took into consideration the rainfall values recognised in Darjeeling Himalaya as the threshold in the formation of earth and debris flows (Froehlich and Starkel, 1987). These features appear at the local scale after one-day rains above 200 mm and two–three days of continuous rains above 300–400 mm. At the regional scale these features are very frequent when the daily rainfall exceeds 300 mm combined with continuous two–three-day rains above 500–600 mm (Froehlich et al., 1990; Starkel and Basu, 2000; Starkel, 2004b).

For a better tracing of the course of summer rainfalls we selected the daily records for June–September 1998 at three stations: Ambootia, Dalsingpara and Cherrapunji (Fig. 4). That year was characterised in all regions by some extreme events. Extreme rainfalls were exemplified by hourly rain intensities for continuous rain in October 1968 at Nagri Farm near Darjeeling and long-lasting rain in June 2002 at Cherrapunji (Fig. 6).

The calculations on the intensity of geomorphic processes are based on data collected during previous expeditions mainly in the Darjeeling and Cherrapunji regions (Starkel and Basu, 2000; Starkel and Singh, 2004) and published. Those data characterise the infiltration parameters, the rate of denudation and the rate of aggradation.

## 3. Darjeeling Himalaya

The marginal part of low Himalaya to the west of Tista valley, rising from 200 to 2500 m a.s.l. is composed mainly of gneisses and other metamorphic rocks (Table 1). This young mountain landscape is characterised by steep slopes (20–40°) and narrow deep valleys. The forest cover occupies 38% of the total area, tea gardens 30–40%

Table 2

Probability of annual rainfall totals in mm calculated for three stations: Darjeeling (1968–1986), Chuapara (1926–2001) and Cherrapunji (1903–2001)

| | 90% | 50% | 20% | 10% | 5% | 2% | 1% | 0.50% | 0.20% |
|---|---|---|---|---|---|---|---|---|---|
| Darjeeling | 2272 | 2735 | 3212 | 3523 | 3813 | 4178 | 4443 | 4703 | 5038 |
| Chuapara | 3480 | 4434 | 5355 | 5940 | 6479 | 7149 | 7634 | 8105 | 8711 |
| Cherrapunji | 8086 | 10,706 | 13,212 | 14,797 | 16,256 | 18,065 | 19,372 | 20,640 | 22,270 |

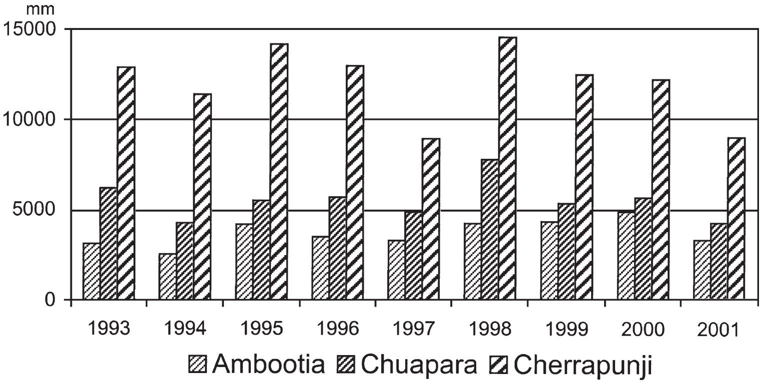

Fig. 3. Annual rainfalls in Ambootia, Chuapara and Cherrapunji from 1993 to 2001.

in general (locally to 80%). The sandy–silty regolith usually does not exceed 1–2 m depth and is very permeable (infiltration rate of 100 mm is between 3 and 25 min (Froehlich et al., 1990). The annual precipitation fluctuates between 2000 and 4000 mm. Every year brings one or two days with rain above 100 mm and once in 10 years above 300 mm (Fig. 5, Table 4). Two–three successive days with rainfall of heavy downpour character above 300–400 mm appear once in 5–10 years causing the formation of earth flows or debris flows at a local scale (Starkel and Basu, 2000; Starkel, 2004b).

Extreme continuous rain extending over a regional scale (at least several thousands km$^2$) is recorded once in 30–50 years and may pass even 1000 mm in 3 days (Starkel 1972a; Froehlich and Starkel, 1987). In 1968 a simultaneous passing of threshold values both by slope and channel processes was caused by the superposition of a heavy downpour (150–200 mm in 4 h) in the final stage (Fig. 6). This was reflected in the flowing or sliding of total soil covers from about 20–25% of slope surfaces under tea gardens but only 1–2% under forest (Starkel, 1972a). Simultaneously in the deforested catchments debris flows caused the rise of channel floors up to 5–10 m and in other reaches downcutting up to 5 m. Similar connectivity of simultaneous response of slope and channel systems has been recorded in New Zealand by Selby (1974) and Crozier (1989) and in England by Harvey (2001). After several years, due to the succession of vegetation, a total relaxation followed with gradual filling of shallow depressions while in aggraded valley floors incision occurred, reconstructing the channels towards their previous conditions. The effects of downcutting depended on the river energy and the size of the deposited debris. The debris flows composed of coarse blocks persisted in the valley floors (Fig. 7). In the largest rocky landslide about 200 m deep at the Amboootia Tea Estate the symptoms of stabilization were observed much later, after 20–30 years (Froehlich et al., 1991; Starkel and Basu, 2000).

## 4. Margin of the Bhutanese Himalaya

Similar to the Darjeeling region west of Tista valley, the margin of the western part of Bhutanese Himalaya rises to about 2000 mm above the piedmont fans. This margin is built mainly of metamorphic rocks but with a distinct calcareous component. The mountain front is dissected by rivers of different sizes depending on river catchment area. The tributaries of the Brahmaputra are characterised by very sharp rises and falls of discharge even several times during one rainy season (Goswami, 1998). Their braided channels undergo frequent avulsions over the extensive alluvial fans (Starkel and Sarkar, 2002). The mountain margin is generally less deforested than the Darjeeling Himalaya but in some valleys there is extensive mining activity.

Table 3
Annual rainfalls between 1993–2001 in mm at three representative stations

| | Amboootia | Chuapara | Cherrapunji |
|---|---|---|---|
| 1993 | 3120 | 6165 | 12,882 |
| 1994 | 2535 | 4246 | 11,402 |
| 1995 | 4176 | 5492 | 14,182 |
| 1996 | 3489 | 5671 | 12,971 |
| 1997 | 3300 | 4848 | 8931 |
| 1998 | 4233 | 7787 | 14,587 |
| 1999 | 4335 | 5355 | 12,503 |
| 2000 | 4878 | 5671 | 12,255 |
| 2001 | 3352 | 4282 | 9037 |
| Mean | 3713 | 5502 | 12,083 |

The rainfall records are collected from the tea gardens located mainly on the plains several kilometres away from the mountain front. The total annual rainfall fluctuates between 4000 and 6000 mm but during some years it rises to about 7000–8000 mm (Tables 2 and 3). At the mountain front the rainfall totals are probably at least 1000 mm higher (comparing with the margin of Darjeeling Himalaya). In Chuapara in 1993–2001 the mean annual number of days with precipitation >100 mm reached 7–8 days and every third year a daily rainfall above >300 mm is recorded (Fig. 4, Table 4). But four series of consecutive days during which the total rainfall reached 600–900 mm were also registered. Between 19 and 21 July 1993, 840 mm it was recorded. At that time other stations in this region reported even 1400–1600 mm in four days with the highest daily rainfall of about 800 mm (Figs. 8 and 9). The clustering of extreme rainfalls and formative events in three years (1993, 1996 and 1998 — cf. Fig. 8) decreased the resilience of the system (Campbell and Ericksen, 1990; Brunsden, 2001) and made impossible the return to the former stability and in contrast caused the extension of smaller landslides, deepening of valleys by debris flows, widening of braided channels and finally the building up of alluvial fans, processes described as the propagation of instability by Brunsden (2001). The mean annual rise of channel beds up to 3 cm was registered on several alluvial fans. The comparison of two satellite images after the floods in 1996 and in 1998 shows a distinct extension of areas of fresh aggradation by about 30–50% (Fig. 10). Many smaller landslides and debris flow were unified after several heavy rains of 1998, braided channels of Pagli and Titi rivers expanded. From this analysis we concluded the significant role of clustering of extreme events in the acceleration of transformation of relief at the margin of the Bhutanese Himalaya (Starkel and Sarkar,

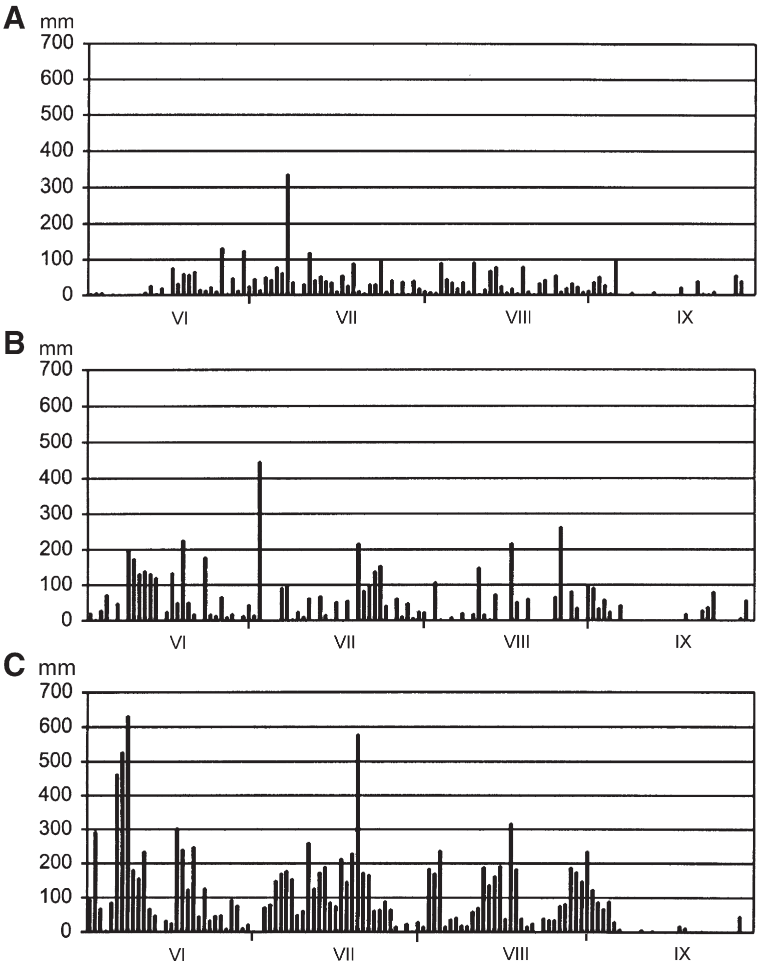

Fig. 4. Daily rainfalls during four summer months (VI–IX) in 1998. A — Ambootia, B — Dalsingpara, C — Cherrapunji.

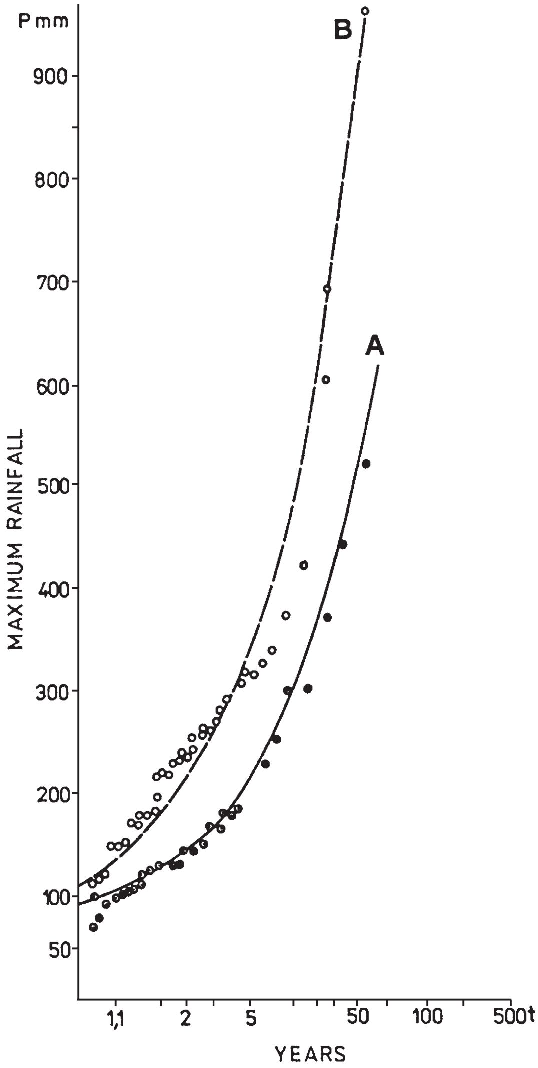

Fig. 5. Recurrence intervals of highest rainfalls during 1-day and 3 consecutive days in Darjeeling (1949–1986) (after Froehlich et al., 1990).

2002), which had not been previously recorded at the margin of Darjeeling Himalaya. Still it is not clear, how far these clusters of extreme events are a longlasting feature of this region or whether this change in frequency is connected only with the last decades.

## 5. The Meghalaya Plateau near Cherrapunji

Cherrapunji Town is located at the southern slope of the Meghalaya horst, which rises to about 1800 m a.s.l. at the spur, surrounded by canyons up to 1000 m deep. Its surface part is composed of thick horizontally bedded sandstones and siltstones passing south into limestone facies (Table 1). The deforestation of the plateau and shifting cultivation in the past and the continuous exploitation of coal beds has left either exposed bedrock or the remains of lateritic cover, armoured by a surface layer of coarse gravely residual debris with very sparse grass cover (Ramakrishnan, 2001; Starkel and Singh, 2004). The underlying weathered regolith is characterised by very low infiltration rates of the order of 100 mm in 3–4 h.

The recorded annual rainfall in Cherrapunji fluctuates between 6283 and 23,663 mm (Soja, in Starkel and Singh, 2004; Prokop and Walanus, 2003). During four summer months (VI–IX) in the period 1993–2001, 28 days with rainfall above 100 mm and five days with rainfall above 300 mm were registered annually. In 1995 the highest daily rain of 1563 mm was recorded. Likewise clusters of successive several days with rainfall above 100 mm every day with totals passing 1000 mm are very frequent (Fig. 6). Among the extremes are a four-day rainfall of 3017 mm and a six-day rainfall of 2193 mm (Fig. 9). Typical for Cherrapunji are also heavy downpours during the spring months of almost every year; their intensity passes 1 mm $h^{-1}$. The mean annual value of such premonsoon heavy rains reaches 7.7 days (above 100 mm) and 1.6 days (above 300 mm). Jointly in Cherrapunji the mean annual number of days >100 mm is 37.3 days and >300 mm — 6.6 days (Table 4).

The truncated soil and the armoured surface layer 10–30 cm thick on top are the products of such high frequency extreme rainfalls. This resistant layer protects the remains of regolith against degradation although the bare rocky fragments accelerate rapid overland flow on the slopes. The measurements of $^{137}$Cs content in soil profiles made by W. Froehlich (Froehlich, 2004) helped to calculate the degradation rate, which is of the order of 0.21 kg $m^{-2}$ $year^{-1}$. The fluctuations of water level in the

Table 4
Number and frequency of extreme rainfalls in 3 regions

| Station | Period | Number of days | | Mean annual | |
|---|---|---|---|---|---|
| | | >100 mm/day | >300 mm/day | >100 mm/day | >300 mm/day |
| Darjeeling | 1964–1985 | 24 | 2 | 1.1 | 0.1 |
| Dalsingapara | Season VI–IX 1993–2001 | 69 | 3 | 7.7 | 0.3 |
| Cherrapunji | Season VI–IX 1993–2001 | 255 | 45 | 28.3 | 5.0 |
| Cherrapunji | Beside season VI–IX 1993–2001 | 81 | 14 | 7.7 | 1.6 |
| Cherrapunji | Total 1993–2001 | 336 | 59 | 37.3 | 6.6 |

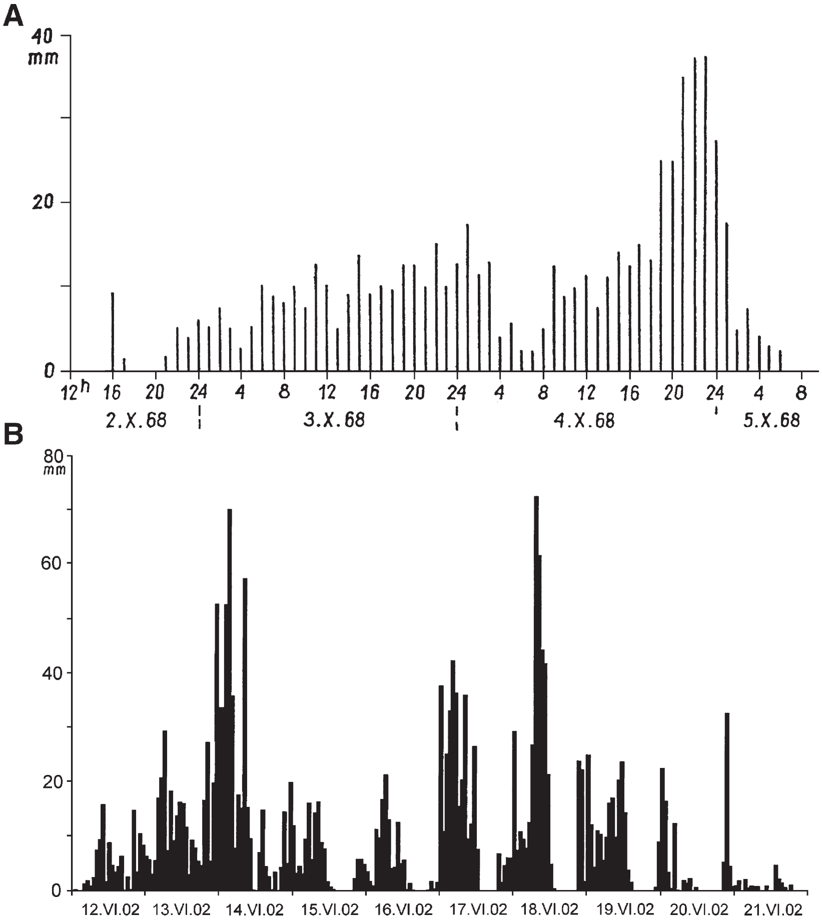

Fig. 6. Rainfall intensity per hour during continuous rain 2–5 Oct. 1968 at Nagri Farm near Darjeeling (after Starkel, 1972a) and rainy decade 12–21 June 2002 at Cherrapunji (after Soja, in: Starkel and Singh 2004).

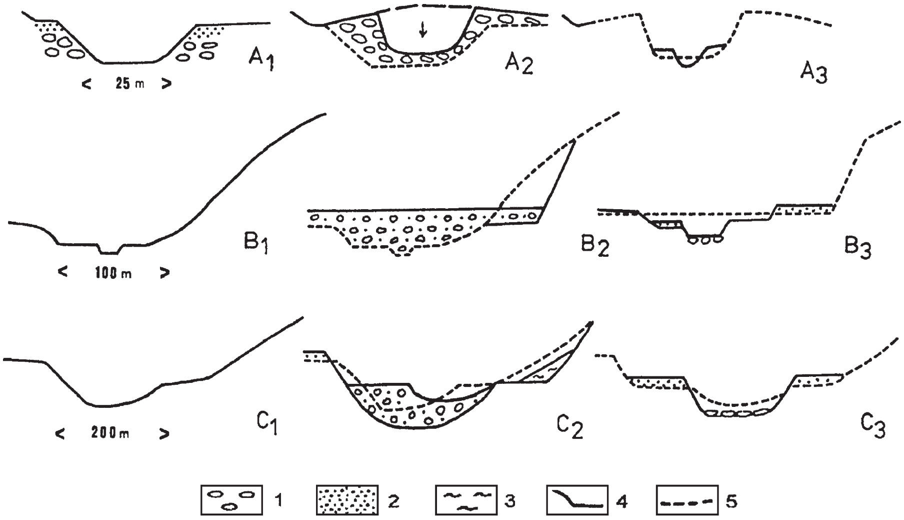

Fig. 7. Transformation of river channels of various sizes (A–C) due to rare extreme events (after Starkel, in. Starkel and Basu 2000). A — Small creek (Posam), B — mean size river (Little Rangit), C — large transfluent river (Tista); 1. before event, 2. just after event, 3. during relaxation phase. Signatures: 1. coarse debris (channel facies or debris flows), 2. fine sediments (overbank facies), 3. colluvium, 4. new cross section, 5. previous cross section.

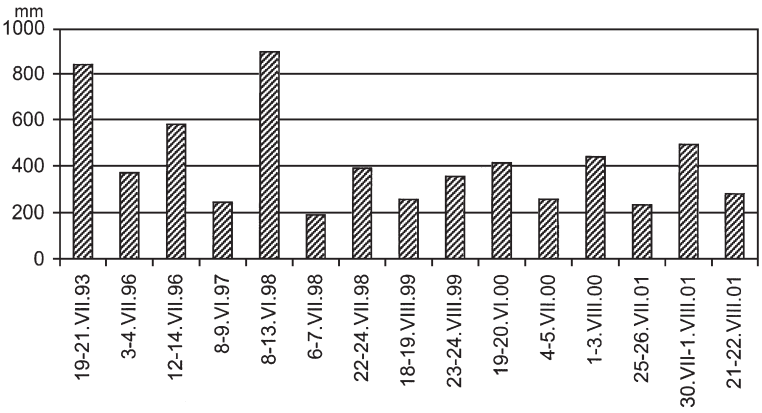

Fig. 8. Heaviest rainfalls recorded at Dalsingpara Tea Estate between 1993 and 2001. Please note the cluster of extreme events between 1993 and 1998.

small Maw-Ki-Syiem creek (22 ha catchment) indicate that during heavy rain the discharge may rise rapidly even to 50–100 $m^3$ $km^{-2}$ $s^{-1}$ of specific runoff and later also rapidly drop to the order 0.01–0.05 $m^3$ $km^{-2}$ $s^{-1}$, the values characteristic also for the dry winter season. The longterm human intervention in these globally extreme pluvial conditions has created a new dynamic in the circulation of matter, in which the new parameters of substratum (which replaced a dense vegetation cover and thick soil of the primary ecosystem) protect the surface against erosion very efficiently (Ramakrishnan, 2001). The formation of iron crusts on the bedrock in shallow channels during dry seasons protects them against erosion, which in contrast is concentrated in deep canyons. Waters falling down across thousands of episodic waterfalls into canyons facilitate formation of rockfalls and the removal of coarse debris of up to several meters in diameter.

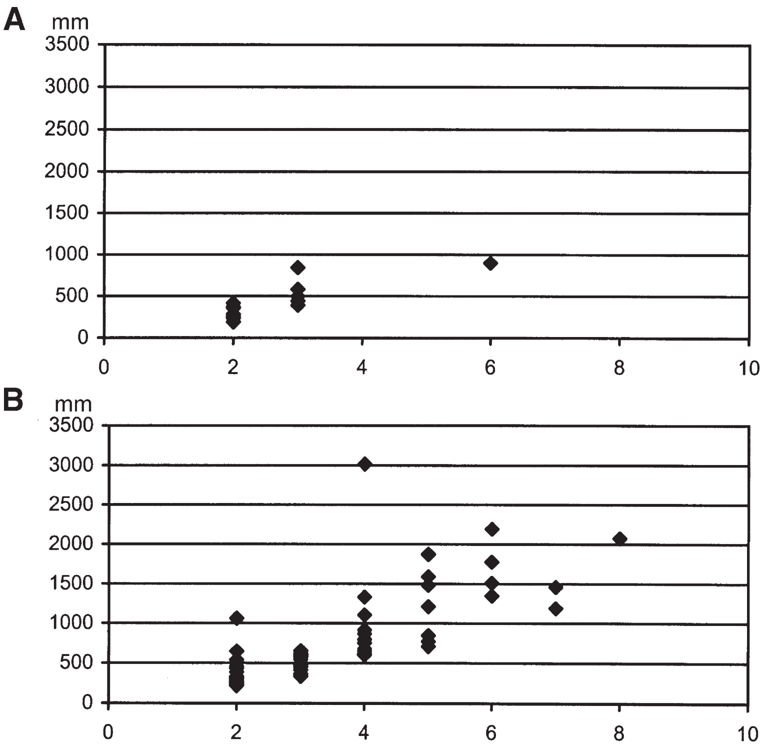

Fig. 9. Number of consecutive days, on *x*-axis, with heavy rains (above 100 mm per day) and their total rainfall registered between 1993 and 2001 at two stations: A — Dalsingpara (margin of Bhutanese Himalaya) and B — Cherrapunji.

## 6. Comparison of rainfalls and their effects in Eastern India

The characteristics of heavy rainfall and high-magnitude floods in various parts of monsoon India show that geomorphologically significant extreme events occur on an interval of decades (Gupta, 1998). This is also the case in the Darjeeling Himalaya (Starkel, 1972a). The comparison of rainfalls in the three regions of the mountain margins in Eastern India has shown not only the differences in rainfall totals and their annual probability (Table 2) but also great fluctuations from year to year, suggesting various frequencies of extreme events (Table 4). It may be well illustrated by the rainy season of relatively the wet year 1998 (Fig. 4) when Ambootia registered 6 days with rainfall $>100$ mm, Dalsingpara 17 days and Cherrapunji 40 days (among them 6 days $>300$ mm). The selected examples of events and comparison of selected years show substantial differences between the three regions. In the Darjeeling region rainfalls passing the regional scale threshold values are recorded 2–3 times per century and those passing the local scale threshold values occur once in about 10 years. At the margin of the western part of Bhutanese Himalaya in the last decade (Fig. 9) we observe three or even four such continuous rains. The reaction of slope and channel systems must be different (Fig. 11). During periods of low extreme-rain frequency the dynamic system tends to return to the previous equilibrium, mainly by restoration of the vegetation cover and soil. But as a result of 19th century deforestation in this tectonically active Darjeeling Himalaya we observe the continuous tendency to aggradation on the valley floors, moving upstream (Starkel, 1989). A similar tendency has been recorded in the Nepalese Himalaya (Brunsden et al., 1981).

Fig. 10. Comparison of two satellite images from margin of Bhutanese Himalaya in the catchment of Pagli and Titi rivers: December 1996 and November 1998. 1. Landslides, debris flow and braided channels registered in 1996, 2. extension after 1998 events (after Starkel and Sarkar, 2002).

Conversely, the repetition of formative events every two or three years (e.g. clustering) not only preserves the trend towards dissection and lowering of the mountain front and aggradational growth of the piedmont of the Bhutanese Himalaya, but also causes their acceleration due to the superposition of secondary events, during which the thresholds for initiation of rapid processes in this unstable slope and channel system may be lowered (Brunsden, 2001; Starkel and Sarkar, 2002). The extension of erosional forms on the slopes and colluvial–alluvial forms in the depressions leads to propagation of instability in the whole area (Thomas, 2001).

In the slope–channel systems of the Cherrapunji region the dense jungle in the natural environment which existed before deforestation was able to reduce the geomorphic processes even in conditions of daily rainfalls of several hundred mm and of a high frequency of heavy rains every year. The protective role of vegetation may still be observed on the steep forested sides of canyons (Starkel and Singh, 2004; Prokop, 2005). Deforestation and various kinds of exploitation of mineral resources have led to the removal of the primary soil cover and the development of a new resistant system, facilitating accelerated runoff without distinct erosional changes (Starkel and Singh, 2004).

Summarising, in the generally uniform humid monsoon climate, at the mountain margins to a large extent deforested by man, the frequency of events exceeding the thresholds of processes relating to transformation of the slopes and valley floors is different depending on regional environmental conditions. Nevertheless it is difficult to separate natural causes from human-induced

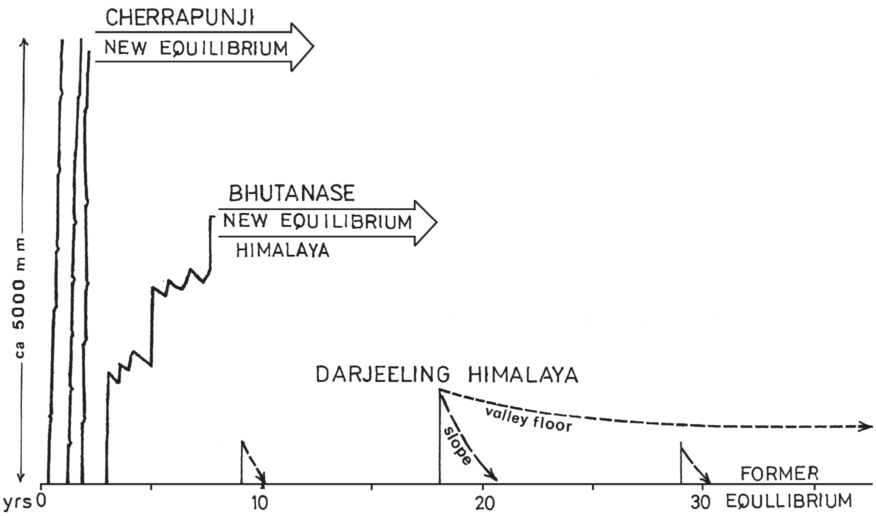

Fig. 11. Model of frequency of extreme events and trends to formation of new equilibrium of geomorphic systems in three investigated regions.

changes (Usher, 2001). Depending on the magnitude and frequency of events either landscape rejuvenation may be delayed by a trend towards relaxation and to return to a previous equilibrium condition (as in the Darjeeling Himalaya), or the frequent formative events (Brunsden, 1993) lead to the gradual establishment of a new dynamic equilibrium, which accelerates transformation (Bhutanese Himalaya foreland) and even initiates a new trend of landscape evolution (Cherrapunji region — Fig. 11).

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