POLSKA AKADEMIA NAUK
INSTYTUT GEOGRAFII I PRZESTRZENNEGO ZAGOSPODAROWANIA
IM. STANISŁAWA LESZCZYCKIEGO

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WSPÓŁCZESNA EWOLUCJA PIEDMONTU SIKKIMSKO-BHUTAŃSKICH HIMALAJÓW

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Leszek Starkel, Subir Sarkar, Roman Soja, Paweł Prokop

PRESENT-DAY EVOLUTION OF THE SIKKIMESE-BHUTANESE HIMALAYAN PIEDMONT

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RECENZENCI TOMU:
Piotr Migoń, Zbigniew Zwoliński

ADRES REDAKCJI:

Dział Wydawnictw IGiPZ PAN
ul. Twarda 51/55, 00–818 Warszawa
e-mail: e.janko@twarda.pan.pl

Opracowanie redakcyjne i techniczne: Ewa Jankowska
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e-mail: drukarnia@klimiuk.com.pl

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1. INTRODUCTION

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1.1. THE HIMALAYAN MOUNTAIN FRONT AND SUBMONTANE FOREDEEP

The mountain ranges of the Alpine system are accompanied by alluvial plains in their forelands. However, the character of and relationships between highland and piedmont may differ in relation to tectonic activity (Gansser 1964; Starkel 1989, 2005).

The mountain front is either a low, relatively gentle transition to the foredeep, or else very sharp and steep. In the case of the Himalaya we observe continuous tectonic activities and expansion of the mountain system to the south with via a system of faults and overthrusts (Gansser 1964; Valdiya 1998). The Lesser Himalaya were overthrust over the Neogene – early Quaternary molasse of the Siwaliks (along the Main Boundary Thrust – MBT) and again the Siwalik belt began to be overthrust from 1.6 million years BP over the alluvial plain (Himalayan Frontal Thrust – HFT). This process is continuing at various rates and is complex in character. The Siwalik zone is usually 20 –50 km wide, with a maximum width of 100 km in the west while it is reduced in or even totally absent in the Sikkimese-Bhutanese part where it is buried by metamorphic rocks of the Lesser Himalaya (Fig. 1).

The present-day foredeep is 200–300 km wide in the western part of the Ganga catchment and only 100–150 km wide along the Brahmaputra. It is filled by Quaternary alluvial sediments with a thickness of 5–6 km near the HFT. The surface form is complex and inclined towards the south, and is built of boulders and gravels in the 7–15 km wide marginal part (called the Bhabar zone), sand and gravels in the middle part (called the Terai – 40 km wide) and farther downstream of sandy loams and even clays. The channel pattern and gradient mostly coincide with lithology and turn from braided to meandering (Jain, Sinha 2003; Starkel 2004).

The hydrological regime and sediment load pattern in the Ganga-Brahmaputra plain is closely related with type of river system, be this mountain-fed, foothills-fed or plain-fed (Jain, Sinha 2003). The first group represented by the Ganga, Gandak, Kosi and Tista have their headwaters in the High Himalaya and are fed partly by meltwater. These rivers form mega-fans with frequent avulsions (Singh 1992), and keep their braided pattern far down-

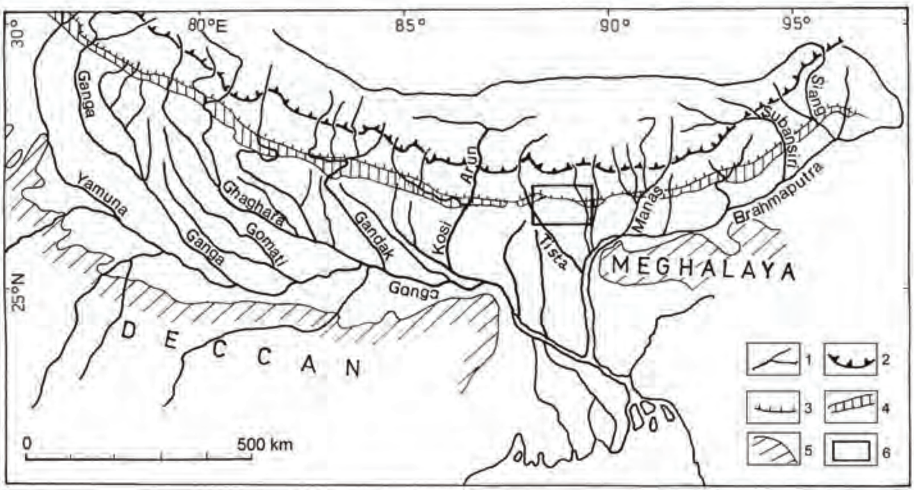

Fig. 1. The Himalayan range and its foredeep
1 – rivers, 2 – Central Himalayan Thrust, 3 – Main Boundary Thrust, 4 – the Siwaliks, 5 – margin of Deccan and Meghalaya Plateaus, 6 – research area

Himalaje i rów przedgórski
1 – rzeki, 2 – nasunięcie centralnych Himalajów, 3 – główne nasunięcie brzeżne, 4 – strefa Siwalików, 5 – brzeg wyżyn Dekanu i Meghalaya, 6 – obszar badań

stream. The foothills-fed rivers start in the marginal part of the Himalaya (mainly the Siwalik zone) where rainfall is higher, building a system of small fans (Bhabar zone) and changing channels from braided to meandering within the wide inter-fan zones (cf. Shukla, Bora 2003). The plain-fed rivers are also located in the same zone, starting as meandering systems and being supplied by groundwater and summer rains (Jain, Sinha 2003).

The channel pattern in the Ganga-Brahmaputra plain varies greatly in connection, not only with the hydrology, but also with young tectonic movements.

The western part of the Ganga basin is characterised by a system of parallel NW–SE directed streams, which push the Ganga to the southern margin of the foredeep. In the eastern part and on the Ganga-Brahmaputra interfluves the river pattern is controlled by mega-fans of the Kosi and Tista. The E-W directed River Brahmaputra collects waters from a great number of straight N–S tributaries from the Himalaya. Neotectonic uplift or subsidence is expressed not only in river reaches following fault lines, but also in a differentiated tendency for downcutting or aggradation to take place. The river channels of the Western Ganga Plain are incised 10–15 m in the late Pleistocene terrace while aggradation is dominant to the east (Singh 1992; Jain, Sinha 2003). The repeated nivelations plus dating of terraces at the edge of the Himalaya show that the rate of uplift is reaching even 5–10 mm year^{-1} (Valdiya 1998), while some blocks in the piedmont zone built of late Quaternary sediments have later been lifted up and dissected to several dozens of meters (Guha et al. 2007). The main Himalayan overthrust is still active. Therefore, in studying present-day processes in the Himalayan piedmont, we must take into consideration, not only hydro-climatic factors and the inherited landscape, but also ongoing endogenic changes in the active orogenic system.

1.2. LOCATION OF RESEARCH AREA

The present study is concentrated in the piedmont zone of the Sikkimese-Bhutanese Himalaya, between the Tista and Jainti rivers, with both belonging to the Brahmaputra catchment (Fig. 2).

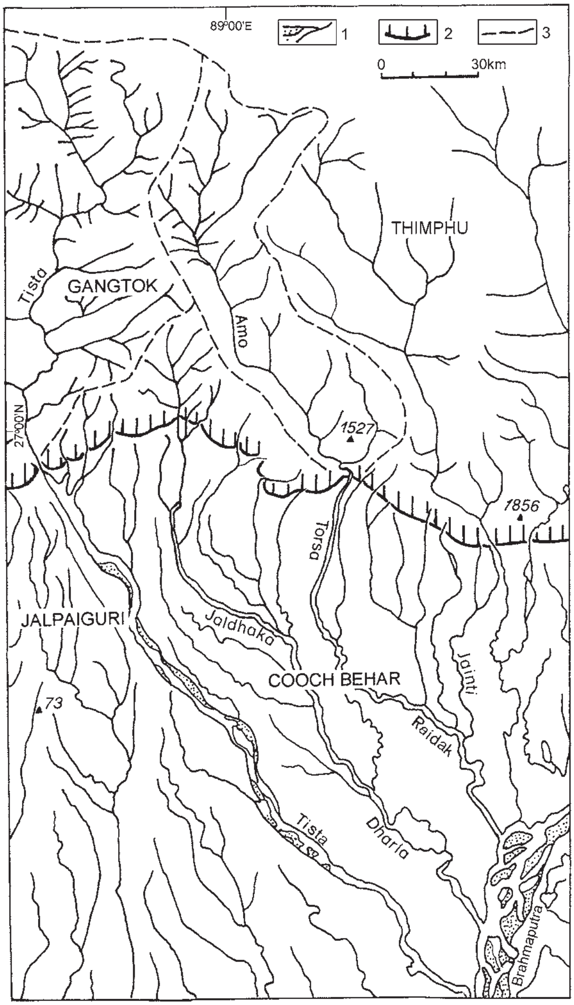

Fig. 2. Location of research area against the background of the Sikkimese-Bhutanese Himalaya and part of the Ganga-Brahmaputra Plain
1 – rivers, 2 – Himalayan front, 3 – watershed of Tista and Torsa rivers

Położenie obszaru badań na tle Sikkimsko-Bhutanskich Himalajów i części Niziny Gangesu-Brahmaputry
1 – rzeki, 2 – brzeg Himalajów, 3 – zlewnie rzek Tista i Torsa

The southern slope of the Himalayas, 120–150 km wide, consists of the High Himalaya rising in this part to 6000–7000 m a.s.l., as well as the Lesser Himalaya at 2000–4000 m a.s.l. This is the only reach of the Himalayan arc, in which the Siwalik rocks building the foothills disappear under the overthrust or form a very narrow belt (Gansser 1964).

The Ganga-Brahmaputra Plain (100–150 km wide) starts from the piedmont zone (called Duars) and descends down from 300–350 m a.s.l. to below 50 m along the Brahmaputra at the southern margin of the Plain. The neotectonic movements in the piedmont zone should also be reflected in variability of fluvial forms.

The area is located just north of the wide gap between the Deccan Plateau and the Meghalaya horst, and is open to free advection of cyclones. It therefore experiences the highest annual rainfall and most frequent heavy rains along the whole Himalayan front, values for both factors declining in both directions: to the west as well as to the east (Dhar, Nandargi 2000; Starkel, Sarkar 2002; Baillie, Norbu 2004; Soja, Starkel 2007).

1.3. AIM OF STUDY

The specific features of geology and relief and the hydroclimatic conditions of the investigated reach of the Himalayan piedmont combine to create conditions upon which to elaborate a model of the differentiated evolution of the piedmont zone of a young mountain system.

This study has thus attempted to show the role of different factors in the present-day evolution of the Sikkimese-Bhutanese Himalayan piedmont. The said factors include tectonic activity, size and location of catchment, extreme rainfalls and floods, their clustering and to some extent also human activity.

2. PRESENT STATE OF RESEARCH

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Our knowledge of the geology, relief and other elements of the present-day environment of the margin of the Sikkimese and Bhutanese Himalaya and their piedmont zone between the Tista and Jainti rivers is mainly general and fragmentary. In the monographs on the Himalayan Geology by Gansser (1964) and later by Valdiya (1998) it is stressed that the Siwalik belt is missing from part of this reach (Fig. 1). The Neogene-early Quaternary molasse beds are buried under the overthrust of the Lesser Himalaya called the Main Boundary Thrust. On its foreland is the piedmont zone called Duars, which is a complex of Quaternary terraces and fans. The western part of Duars between the Rivers Tista and Jaldhaka was surveyed by Nakata (1972, 1989), who distinguished several higher surfaces and terraces, taking into consideration their relative elevation above the river channels, soil formation as well as (to some extent) the presence of several fault lines and granulometry.

In the meantime some attention being paid to floods and aggradations on alluvial fans in Duars, these damaging railway and road bridges and tea gardens. Among these works a very valuable item is the paper by Dutt (1966), presenting the first data on annual records of river discharges and sediment loads in the Lish, Gish and Neora rivers.

In the 1980s geomorphologists from North Bengal University studied landslides and alluvial fans in the catchments of two left-bank tributaries of the Tista, called the Lish and Gish (Basu, Ghatowar 1986, 1988, 1990; Basu, Ghosh 1993). Comparing several surveys from the last century they also evaluated the role of land-use changes and their geomorphic effects. They concluded that the aggradations in the riverbeds of the Lish and Gish may even reach 0.5 m a year.

During studies on landslides and floods in the Darjeeling Himalaya, W. Froehlich sampled the sandy silts and clays of overbank deposits over the floodplain of the Tista near Jalpaiguri, using the ^{137}Cs method to state the rate of vertical accretion reaching up to 2–4 cm yr^{-1} (Froehlich, Walling 2002).

Geologists from the Geological Survey of India published a general sketch of the margin of the piedmont zone (Pawde, Saha 1982), and later surveyed the Quaternary sediments of the Himalayan foreland in West Bengal to distinguish several formations in the piedmont zone (Chattopadhyay, Das 1992; Das, Chattopadhyay 1993a, b).

The stratigraphic position was mostly described on the basis of lithology (facies), and type of overlying soil and tectonic deformations along fault lines (W–E and N–S directed). The boulder beds of the Samsing formation in the fan-head were recognised by Nakata (1972) as superimposed debris flows, while Das and Chottapadhyay (1993a) described it as the remnants of Pleistocene glacial drift, while describing the surrounding Matiali formation as a glacio-fluvial unit (following an old unrealistic concept of Kar (1968)).

At the end of the 20th century, more attention began to be paid by us to the considerable fluvial activity of various piedmont rivers east of the Tista . A preliminary concept was devised as regards the great role played by clusters of floods much higher than in Darjeeling Himalaya in the transformation of this part of the piedmont zone (Starkel, Sarkar 2002; Starkel 2004; Sarkar 2004b, Soja, Starkel 2007; Sarkar 2008).

In the meantime, Guha et al. (2007) studied the complex of high elevated terraces in the Jaldhaka river catchment. This part of the piedmont differs greatly from neighbouring in the absence of its Siwalik zone and the presence of incised river channels in the uplifted blocks of piedmont. They discovered anticlines, bending faults, back-tilting and thrusts in the uplifted young Quaternary deposits dated between 22 and 34 ka BP, which explain the presence of well expressed W–E directed fault scarps parallel to the Main Boundary Thrust (Fig. 5).

Beside these studies on the geology and relief of the piedmont zone there are several papers describing the area’s rainfall regime (Baillie, Norbu 2004; Bookhagen, Burbank 2006; Quadir et al. 2007). This is characterised by higher precipitation than in the foreland of the Darjeeling Himalaya west of the Tista, as well in the margin of the Eastern Bhutanese Himalaya (Ramaswamy 1987; Dhar, Nandargi 2000; Grujic et al. 2006). This is explained by the existence of a wide gap between the Deccan and Meghalaya Plateaus, where the first barrier exists for the humid air masses from the Bay of Bengal to the high edge of the Western Bhutanese and Eastern Sikkimese Himalaya.

3. METHODS OF ELABORATION AND AVAILABLE MATERIALS

Leszek Starkel, Paweł Prokop, Roman Soja

Materials and data for the present study have been collected from maps and satellite images, as well as published and unpublished records especially on rainfall, hydrology and land-use collected from various agencies and tea estates, as well as during field survey.

a) Topographic maps and satellite images

Two sets of Survey of India (SOI – Dehra Dun) topographic maps for the studied area in the piedmont zone between the rivers Tista and Jainti were available: from the years 1929–30 (1:63 360) and 1964–65 (1:50 000), but restricted to the territory of India. These maps have shown relief by reference to contours either of 50 or 100 feet (in 1930) or 20 meters (in 1964–65), and depict river channels with unvegetated bars.

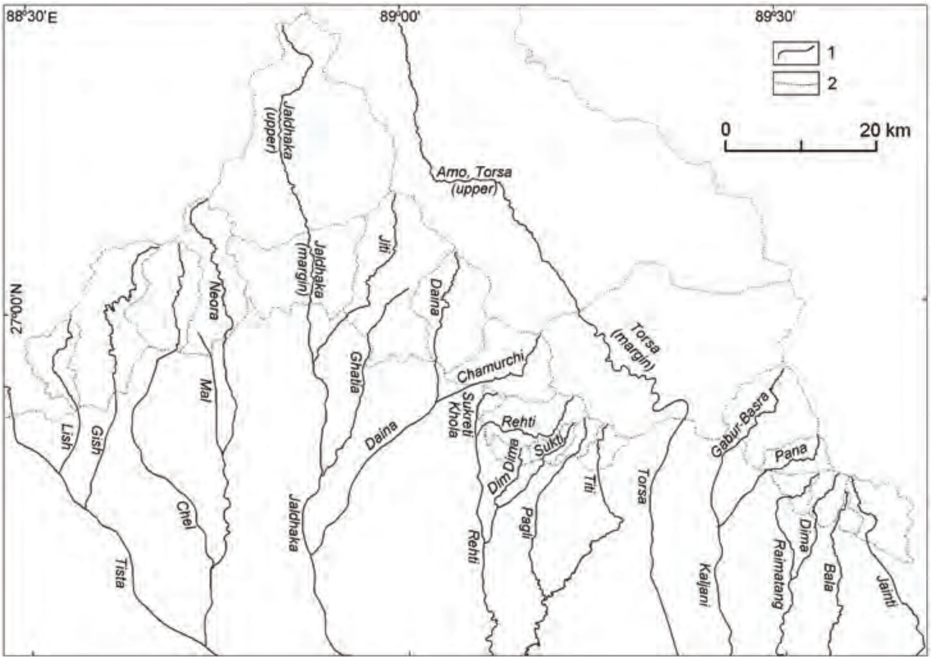

Fig. 3. Main rivers and mountain catchments in the research area (see Table 1) (elab. by P. Prokop). 1 – rivers, 2 – watersheds of mountain parts

Główne rzeki i ich górskie zlewnie w obrębie terenu badań (patrz tabela 1) (oprac. P. Prokop) 1 – rzeki, 2 – granice zlewni w górach

The first satellite images in printed form on a scale of 1:50 000 were delivered by the Geography Department of North Bengal University, and represented only selected areas. These were surveyed either in December 1996 or in November 1998. Very rarely images from these two dates were superimposed, thereby helping in the recognition of the extent of landslides and braided channels after successive extreme rainfall events (Starkel, Sarkar 2002).

The satellite images in digital form for the whole area between 1991 and 2001 have been analysed to compare changes after the several great floods occurring during this decade. There has been further supplementation in the form of satellite imagery from Google website (earth.google.com) from the year 2005.

Table 1. Catchment area and length of rivers draining mountains (elab. by P. Prokop)

Catchment	Area (km^2)	Length of river (km)
Tista	8637.8	182.0
Lish	50.6	14.9
Gish	157.1	32.6
Chel	97.3	16.3
Neora and Mal*	111.0	24.9
Jaldhaka (upper and margin)	787.5	45.4
Jaldhaka (margin)	346.8	10.7
Jiti and Ghatia*	193.4	21.2
Daina	108.7	17.6
Chamurchi	93.6	13.7
Sukrehti Khola	7.9	3.4
Rehti	65.7	17.3
Dimdima	4.8	2.8
Sukti	16.6	7.2
Pagli	15.9	5.5
Titi et al.*	21.5	6.7
Amo, Torsa (upper and margin)	3804.8	172.0
Torsa (margin)	507.9	31.9
Gabur-Basra	103.5	14.3
Pana	33.9	10.4
Raimatang	20.2	6.2
Dima	27.7	8.9
Bala	10.6	5.3
Jainti	62.5	11.7

* length only of first river

Land use/cover data were derived from multispectral satellite images for the year 2001, these being either from the Landsat 7 ETM+ (downloaded from www.landcover.org) or the IRS-1D (acquired from the National Remote Sensing Agency in Hyderabad, India). The topographical maps at the scale of

1:50 000 for the year 1964–65 were used in checking the spatial distribution of forests and tea gardens. The digital elevation model (DEM) with a spatial resolution of 90x90 m from Shuttle Radar Topographic Mission (SRTM – downloaded from the www.landcover.org) was used to quantify topography (Rabus et al. 2003). The maps were transferred into digital form and rectified together with the satellite data, to the Universal Transverse Mercator coordinate system in a GIS (ILWIS) environment (*International Institute*... 1997). On basis of satellite images compared with topographic maps it was possible to measure river length, catchment area and land use in particular river basins, especially in their mountain parts (Fig. 3, Table 1).

b) Rainfall records

Most of the records were collected from about 30 tea gardens within the territory of India. These data represent annual, monthly and daily records, mainly for the last decade of the 20th century.

In some cases rainfall data have been found to be restricted to annual totals and selected extreme events. Longer time series of rainfall data are only available from the Makrapara and Chuapara tea gardens (from 1930 to 2006). Mean annual records were also available from state meteorological stations (IMD) in the surrounding areas.

The rainfall record (both annual and daily) from Bhutanese territory close to the Indian border has been made available for the period between 1990 and 2005.

In general, the information on rainfall is rather sparse, though it was possible to reconstruct spatial rainfall patterns on an annual scale and during selected heavy rain events (cf. Figs. 10–16).

c) Hydrological records

It was difficult to obtain hydrological data for various reasons. Nevertheless, leaving aside extreme discharges of the main rivers it was possible to obtain daily records for the rivers Torsa and Jaldhaka for monsoon seasons 1999 to 2002, as supplemented by information on suspended sediment load. In addition, the Irrigation and Water Department, Jalpaiguri, made repeated channel cross-sections after extreme floods near bridges, and measured the rate of channel aggradation (mainly on the Jaldhaka and Torsa). Similar observations were made in the Lish, Gish and Chel rivers in the 1950s (Dutt 1966).

d) Land-use data

There are general maps for Jalpaiguri district representing forest areas and tea gardens. For the Bhutanese part, mainly forested, detailed information does not exist. Maps were supplemented by satellite pictures, which served to calculate the main land-use types in the piedmont zone and the hilly part of particular river catchments. Some elements of infrastructure like bridges and embankments of river channels were also taken into consideration.

Four land-use/cover classes were delimited: forests, tea gardens, active river channels (with water or dry) and other. The last class comprises agriculture (paddy rice), settlement and grasslands due to low discrimination accuracy between them on a satellite image. The boundaries between classes were digitized manually on screen, using the visual interpretation technique.

Population density was calculated on the basis of census data collected for India (*Census of India* 2001) and Bhutan (*Office of the Census*... 2006) at the district and CD blocks level.

Historical reports were used as sources of supplementary information concerning land-use changes in the 19th century (Allen et al. 1906).

e) Field survey

In the course of several field visits (each 3–4 days long) in the years 2000–2007 (also earlier since 1993 by S. Sarkar), observations and measurements were made, particularly on river channels, floodplains and surrounding gullies, landslides and debris flows, as well as in respect of the granulometry of channel and overbank facies. Repeat surveys have been carried out two to four times in the same area to assess the change in channel pattern, extension of braiding, revegetation of bars, etc. These changes were also documented by means of photography, and set against satellite imagery.

During fieldwork rainfall records and information about floods were gathered from tea-garden managers.

f) Detailed characteristics of selected valley reaches

With a view to exact and quantitative information being obtained on the changes in channel pattern, extension of braided channels, avulsions, revegetation from 1930 and especially between 1991 and 2001, 13 key areas representing valley reaches and alluvial fans at the mountain margin were identified (cf. Fig. 28).

4. GEOLOGY

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The several tectonic units of the Sikkimese-Bhutanese Himalaya overthrust towards the south (Fig. 4) are built mostly of metamorphic rocks (Darjeeling gneisses, Daling schist and quartzite, Damuda sandstone with quartzite and shale). To the east of the Jaldhaka valley the marginal part is built of Buxa series represented mostly by dolomite and shales. The Main Boundary Thrust separates them from the Siwaliks built of sandstones, conglomerates and mudstones, which are overthrust over the Quaternary foredeep along the Himalayan Frontal Thrust. In the studied part, the Siwalik belt is partly missing between the Chel and Pana Rivers where the Himalayan front retreats several kilometres north following N–S directed fault lines along the rivers Chel, Rehti, etc. (Figs. 5 and 6).

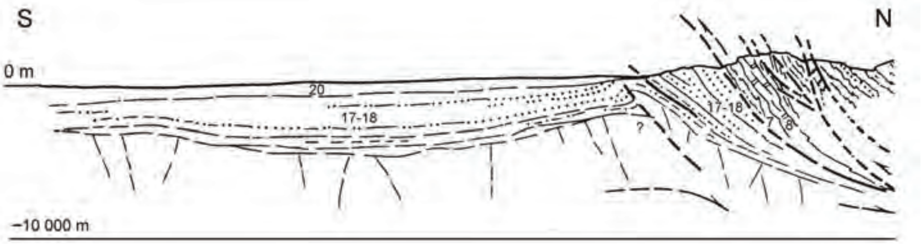


Fig. 4. Cross-section of the Himalayan margin and foredeep along the Torsa river (based on Gansser 1964)

1 – gneisses, 7–8 – Daling and Buxa Formation, 17–18 – the Siwaliks, 20 – Quaternary formations

Przekrój brzeżnej części Himalajów i rowu przedgórskiego wzdłuż doliny rzeki Torsa (wg Gansser 1964)

1 – gnejsy, 7–8 – formacje Daling i Buxa, 17–18 – strefa Siwalików, 20 – utwory czwartorzędowe

The foreland of the Himalaya is built of Quaternary sediments, which show a distinct fractional differentiation starting from boulders and gravels in the root part of piedmont fans and terraces, at a distance of 5–10 km from the margin turning to sand, and farther downstream to sandy loam and silt. This zone is composed of several distinct blocks expressed in relief forms (Fig. 7), as indicated on geological maps by Nakata (1972), Das and Chattopadhyay

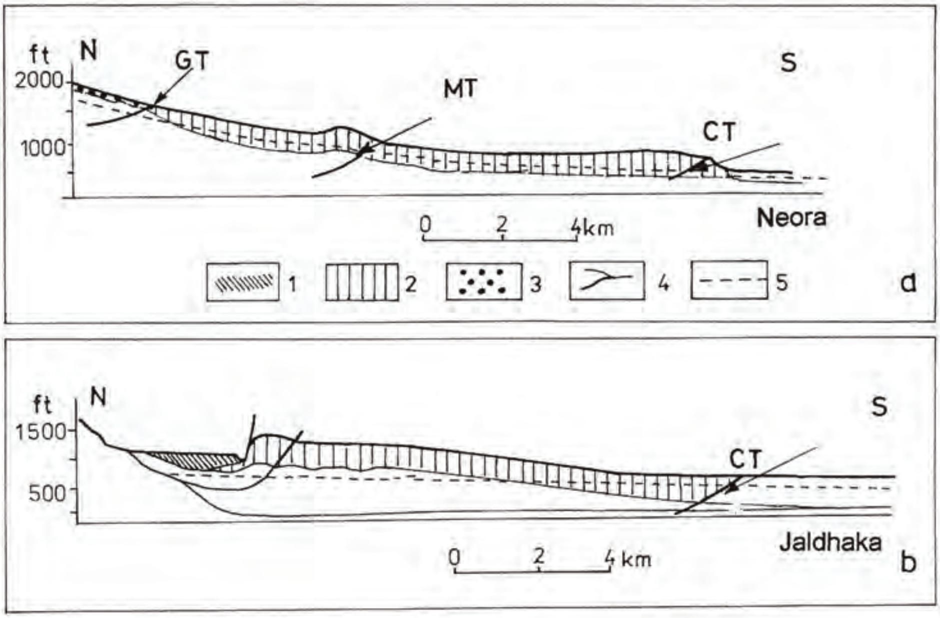


Fig. 5. Simplified longitudinal geological cross-sections:
a) between the Neora and Murti, b) between the Jaldhaka and Ghatia rivers (based on Guha et al. 2007)
1 – higher river terrace, 2 – Matiali formation (upper Pleistocene), 3 – conglomerates of the Samsing formation, 4 – thrust (GT, MT, CT), 5 – long profile of river channel
Uproszczone przekroje geologiczne:
a) między rzekami Neora i Murti, b) między rzekami Jaldhaka i Ghatia (wg Guha i in. 2007)
1 – wyższa terasa rzeczna, 2 – formacja Matiali (górny plejstocen), 3 – zlepieńce formacji Samsing, 4 – nasunięcie (GT, MT, CT), 5 – profil podłużny koryta rzeki

(1993a) and Guha et al. (2007). Therefore, the chronological classification of terraces by earlier authors based on hypsometric parameters may not be accepted. Nevertheless, above the recent floodplain we may distinguish at least two or three older gravel bodies, which differ in their depth and colour of overlying soil. Nakata (1972, 1989) and Das and Chattopadhyay (1993b) distinguished high terraces (Matiali, Rangamati) with red soils, higher river terraces with yellow soils and middle and lower river terraces with thin black soil.

Among the elevated parts thick gravel beds dated 34–22 ka BP in the Jaldhaka basin rise to 60 m above the river bed (Guha et al. 2007). The higher raised block west of the Torsa is probably of similar age or older (cf. Fig. 8).

The pattern of fault lines in the piedmont zone is very characteristic, i.e. parallel or rectangular to the mountain front. The parallel one is directed to the W–E or WNE–ESE as expressed in scarps, which follow shallow anticlines, bending faults or a back-tilting thrust (Figs. 5 and 7). The most distinct of them follows the course of the Siwalik frontal thrust in the west and probably represents its undeveloped sector, in which the Quaternary overthrusting is still in propagation (Guha et al. 2007). The N–S or NNE–SSE directed rectangular fault lines are reflected in straight river courses which have their prolongation to the north in the form of a straight course of the foothill scarp, like the mountain front between Daina, Rehti and Dimdima. It is possible that the longitudinal direction of many rivers in the southern part of the Brahmaputra plain also follows deep fault lines in the substratum.

5. RELIEF AND THE RIVER DRAINAGE NETWORK

Leszek Starkel

The two principal morphotectonic units, the Himalaya and the Ganga-Brahmaputra Plain are separated by a steep, 500–1500 m high escarpment dissected by river valleys of various orders. It is the present-day relief transformation of this scarp and the piedmont at its foreland that have constituted the target of this study.

5.1. THE MARGIN OF THE HIMALAYA

The southern slope of the rising Himalayan range consists of two zones: the High Himalaya elevated above 7000 m a.s.l. and dissected by valleys between 3000 and 4000 m deep, and the Lesser Himalaya elevated to 2000–4000 m a.s.l. and dissected by valleys up to 2000 m deep. The marginal part is only 1500–2000 m high. Among the rivers draining this part of the mountain range only two, the Tista and the Torsa, start in the glaciated High Himalaya. The river Jaldhaka drains the whole 50 km wide belt of the Lesser Himalaya (Photo 1 and 14, for locations of photo see Fig. 28). The other river valleys are only incised in the marginal part of the mountains, mostly 5–15 km wide (Fig. 3, Table 1).

The scarp of the Himalaya is very distinct, usually rising rapidly from the flat piedmont zone and from a distance looking like a straight latitudinal barrier. In the segment between the Tista and Jainti valleys this is about 115 km long. In reality, this edge does not have a linear structure, but is rather winding, retreating up to 10–15 km to the north in some sections, forming semicircular bays bordered by linear segments of tectonic origin (Figs. 7, 8 and 9). The real length of the Himalayan scarp thus reaches 130 km, while its relative height depends on various elevations of the piedmont surface above sea level.

Moving from the Tista valley to the east one comes across numerous outlets of mountain valleys and root parts of alluvial fans. The major valleys are usually incised more deeply than those of the smaller streams (Fig. 9).

The valley of the Tista, draining an area of 8640 km^2 in the mountains, has the character of a narrow canyon cut in the Siwalik sandstones down to 160 m a.s.l. at the outlet (Photo 1). This indicates active tectonic uplift. To the east up to 12 km distant the straight edge is dissected by several small valleys, with only the Lish draining a larger catchment (Photo 2). The scarp turns to the

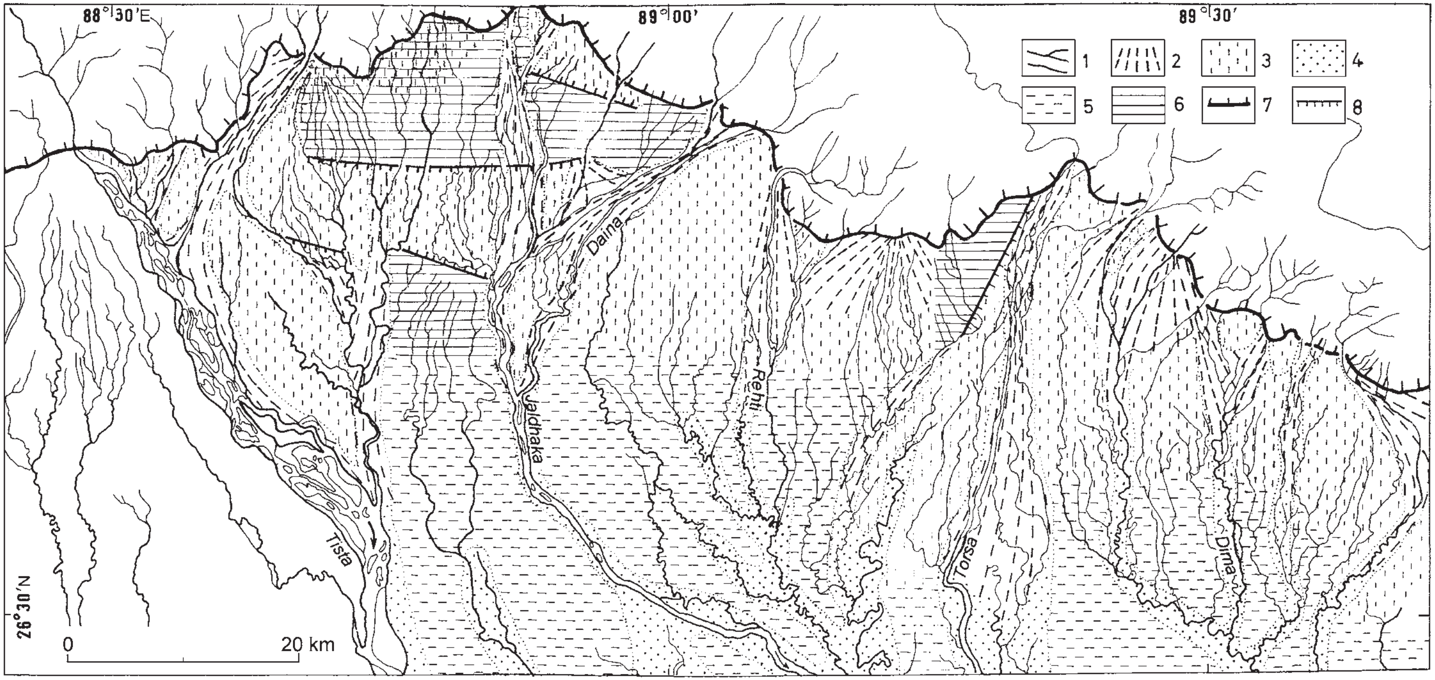


Fig. 7. General geomorphic map (elab. by L. Starkel)
1 – rivers, 2 – young (active) alluvial fan, 3 – older alluvial fan, 4 – floodplain, 5 – lower terrace, 6 – higher (uplifted) terrace, 7 – mountain front, 8 – tectonic escarpment

Ogólna mapa geomorfologiczna (oprac. L. Starkel)
1 – rzeki, 2 – aktywny stożek napływowy, 3 – starszy stożek napływowy, 4 – równina zalewowa, 5 – niska terasa, 6 – wyższa (podniesiona) terasa, 7 – brzeg gór, 8 – próg tektoniczny

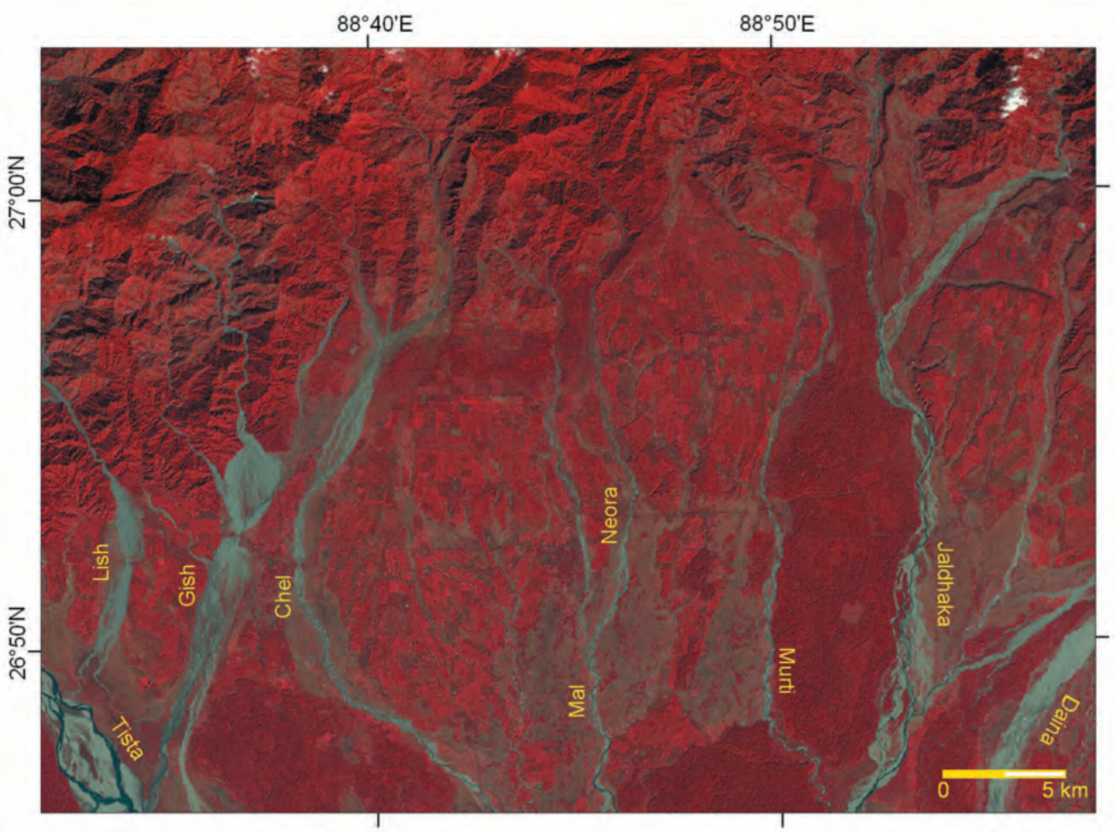
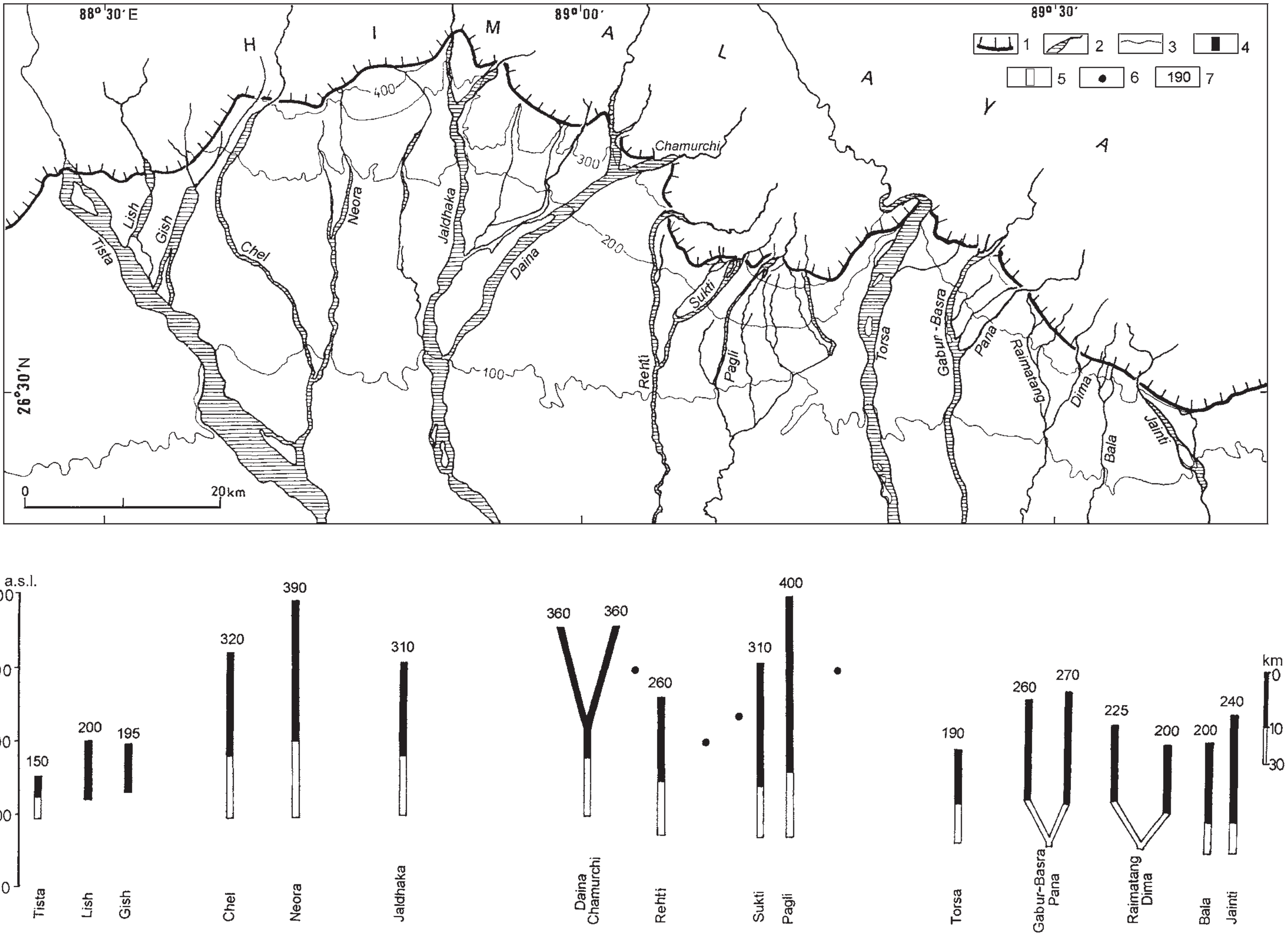


Fig. 8. Satellite image (False Colour Composite – FCC) of area between the Lish, Chel, Jaldhaka and Daina from 2001. Note difference between subsiding parts with wide braided rivers (the Lish, Gish and Chel) and uplifting blocks dissected by narrow valley sections of the Neora, Murti and upper Jaldhaka.

Zdjęcie satelitarne z 2001 r. obszaru między dolinami Lish, Gish, Jaldhaka i Daina. Wyraźna różnica rysuje się między częściami obniżanymi z szerokimi roztokowymi korytami rzek (Lish, Gish, Chel) i podnoszonymi blokami rozciętymi odcinkami wąskich dolin rzek Neora, Murti i górna Jaldhaka

NNE and within the next 10 km two large rivers, the Gish and the Chel with extensive fans join (Photo 4).

The mountain border again turns to a W–E direction for a stretch of 8 km and is dissected by several small streams. In this part, fragments of the old Gorubathan surface with rounded boulders above 2 m in diameter elevated to 700 m a.s.l. or 390 m above the Chel river channel is preserved on the uplifted mountain side (Nakata 1972). After a 2 km long shift to the north there follows a next 12 km W–E section reaching the deeper incised Jaldhaka river (310 m a.s.l., Photo 14). Horsts and grabens with fragments of Pleistocene terraces are to be noted on both sides of the valley (cf. Guha et al. 2007, Fig. 5). The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H I M A L A Y A
1
2
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200
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Chamurchi
Tista
Lish
Gish
Chel
Neora
Jaldhaka
Daina
Rehti
Sukti
Pagli
Torsa
Gabur-Basra
Pana
Raimatang
Dima
Bala
Jainti
0
20 km
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400
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320
390
310
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Tista
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Daina
Chamurchi
Rehti
Sukti
Pagli
Torsa
Gabur-Basra
Pana
Raimatang
Dima
Bala
Jainti

next 28 km scarp is generally directed towards the ESE and is dissected by the Jiti, Ghatia and Daina rivers draining the c. 15 km wide zone of the Lesser Himalaya. The apices of the fans start at 360 m a.s.l. and from the outlet of the Chamurchi valley, which follows the fault line, the sharp Himalaya scarp turns south. Up to a length of 11 km it follows a distinct fault, which is dissected in the middle by the river Rehti (Photo 20). The fan surface of the braided Rehti descends down to an elevation of 240 m a.s.l. The border of mountains then turns to the ENE following the fault line marginally dissected by rivers Sukti and Pagli. The fan of the Pagli has transgressed into the root part by up to 400 m a.s.l., what may only be explained by tectonic uplift higher on the eastern side (Photo 23 and 24).

After the next shift of edge towards the south, the mountain front has the shape of a 14 km long SW–NE directed scarp accompanied by a bench of high terrace elevated to 100 m (Figs. 7 and 44) The outlet of the Torsa is elevated by only 190 m a.s.l. East of the Torsa, the scarp turns south before 4 km farther turning SE again. Further east the 30 km long mountain front is dissected by several streams (the last of them being Jainti river). These drain the marginal mountain belt of about 10 km wide (Photo 39). Their outlets are elevated between 200 and 260 m a.s.l., depending on the position of the active alluvial fans.

Thus the characteristics of mountain fronts show great diversity which as we will see in following chapters is dependent on both tectonic activity and the hydrological regime and sediment load of the different particular streams.

5.2. THE PIEDMONT ZONE

The piedmont zone of Duars has experienced not only the deposition of alluvia, but also young tectonic activity. The piedmont surface is composed of alluvial fans and inclined in the root part between 25‰ and 10‰, before gradually declining to 5‰ and less, and at a distance of 30 km from the mountains to below 2‰, in areas not affected by uplift (Fig. 9). A similar sequence

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Fig. 9. Varied elevation (a.s.l.) of river channels dissecting the edge of the Himalaya between the rivers Tista and Jainti and their gradient downstream (elab. by L. Starkel)

1 – mountain front, 2 – river channel, 3 – contours (m a.s.l.), 4 – difference in elevation of first 10 km from mountain front, 5 – difference in elevation of next 20 km, 6 – elevation of outlets of smaller streams, 7 – elevation of main streams

Zróżnicowana wysokość (n.p.m.) położenia koryt rzecznych u wylotu z Himalajów między Tistą a Jainti i ich spadek z biegiem rzek (oprac. L. Starkel)

1 – brzeg gór, 2 – koryta roztokowe, 3 – poziomice (m n.p.m.), 4 – różnice wysokości pierwszych 10 km koryt od brzegu gór, 5 – różnice wysokości kolejnych 20 km koryt, 6 – wysokość u brzegu gór innych mniejszych potoków, 7 – wysokości koryt głównych rzek

has been observed in the western part of the Ganga Plain (Shukla and Bora 2003).

Between the Chel and Daina-Jaldhaka rivers the active latitudinal faults have dismembered the piedmont into several rising and subsiding blocks. Rivers like the Neora, Murti and others dissect these blocks elevated to 50–80 m in antecedent sections (Guha et al. 2007; Fig. 8, Photo 8–13 and 17).

To the south, about 30 km from the Himalayan front, the meandering river channels are accompanied by floodplain, and reach an elevation declining to the east from 100 to 50 m a.s.l. Tectonic activity is still expressed in the network of river channels. Junctions of streams follow latitudinal faultlines as with the lower courses of rivers Jaldhaka and Kaljani. Finally, at latitude 26°30', the floodplains of all the rivers are at similar elevations of 60–50 m a.s.l. (Figs. 6, 7 and 9).

Distinct changes in the pattern of river channels from braided to meandering are noted with changes in river gradient and sediment load. The straight and incised channels with some tendency towards braiding are only characteristic for rivers crossing the uplifted blocks (Fig. 8).

5.3. TYPES OF RIVER CHANNEL AND DRAINAGE BASIN

The piedmont zone of the Sikkimese-Bhutanese Himalaya is dissected by mountain streams of various sizes and by nascent rivers. In the western part of Himalayan foredeep were recognised three types of streams: the mountain-fed, foothill-fed and plain-fed (Singh 1992; Jain, Sinha 2003). The proportionality to river length against catchment area between the zones of erosion and deposition (aggradation) in the various types differs considerably. The following proposed general typology may be extended to 7 types (Figs. 2, 3 and 6).

1. Large transit rivers originating in the High Himalaya

This group is represented by the Tista and Torsa, with perennial discharge, fed by both rain- and meltwaters. Deep canyons in the marginal part and mega-fans in the foreland point to very high water discharges and a high sediment load. Great alluvial fans and braided channels with frequent avulsions extend far down to the river Brahmaputra (Fig. 7).

2. Rivers dissecting the Lesser Himalaya

The sole river in this group, the Jaldhaka, drains a large catchment, also deeply incised in the Duars, where it drains active rising blocks. As a result, its fan surface is developing farther downstream (Photo 14, 16). Other rivers dissecting the southern part of the Lesser Himalaya with catchments of between 50–100 km^2 (the Gish, Chel, Daina, Chamurchi, Rehti, Gabur-Basra, Jainti etc. – Figs. 3, 7) are located in the belt of higher precipitation and form large alluvial fans (Photo 4, 18, 20, 23, 33, 34 and 38). Aggradation follow upstream into the hills, while farther downstream the braided channels change into meandering ones.

3. Seasonal or episodic rivers draining only the frontal zone of the Himalaya with highly dissected catchments covering 10–30 km^2 (Fig. 7). Their catchment (Sukti, Pagli, Pana, Raimatang, etc.) receives the heaviest rainfall and also exhibits fast growing and steep extensive fans.

4. Small creeks starting at the steep scarp of the Himalaya from deep gullies or great landslides, producing large fans of several square kilometers modelled by debris flows like Khagra Jhora (Photo 22). Further downstream, such creeks usually join a larger river (the Dimdima, Jainti, etc.).

5. Rivers draining the frontal zone of the Himalaya as well as the uplifted blocks of the piedmont zone. Mountain catchments vary in size up to 30 km^2, but the elevated foreland facilitates downcutting and channels of the Neora and Murti rivers are covered by boulders in relatively narrow gullies (Fig. 8, Photo 10, 12, 13 and 17).

6. Rivers starting in the middle or lower parts of alluvial fans, fed by groundwater and heavy rain, have a low gradient and meandering pattern (Fig. 6, Photo 40). Some are located in palaeochannels (as along the Torsa), these being wide and swampy (Photo 31 and 32). Others are incised up to 3–5 meters and are accompanied by point bars and narrow floodplains (Photo 41 and 42). Most of these rivers run southwards, parallel to these originating in the mountains, before finally joining them.

7. Rivers starting on the flat surfaces or on scarps of tectonically raised blocks and fed mainly by rainwater (less by groundwater) like the Kurti and the Sukhajhora between the Chel and the Jaldhaka (Fig. 7).

Progressing downstream with changing rainfall regime, decreasing discharge, channel gradient and sediment load all the rivers gradually change their pattern from braided to meandering. Only large rivers like the Tista, Torsa and Jaldhaka keep their braided character up to the junction with the Brahmaputra.

6. RAINFALL AT THE MARGIN OF THE HIMALAYAN FOOTHILLS AND IN THE PIEDMONT ZONE

Leszek Starkel, Roman Soja, Subir Sarkar

The area between the Tista and Jainti is among the rainiest parts at the Himalayan margin located north of the wide gap between the Deccan Plateau and the Meghalaya Upland. It has a normal seasonal distribution of rainfall, with 80–90% concentrated in four summer months (Fig. 10) and a lack of rain during the winter (0–50 mm). Mean annual rainfall fluctuates between 3000 and 6000 mm and the highest totals occurring close to the steep front of the Lesser Himalaya (Figs. 11, 12). Records from about 30–40 rainfall stations show a very distinct decline in rainfall in both directions: towards the interior of the Himalayas and towards the lowest part of the Himalayan foredeep drained by the rivers of the Brahmaputra system (Figs. 11, 13 and 14).

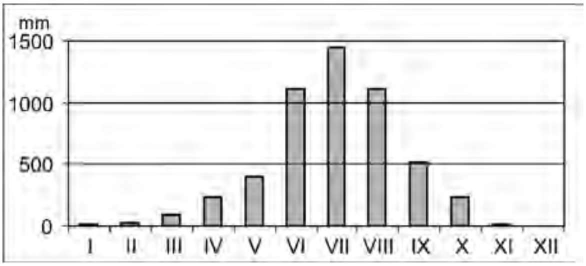


Fig. 10. Annual course for mean monthly rainfall 1996–2005 at Chuapara TE – alluvial fan of the river Pana (elab. by R. Soja and S. Sarkar)

Przebieg roczny średnich miesięcznych opadów za lata 1996–2005 w Chuapara – na stożku rzeki Pana (oprac. R. Soja i S. Sarkar)

The steep southern edge of the Himalaya at elevations between 300 and 600 m a.s.l. receives 4000–6000 mm rainfall annually, this decreasing northwards. At 10 km from the mountain front it drops below 3000 mm, at about 30 km to 1500 mm and further upstream of the river valleys goes down to below 1000 mm (Baillie and Norbu 2004). The marginal part of the piedmont belt (up to 5 km wide) receives 4500–6000 mm. Rainfall also decreases towards the south: at 10 km from the mountain front 3800–5000 mm is recorded and at 30 km the total is still above 3000 mm (raingauge station Cooch Behar on Fig. 11). This can be explained by the stopping of humid air masses by

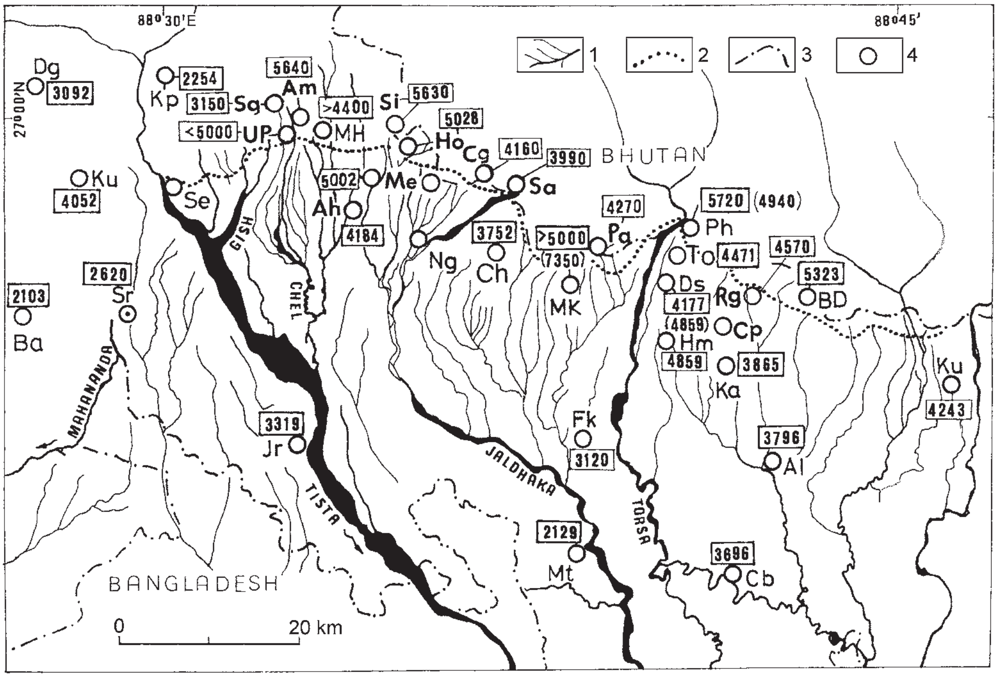


Fig. 11. Mean annual rainfall at the mountain margin and in piedmont zone of the Sikkimese-Bhutanese Himalaya (elab. by L. Starkel)
1 – rivers, 2 – margin of the Himalaya, 3 – state borders, 4 – rain gauge stations
Abbreviation for Figs. 11, 12 and 15: Ah – Aibheel, Al – Alipur Duar, Am – Ambiok, Ab –Ambootia, Ba – Bagdogra, Bd – Buxa Doar, Cb – Cooch Behar, Cd – Central Duars, Cg – Chengmari, Ck – Chhukha, Ch – Chunabati, Cp – Chuapara, Dg – Darjeeling, Ds – Dalsingpara, Fk – Falakata, Gh – Ghatia, Hm – Hasimara, Ho – Hope, Ji – Jiti, Jr – Jalpaiguri, Kd – Kalehim, Ki – Kumai, Kp – Kalimpong, Kr – Kumargrane, Ku – Kursong, Lv – Longview, Mt – Matabhanga, Mb – Maynabaree, Me – Meteli, Mh – Mission Hill, Mk – Makrapara, Ng – Nagrakata, Pg – Pagli, Ph – Phuntsholing, Rg – Raimatang, Rr – Ranglie-Rangliot, Sa – Samchi, Se – Sevoke, Sg – Samabeobong, Si – Sibsu, Sr – Siliguri, Th – Tindharia, To – Torsa, Up –Upper Phagu

Średni opad roczny w części brzeżnej gór i na przedpolu Sikkimsko-Bhutańskich Himalajów (oprac. L. Starkel)
1 – rzeki, 2 – brzeg gór, 3 – granice państwowe, 4 – stacje opadowe – skróty nazw podano w tekście angielskim

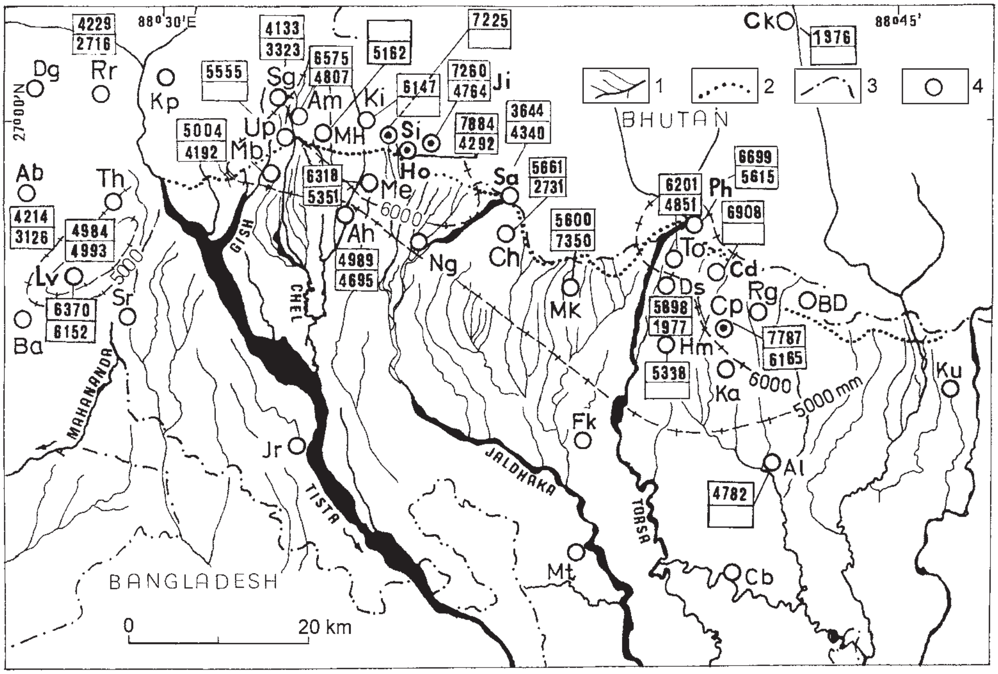


Fig. 12. Map of annual rainfall in 1993 (lower box) and 1998 (upper box) in the piedmont zone and at the Himalayan margin (elab. by L. Starkel). Signs and abbreviation as on Fig. 11, isohyetes for 1998.

Opad roczny w 1993 (dół) i 1998 (góra) w strefie piedmontu i w części brzeżnej Himalajów (oprac. L. Starkel). Objaśnienia jak na ryc. 11, izohiety dla 1998 r.

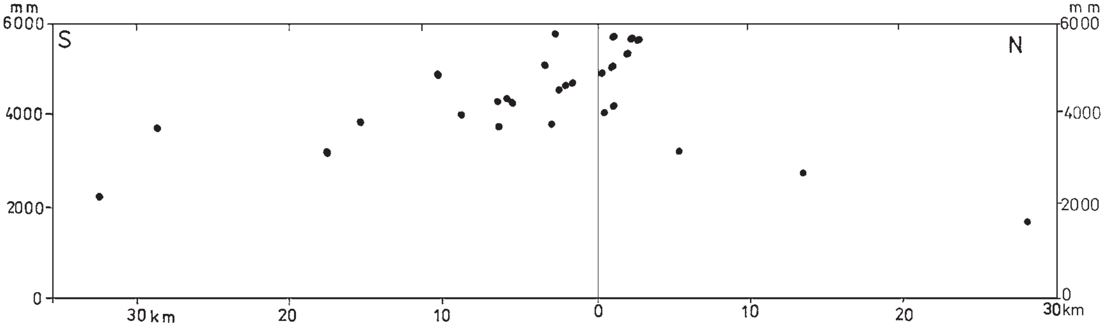


Fig. 13. Mean annual rainfall (for the last 10-20 years) along a S-N transect of the piedmont and margin of the Himalaya. 0 – line indicating front of mountains. Rapid rainfall decline entering mountains, much slower towards piedmont (elab. by L. Starkel).

Średni opad roczny (za około 10-20 lat) w przekroju południe-północ przez piedmont i brzeżną część Himalajów. Linia 0 – oznacza brzeg gór. Gwałtowny spadek opadu ku wnętrzu gór, wolniejszy na przedpolu (oprac. L. Starkel).

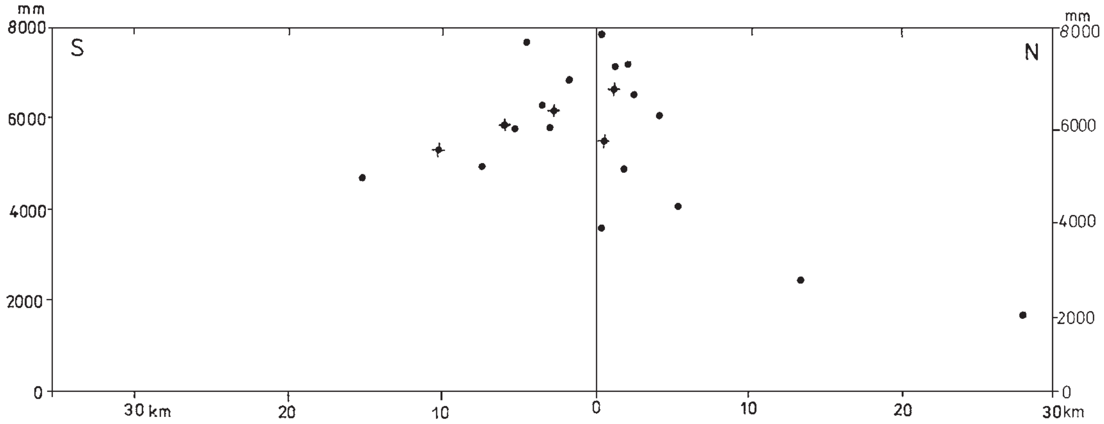


Fig. 14. Annual rainfall in 1998 (the highest recorded in recent decades) along a S-N transect from plain to mountains. Stations are located on one line along the Torsa river with crosses showing a distinct decline with growing distance from the hills (elab. by L. Starkel)

Opad roczny w 1998 r. (najwyższy notowany w ostatnich dekadach) w przekroju południe-północ przez piedmont i brzeżną część gór. Stacje zaznaczone krzyżykiem położone są na jednej osi wzdłuż biegu Torsy i pokazują wyraźny spadek z rosnącą odległością od gór (oprac. L. Starkel) the Himalayan range and frequent stabilization of the front line over several weeks. The gradient towards the south is thus gentler than that in the mountains.

A gradual increase in precipitation from west to east has been observed in the study area. Mean annual rainfall in Longview T.E. west of the river Tista is above 5000 mm, while to the east three areas may have similar or even higher values of about 6000 mm (Fig. 11).

Since 1990, exceptionally high annual precipitation has been recorded in areas between the Tista and Jainti since 1990 due to heavy continuous rainfall. Among these totals, two are characteristic (Fig. 12). In 1993 Makrapara T.E. recorded 7350 mm at the piedmont west of the Torsa, while Chuapara T.E. recorded 6165 mm 19 km to the east.

Exceptionally high precipitation was recorded in 1998, when several heavy rains were noted (Figs. 12, 14). At the base of the steep escarpment and to the east of the Torsa, Chuapara T.E. recorded 7787 mm, Central Duars T.E. 6908 mm, while along the Jaldhaka valley, Hope T.E. recorded 7884 mm and Jiti T.E. 7260 mm. In the open wide valleys where clouds could penetrate deeper into the mountains the total rainfall was much lower, as for example along the Torsa valley (6200–6700 mm) and Daina valley (3644 mm). Along the upper Chel valley rainfall fluctuated between 4000 and 6000 mm.

The period 1993–2001 featured several heavy rain episodes which have been elaborated statistically in detail in the case of Dalsingpara T.E. (Soja, Starkel 2007; Fig. 15). Altogether 69 days with rain >100 mm day^{-1} and 3 days >300 mm were recorded. Total rainfall on consecutive days reached between 600 and 900 mm in four occasions during the period. The highest recorded daily rainfall in the study area was 800 mm.

Clustering of heavy and continuous rain, noted either in every year or at 1–3 year intervals, is a very important factor from the geomorphological point of view. These make revegetation impossible and return to the former stable channel and then facilitate the propagation of instability (cf. Brunsden 2001), a preliminary characterisation of these events has been offered by Starkel and Sarkar (2002), as well as by Soja and Starkel (2007).

In 1993, continuous rain between 19 and 21 July extended to the east of the Daina (Fig. 15). The largest fall was at Makrapara T.E. (1606 mm), where 838 mm of rainfall was recorded on 21st July, as well as at Hasimara T.E., where 1379 mm fell between 19 and 21 July and 791 mm was recorded on 21st July. Much less rainfall was recorded closer to the mountain front.

The 1996 event (11–14 July) event was less extreme and concentrated in two areas. The Tista-Gish basins i.e., Sevok bridge on the Tista, recorded

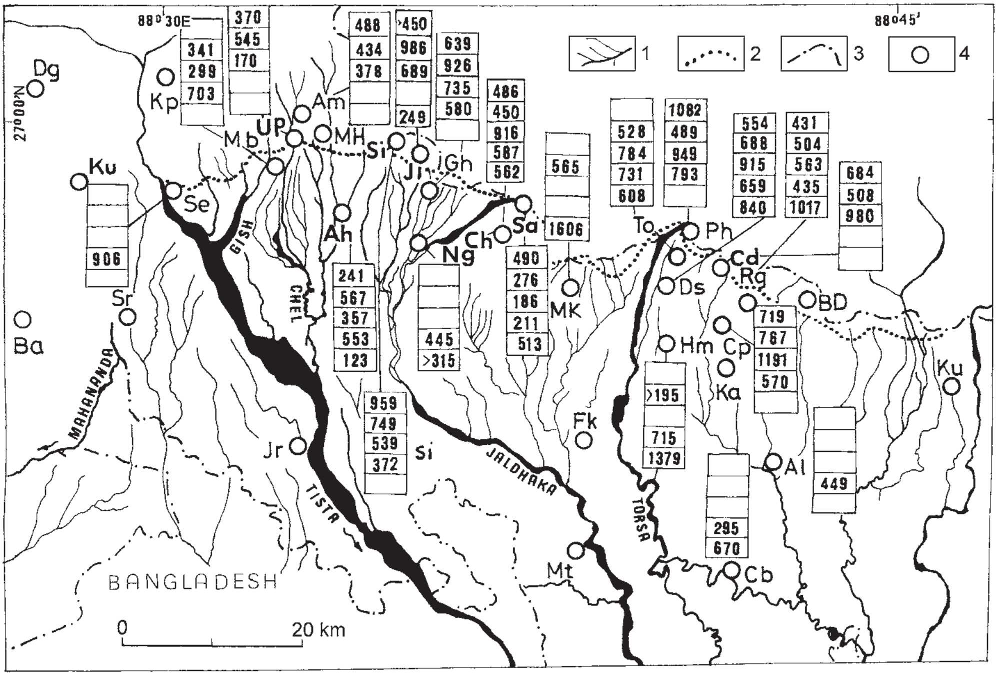


Fig. 15. Map of several extreme continuous rain events in piedmont zone and at the Himalayan margin a) 19–21.07.1993, b) 11–14.07.1996, c) 8–13.06.1998, d) 20–24.07.1998, e) 31.07–4.08. 2000 (from bottom to top) (elab. by L. Starkel). Signs and abbreviations as in Fig. 11.

Mapa rozkładu kilku ekstremalnych serii opadowych w strefie piedmontu i w brzeżnej części Himalajów

a) 19–21.07.1993, b) 11–14.07.1996, c) 8–13.06.1998, d) 20–24.07.1998, e) 31.07–4.08.2000 (od dołu do góry) (oprac. L.Starkel). Objaśnienia jak na ryc. 11.

906 mm, while Maynabaree T.E. near river Gish had 703 mm and the Torsa basin site of Phuntsholing recorded 793 mm with daily maxima of 431 mm and Dalsingpara T.E. 659 mm. It is interesting to note here in the Jaldhaka-Daina interfluves received much less rainfall i.e., between 200 and 500 mm.

Three series of continuous rainfall events were noted in 1998. The first one was recorded in between 8–13 June, concentrated east of the Torsa. Chuapara T.E. recorded 1191 mm and (close to the mountain front) Phuntsholing recorded 949 mm and Central Duars T.E. 980 mm. The Daina-Jaldhaka interfluves also received heavy rainfall, Chunabati T.E. recording 916 mm and Ghatia T.E. 735 mm. After 2–3 days' break the next heavy rain occurred between 15 and 18 June when the piedmont area of the Jaldhaka basin recorded up to 900 mm (Jiti T.E. 874 mm) and the Torsa catchment above 500 mm. After several local heavy rainfalls (at Dalsingpara 225 and 445 mm) the next event of continuous rain occurred between 20 and 24 July. This time rain concentrated in the upper Jaldhaka basin (Ghatia T.E. 926 mm, Jiti T.E. 986 mm) and on the piedmont east of the Torsa (Chuapara T.E. 767 mm and Dalsingpara T.E. 688 mm).

The last event under consideration took place between 31st July and 4th August 2000, concentrated again at the mountain front east of the river Torsa (Phuntsholing 1082 mm, Central Duars T.E. 684 mm) and near the Jaldhaka river (Sibsu 959 mm, Ghatia T.E. 638 mm).

The recent rainfall record from the eastern part between the Torsa and Pana reveals the occurrence of heavy rain during 3–5 consecutive days in almost every alternate year, this causing more or less local floods, as when Chuapara T.E. recorded 578 mm between 31st July and 2nd August 2001, 726 mm between 6 and 10 July 2003 and 549 mm between 8 and 11 July 2005 when Dalsingpara T.E. recorded 706 mm.

Many of these records point to the highest recorded stations being located several km south of the mountain front (Fig. 13). This does not mean that the rainfall could not be higher at the Himalayan edge. It is clear that the rain supplies, not only the rivers flowing from the Himalayas, but also others starting on the alluvial fans in the piedmont zone.

Alongside the increasing frequency of extreme rainfall in the last 10–15 years we may also observe a multiannual trend in the last 40 years towards a decline in annual rainfall, as exemplified by Dalsingpara TE (Fig. 16).

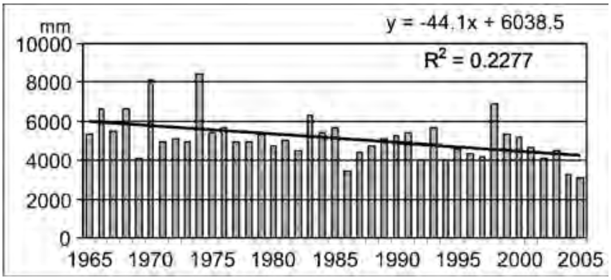


Fig. 16. The long-term downward trend for annual rainfall at Central Duars TE (Rangamati) from 1965 to 2005 (elab. by R. Soja)
Wieloletni trend spadku opadów rocznych notowany w Central Duars (Rangamati) od 1965 do 2005 r. (oprac. R. Soja)

7. CHARACTERISTICS OF THE HYDROLOGICAL REGIME

Roman Soja, Subir Sarkar

In the piedmont zone of Duars there are various rivers representing the four different types of hydrological regime controlled by relief, rainfall pattern and lithology of catchment:

1. Large rivers starting in the High Himalaya are fed by glaciers, snowmelt and rainfall, which in the Duars have the character of allochtonous streams.

In the studied part of the Sikkimese-Bhutanese piedmont there are two rivers of this type (Fig. 2). The Tista on the western margin drains Sikkim with the glaciated massif of Kanchenjunga. The extreme floods that are among the largest in the Himalaya (up to 20,000 m^3s^{-1}) are connected with continuous heavy rain in the marginal part of the Lesser Himalaya (Sarkar 2008). Rising temperature and monsoonal rain accelerate the melting of snow and ice in the High Himalaya. As a result, from August to October, higher discharges are recorded, contrary to the very low ones from December through to March.

A similar regime is characteristic for the Torsa, which at the outlet from the Himalaya near Phuntsholing drains an area of 3800 km^2. The river Torsa, about 130 km long in the Himalaya and then of 110 km in the plains, starts its journey from China at an elevation of over 6000 m a.s.l. from two glaciers. The discharge in the headwaters is regulated by large transfluent lakes. The Torsa crosses Bhutanese territory (named Amo or Amo Chu) in a deep canyon with incised meanders. The highest glaciated part is in the belt of low precipitation of 500–700 mm or less. The latitudinal mountain ridges resist the invasion of humid air masses, though new data reveal that the annual rainfall in the Chinese part deep into Himalayan territory may frequently exceeds 2000 mm, while that in the Bhutanese part is of 3000 mm. In the outlet part after the junction with the Pa Chu tributary upstream of Phuntsholing, the braided river extends and finally the present Torsa drains over the extensive alluvial fan. The paleochannels only carry water during the rainy season, the dry season seeing most of the discharge infiltrating into the alluvium. A rising water level of the Torsa is common during heavy and continuous rains, almost every year exceeding 500 mm in 3–5 days.

The hydrometric station on the Torsa is located at the NH bridge near Hasimara, 15 km away from the mountain front. The catchment area at this point is of 3920 km^2. The wide braided channel at the bridge is narrowed to

400 m. The embankments between the two bridges stabilise the channel (cf. Fig. 48 (B)).

The hydrometric record from the years 1998–2002 (including water level, discharge and concentration of suspended load) has been analysed. The annual course reveals two distinct seasons. The rise in water level and discharge begins in March or April continues to the end of July or August and gradually declines up to the next rainy season. The annual amplitude to water level reaches 350 cm, which is found higher in the measured cross-section than in braided parts.

In winter the river is supplied by groundwater. The first rapid rise in discharge is recorded in June. Heavy rains normally end in mid-September, but high water levels continue to October, supplied by melt water from the high Himalaya.

The highest discharge reached 3800 m^3s^{-1} and the lowest 19.97 m^3s^{-1} in the period 1998–2000. The largest discharge is partly controlled by the braided Torsa channel upstream, the great volume of channel cross-section and outflow across the floodplain reducing the high water level (Fig. 17).

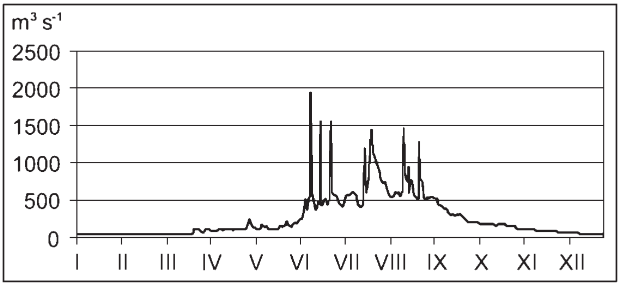


Fig. 17. Daily water discharges of the river Torsa in 1998, at the Hasimara cross-section (elab. by R. Soja, S. Sarkar)
Przepływy dobowe rzeki Torsa w przekroju Hasimara w 1998 r. (oprac. R. Soja, S. Sarkar)

The response of the Torsa to the series of extreme rainfall events is exemplified by daily discharges at Hasimara, and by daily rainfall at Phuntsholing at the Himalayan margin (15 km distance). During the first three days of a 7-day rainstorm (of 6–12 June 1998), rainfall oscillated by about 200 mm but was not reflected in a change of discharge. However, on 12th June a heavy storm of 800 mm caused an increase in discharge to 2000 m^3s^{-1}. Similar relations were observed between 20 and 24 July 1998 (Fig. 18) and 30 July and 3 August 2000 (Fig. 19). In July 1998, 450 mm of rain (688 mm at Dalsingpara T.E.) was followed by a river discharge record of 1450 m^3s^{-1}, while in 2000 year 900 mm of rain (500 mm in one day) was followed by a recorded high discharge on the Torsa of 3800 m^3s^{-1}. The gradual rise and then rapid drop in water level is one of an important characteristic of the Torsa floods.

Sediment load measurements were restricted to suspended load, but the coarse gravels building bars in the channel point to the presence of a high bed load during floods. The suspended load transport fluctuates greatly, and there is no distinct relationship between discharge, concentration of suspended load and total suspended load. The annual sediment load reached 4 million tons in 1998, when several flood waves had passed, while in 2001 the figure was reduced to just 0.8 million tons (Fig. 20). For period between November and April in turn yielded no records, as the amount of suspended load was not measurable.

The suspended load carried beyond is deposited over the floodplain of the lower reach of the Torsa and along the Brahmaputra (cf. Goswami 1998).

2. Rivers with headwaters in the Lesser Himalaya fed by heavy rains in the monsoon season and by groundwater in the dry season.

Rivers of this zone are exemplified by the Jaldhaka, which at the outlet from the mountains drains an area of 787 km^2 and has a length of 45 km (Photo 14). In the headwater area annual rainfall reaches 2500 mm. In Duars, the Jaldhaka joins the left-side tributaries like the Jiti, Ghatia and Daina, which drain only the marginal 10–20 km zone of mountains. Downstream at Dhupguri (85 km length, catchment 1590 km^2) the river assumes a braided character. Measurements of water level and discharge were made at the Dhupguri NH bridge in summer (June-September) between 1998–2001. This hydrometric point is located about 40 km from the mountain front, and flood waves formed at the margin of the Himalaya are flattened. The fluctuations in water level only reach 2 meters. The annual course to discharges is similar to that along the Torsa, but the dynamic is much greater (Figs. 21 and 22). The lowest observed discharge was 16.5 m^{3}s^{-1}, and the highest the 5000 m^{3}s^{-1} noted on the 4th August 2000. The specific runoff thus reached 3145 l s^{-1}km^{-2}. High runoff was caused by 5-day rainfall of about 900 mm at the mountain margin. Sibsu recorded 450 mm of rainfall on the day before culmination of the flood (Fig. 24). The other example of higher runoff is the sequence of two flood waves of June 1998 (Fig. 23). The specific runoff at Dhupguri was 3 times greater than in Hasimara on the river Torsa. This means that the dynamic of floods in the Jaldhaka catchment is much greater.

The monthly fluctuations of sediment load correlate well with mean monthly discharges (Fig. 25).

Comparing the mean annual discharges in the period 1998–2001 we find similarities for both rivers, i.e. the Torsa on 225 m^{3}s^{-1} and the Jaldhaka on 230 m^{3}s^{-1}. However, great differences have been noted in mean specific runoff i.e., the Torsa 57 l s^{-1}km^{-2} and the Jaldhaka 145 l s^{-1}km^{-2}. That may be explained

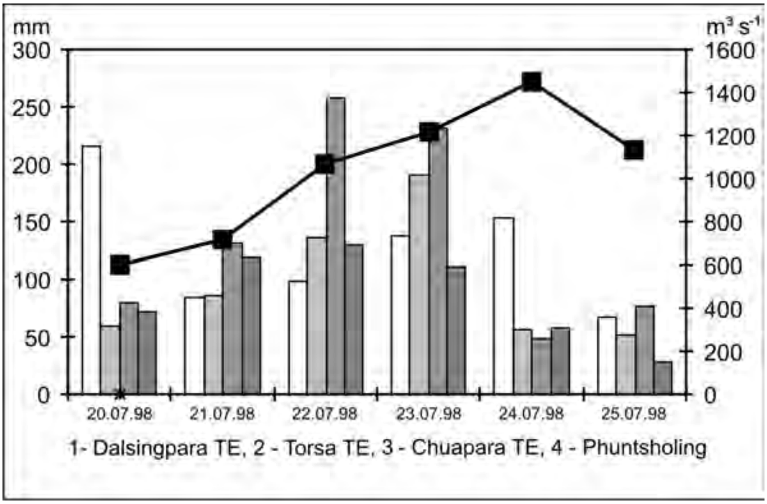


Fig. 18. Daily water discharge of Torsa river between 20 and 25 July 1998 at Hasimara cross-section on the background of rainfalls recorded at raingauges in Dalsingpara, Torsa TE, Chuapara, Phuntsholing (elab. by R. Soja, S. Sarkar)

Przepływy dobowe rzeki Torsa w przekroju Hasimara w dniach 20-25 lipca 1998 r. na tle opadów w Dalsingpara, Torsa TE, Chuapara, Phuntsholing (oprac. R. Soja, S. Sarkar)

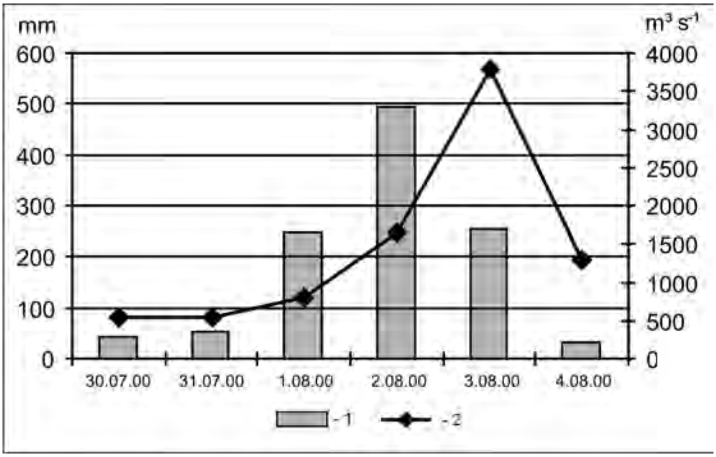


Fig. 19. Daily water discharge of Torsa river between 30 July and 4 August 2000 at Hasimara on the background of rainfalls recorded at Phuntsholing (elab. by R. Soja)
1 – rainfall (mm), 2 – discharge ($m^{-3}s^{-1}$)

Przepływy dobowe rzeki Torsa w dniach 30 lipiec – 4 sierpień 2000 r. na tle opadów w Phuntsholing (oprac. R. Soja)
1 – opad (mm), 2 – przepływ ($m^{-3}s^{-1}$)

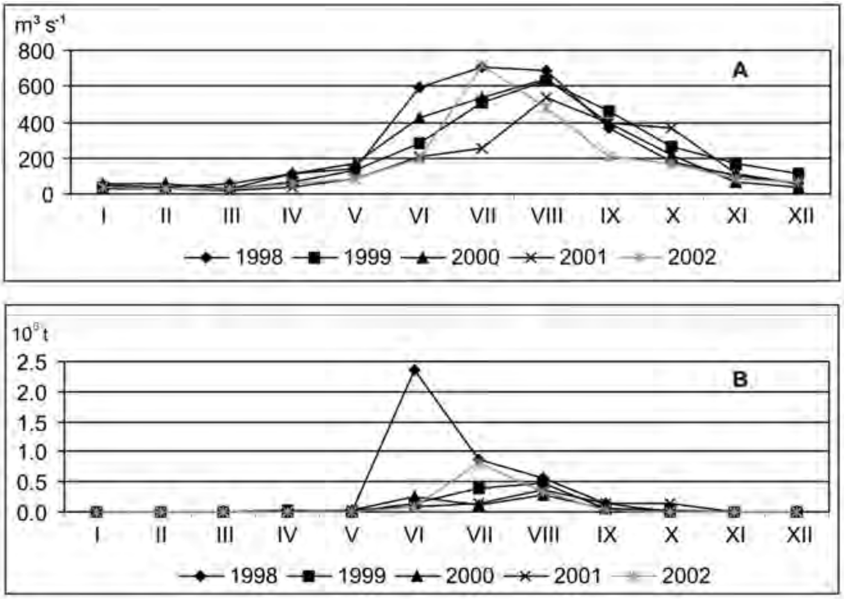


Fig. 20. Monthly fluctuations in mean discharges (A) and total suspended outflow (B) of the river Torsa at Hasimara between 1998 and 2002 (elab. by R. Soja, S. Sarkar)

Przepływy miesięczne (A) i transport zawiesiny (B) rzeki Torsa w przekroju Hasimara w latach 1998–2002 (oprac. R. Soja, S. Sarkar)

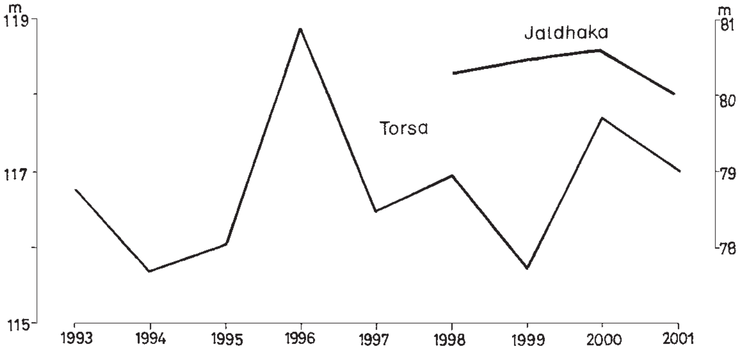


Fig. 21. Fluctuations in annual highest flood water level recorded on the Torsa at Hasimara and on the Jaldhaka at Dhupguri (elab. by L. Starkel, S. Sarkar)

Maksymalne stany wody rzek Torsa w przekroju Hasimara i Jaldhaka w przekroju Dhupguri (oprac. L.Starkel, S. Sarkar)

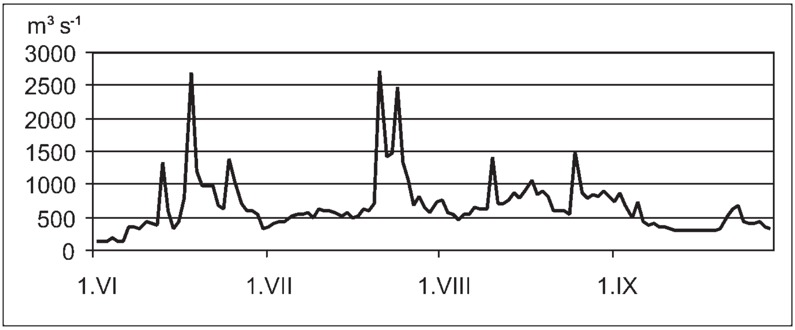


Fig. 22. Fluctuations in water discharges of the river Jaldhaka between June and September 1998 at Dhupguri (elab. by R. Soja, S. Sarkar)

Przepływy dobowe rzeki Jaldhaka w Dhupguri od czerwca do września 1998 r. (oprac. R. Soja, S. Sarkar)

by differences in the infiltration of water in bedrock and alluvia. But the main reason is that the area of the mountain margin with the heaviest rainfall differs greatly. In the case of the Torsa this is only 15 km long, while and in the Jaldhaka catchment it is above 40 km.

3. Rivers draining the margin of the Himalaya, crossing Duars, and only carrying water during the rainy season.

The interfluves between the Tista, Jaldhaka and Torsa in the upper parts of the piedmont are drained by smaller rivers which have headwaters in the highly-dissected 10–15 km wide marginal part of the Himalaya receiving 4000–5000 mm of rain annually. Heavy rains create flash floods, which carry coarse bed load and deposit over the extensive fan system (Photo 4, 20 and 23). In the hills, water level rises several meters and flood waves either reach larger rivers or dissipate gradually. Water infiltrates into alluvia and it is frequent after the rainy season for these braided channels to be totally dry. The 1952 records from the Lish, Gish and Chel (Dutt 1966) show that, at a distance of 3–5 km or less from the mountain water flows only locally (Table 2) downstream 20–30 km (as along the Rehti), groundwater appears again in the channel.

Table 2. River discharge of some rivers in Kalimpong Subdivision in the year 1952 (after G.N. Dutt 1966)

River	Drainage area (km^2)	Forests (%)	Maximum discharge (m^3s^{-1})	Maximum run-off ($m^3s^{-1}km^{-2}$)	Minimum discharge (m^3s^{-1})	Maximum: minimum ratio	Annual rainfall in drainage area (mm)
Lish	49.2	37	254.7	5.176	0.25	1000	4877
Gish	160.6	42	630.2	3.922	0.08	7423	5385
Chel	103.6	47	184.5	1.777	0.06	3260	6096
Neora	134.7	69	242.1	1.797	2.40	101	6350

Only the forested Neora river valley in the area with a tendency towards uplift shows a different annual course for discharge and high water storage (Table 2).

4. Rivers starting in the plains, fed by groundwater and with rising discharge during heavy rain.

In the middle or lower parts of the alluvial fans there are larger or smaller creeks with meandering channels cut up to 2–3 m in alluvia, which are flowing throughout the year (Photo 41 and 42). These rivers are supplied by groundwater, this frequently appearing at the surface in form of springs. Some of these streams start and end on the surfaces of alluvial fans, sometimes being located in the depressions of former palaeochannels. Groundwater is joined during the rainy season by heavy rain in the piedmont zone in supplying these streams, causing a rise in water level of up to 2–3 meters. This therefore follows the lateral migration of channels and formation of sandy-gravely point bars. The hydrological records for these rivers are not available but the presence of villages and tea gardens along them indicates that these perennial rivers never flood the fans or terrace plains in which they are incised.

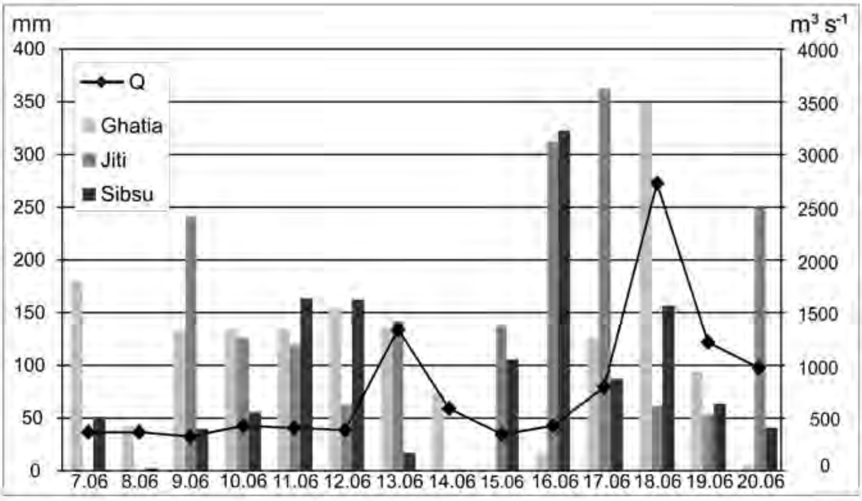


Fig. 23. Daily water discharge (Q) of the river Jaldhaka between 7 and 20 June 1998, against the background of rainfall recorded at three rain gauges in Ghatia, Jiti and Sibsu (elab. by R. Soja, S. Sarkar)

Przepływy dobowe (Q) rzeki Jaldhaka w dniach 7–20 lipca 1998 r. na tle opadów na stacjach pomiarowych w Ghatia, Jiti i Sibsu (oprac. R. Soja, S. Sarkar)

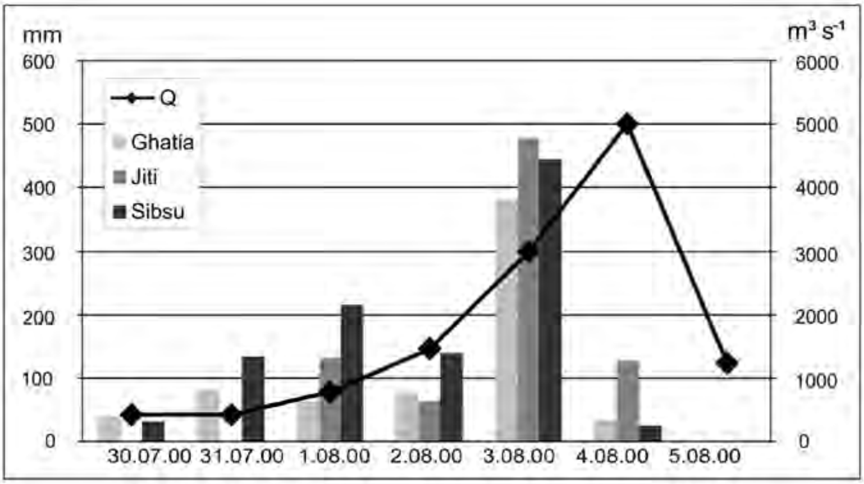


Fig. 24. Daily water discharge (Q) of the Jaldhaka between 30 July and 5 August 2000 against the background of rainfall recorded at three rain gauges in Ghatia, Jiti and Sibsu (elab. by R. Soja, S. Sarkar)

Przepływy dobowe (Q) Jaldhaki w dniach 30 lipca – 5 sierpnia 2000 r. na tle opadów na stacjach pomiarowych w Ghatia, Jiti i Sibsu (oprac. R. Soja, S. Sarkar)

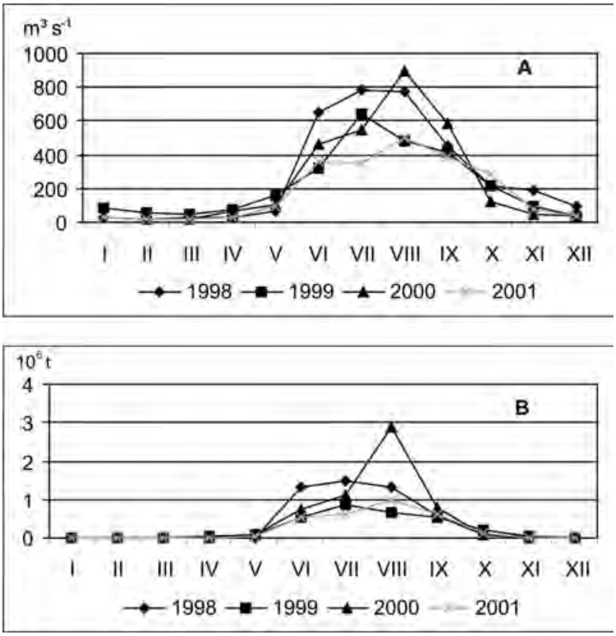


Fig. 25. Monthly fluctuations of mean discharge (A) and total suspended sediment outflow (B) of the river Jaldhaka in the years 1998–2001(elab. by R. Soja, S. Sarkar)

Przepływy miesięczne (A) i transport zawiesiny (B) rzeki Jaldhaka w latach 1998–2001 (oprac. R. Soja, S. Sarkar)

8. LAND USE AND ITS TRANSFORMATIONS

Paweł Prokop

The gradual depletion of forest from north to south at the expense of agriculture, is the most notable feature of the present-day land use/cover structure (Fig. 26, Tables 3 and 4). The structure reflects the relief of three large geomorphic units: mountains, alluvial fans and plains. Each of these has different climatic conditions, lithology and soils which determine human activity, pursued mainly through the development of various forms of agriculture, settlement, to a limited extent mineral extraction. The present-day land use/cover structure is the result of human impact ongoing for centuries, if accelerated when the British East India Company took control of Bengal in the mid-19th century. Since then there has been large-scale and heedless deforestation, initiated through the foundation of tea plantations and the heavy demand for timber for railway and building construction. The 20th century was in turn marked by demographic explosion. Population was additionally increased through migration of people from Nepal to the Indian part of the Himalayas and migration from the Bengal plains to the tea plantations located close to the Himalayan Foreland. The total population in the study area (according to the census of India and Bhutan) is ca. 2.7 million, of which 8.8% live in urban areas. Although there are no large cities between the Tista and Jainti rivers, a trend towards faster growth of the urban than the rural population has been noted over the last few decades.

Table 3. Land use in various geomorphic zones in 2001 (cf. Fig. 26, elab. by P. Prokop)

Land use	Mountains		Alluvial fans of Duars		Alluvial plain		Total	
	km^2	%	km^2	%	km^2	%	km^2	%
forest	3315.2	59.4	743.8	29.0	290.0	14.2	4349.0	42.7
tea garden	-	-	799.6	31.1	93.4	4.6	893.0	8.8
other	2227.6	39.9	752.1	29.3	1552	76.1	4530.2	44.5
river	38.1	0.7	271.7	10.6	103.9	5.1	413.7	4.1
total	5579.9	100.0	2567.2	100.0	2038.8	100.0	10185.9	100.0

a) Mountains

Most of the mountain areas are grown by various types of natural forest (Tables 3 and 4). This changes from moist deciduous with the dominant *Sho-*

rea robusta up to 1000 m a.s.l., through tropical evergreen forest with *Quercus* and *Castanopsis* up to 2000 m a.s.l. and a pure *Rhododendron* stand between 2500 and 2800 m a.s.l., to temperate coniferous at elevations of 3000–3500 m a.s.l. Only the upper part of the Jaldhaka and Torsa catchments is covered by sub-alpine fir forest, which gradually changes to alpine grassland above the upper timberline at approximately 4000 m a.s.l. (Champion, Seth 1968).

The margin of the mountains is usually densely populated and human impact on the environment is more visible here than in the upper part of the Himalayas. This relationship is only less evident in the Siwalik zone of the Lish and Gish catchments built up of unconsolidated sandstones and pebbles not suitable for settlement. In both catchments the most deforested area is shifted 5 km northward, where deep weathered Darjeeling gneisses and Daling quartzites and phyllites are dominant (Basu, Ghatowar 1988). This area has long been turned into cultivated fields or pits quarrying coal from a thin belt of the Damuda series, and hence has the highest population density (200 persons km^{-2}).

Deeper into the mountains a relationship between the major river valleys and deforestation is visible. The river channel widths in their upper and middle courses are stable, though closer to the mountain margin they extend laterally. The settlement in this area is confined to the gentle slopes of intermountain basins suitable for agriculture and close accessible transport routes. This is due to road construction along river courses, a dominant feature in the colonization process. The population density in this area is still high, though it decreases gradually eastwards to 120 persons km^{-2} in the Chel and Jaldhaka catchments near Bhutan border. Irregular and small deforested patches are connected with the dispersed settlement of people who thus far have practised slash and burn agriculture. The area within Bhutan has the lowest population density anywhere in the investigated area, at 40 persons km^{-2} near the border with the Indian plains, where Phuntsholing, the largest town in the mountains with 20,000 inhabitants, is located. The quarrying of dolomite along the base of the Indo-Bhutan hills has only local influence on forest cutting but increases the instability of slopes causing large scars in the vegetation. Population density decreases to the north to just 7 persons km^{-2} in the middle part of the Torsa catchment, and to 1 person km^{-2} in the upper part. The small catchments east of the Pana river in Bhutan are less settled, with forest cover of more than 90%.

b) The alluvial fans of Duars

The mountain foreland is built up of alluvial fans and higher elevated terraces. The extent of the fans is roughly bounded by the 100 m contour. A significant part of this area falls within sanctuaries and reserved forest (Fig. 26).

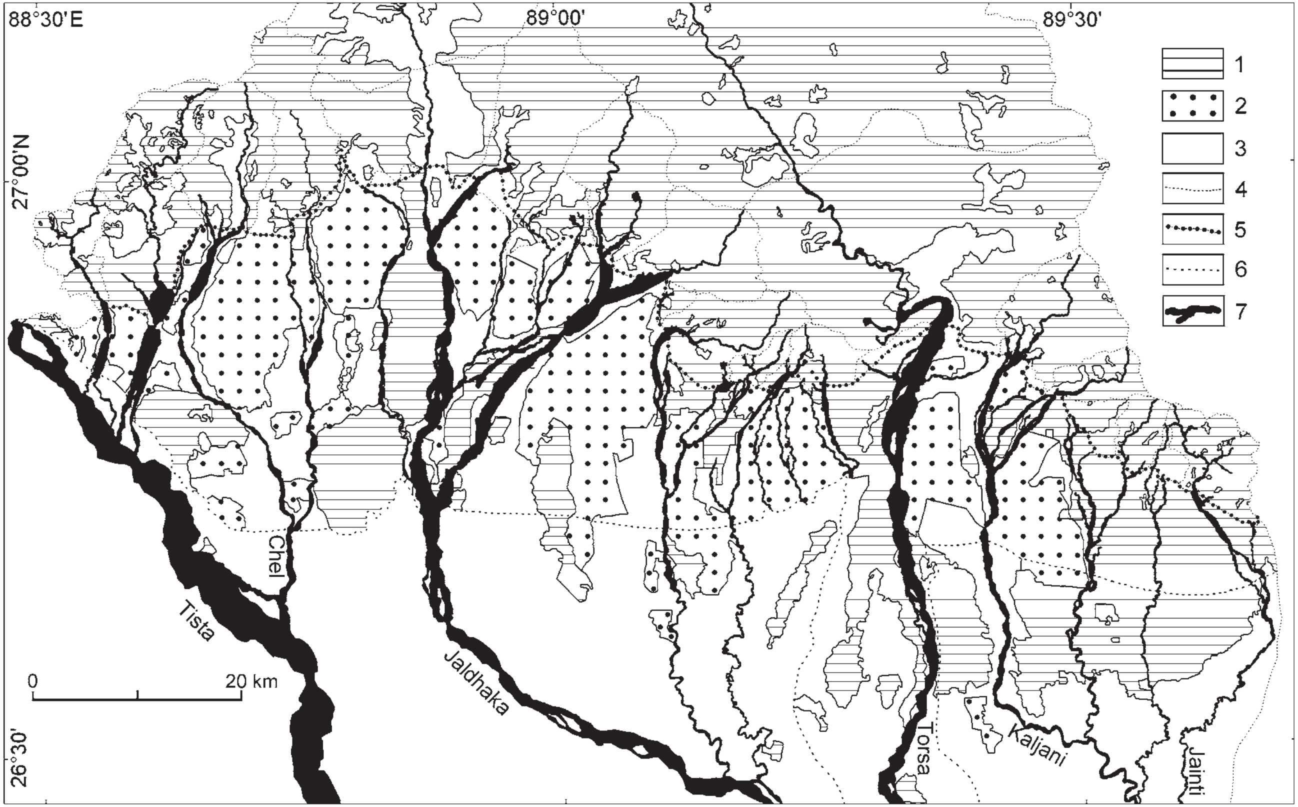


Fig. 26. Land use map (elab. by P. Prokop)

1 – forests, 2 – tea gardens, 3 – others, 4 – Himalayan margin, 5 – river catchments, 6 – alluvial fans of Duars extension, 7 – active river channels

Mapa użytkowania terenu (oprac. P. Prokop)

1 – lasy, 2 – plantacje herbaty, 3 – inne, 4 – brzeg Himalajów, 5 – granice zlewni, 6 – zasięg stożków napływowych, 7 – aktywne koryta rzeczne

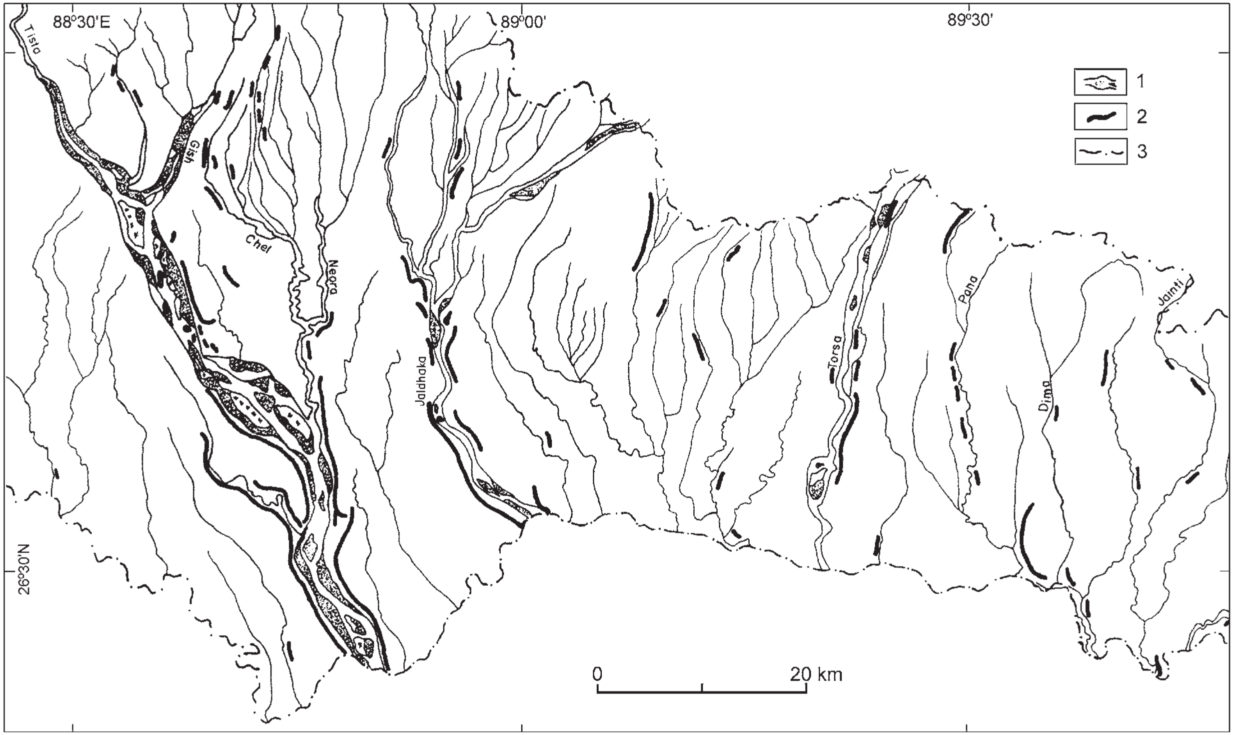


Fig. 27. Flood protective embankments in the Himalayan foreland (before 1990) (elab. by S. Sarkar)
1 – rivers with active and vegetated bars, 2 – embankments, 3 – boundary of Jalpaiguri District

Wały przeciwpowodziowe na przedpolu Himalajów (przed 1990 r.) (oprac. S. Sarkar)
1 – rzeki ze świeżymi i porośniętymi roślinnością odsypami, 2 – wały przeciwpowodziowe, 3 – granica Dystryktu Jalpaiguri

This consists mainly of *Shorea robusta*, the most valuable commercial tree. This forest is mixed with patches of pure deciduous forest with *Schima wallichii* or *Acacia catechu* (Champion, Seth 1968). The largest reserved forests are located along the Jaldhaka – Tondoo Forest, the Torsa – Barajhor Forest and between Dima and Jainti – Buxa Forest. Thus the area under forest increases from 13–33% in the Lish, Gish, Chel, Jaldhaka, Reti, Torsa and Pana catchments to above 76% in the Dima, Bala and Jainti catchments.

Tea plantations occupy the largest part of the alluvial fans of the Lish, Gish, Chel, Rehti and Pana catchments. Forest clearance for tea plantations combined with the building of roads and railways to give rise to settlement and trade. The rural population density now reaches 300–500 persons km^{-2}. Roads and railways were built above normal flood levels. Dozens of kilometres of embankments were constructed along transport lines that crossed rivers (Fig. 27). These gave the impulse to the development of many small urban centres as local administrative headquarters, often at the junctions of rivers and new transport routes.

The decrease in river gradients at the outlet from the mountains causes a decrease in sediment transport capacity and extensive deposition of material eroded from the mountains. The overloaded rivers are liable to shift their braided courses significantly. In many places land surrounding the rivers built of boulders and gravels is covered by grasses with sparse trees or swamp vegetation. The wide braided channels cover ca. 10%, i.e. a substantial part, of the total area.

Annual floods cause a direct loss of forest, tea gardens and settlement, leading to changes in land use/cover. A study in the Buxa Reserve Forest in Jainti catchment shows that 850 ha of forest and 75 ha of tea garden were destroyed by bank failure and shifting river courses between 1993 and 1999 (Sarkar 2008). One of the most important indirect effects of floods is to change soil properties in terms of productivity. During the devastating floods of 1954 about 10 km^2 of cultivated land was laid waste by the deposition of silts in the Gish catchment (Basu and Ghatowar 1988). The accumulation of calcium by floodwater over alluvial fans causes alkalinity of the soil that decreases productivity and quality, leading to the abandonment of tea plantations and the death of trees (Sarkar 2008).

c) The alluvial plain

At a distance of 20–25 km from the mountain front the fans coalesce into an extensive alluvial plain, gradually lowering from 100 to 50 m a.s.l. and built up of fine-grained sediments over bank deposits. The river gradients and channel widths diminish and the turn from braided to meandering. The area covered by active channel decrease to 4% of the total plain area. Along major rivers there are elevated parts of levees or embankments several kilometres in length (Fig. 27). These are favoured sites for larger settlements. River banks are not completely protected, so some parts of the floodplain are inundated every year. Alluvial soils offer some of the most productive agricultural land in the region. As a result, this area has experienced massive transformation of the land use/cover system. Nearly all of the natural forests of the plain have been cleared by a process of agricultural colonisation ongoing for centuries. Tea plantations and forest are preserved only on higher river terraces or remnants of alluvial fans in the north-eastern part of the plain. Almost the whole area has been converted to intensive settled paddy rice cultivation. Rural population density exceeds 500, and in some places reaches 1000 persons km^{-2}, among the highest-known densities in human history.

9. CHARACTERISTICS OF SELECTED RIVER COURSES, FANS AND CHANGES AFFECTING THEM OVER THE LAST CENTURY

Leszek Starkel, Paweł Prokop, Subir Sarkar

In the piedmont area between the rivers Tista and Jainti, 15 key areas have been selected along various river valleys or on alluvial fans which characterise different types of transformation over the last century.

For each of these valleys various parameters were characterised like river length, channel gradient, drainage area (Table 1) as well as general geology, relief, rainfall and land use. The changes in channel parameters for a stretch of 10 to 15 km long sections were calculated on the basis of two sets of topographic maps from 1929–1937 and 1964–1971, and especially satellite images from 1991, 2001 and partly other years (1996–1998). These maps and calculations are as shown in Table 5 and Figs. 28–55, and partly supported by records on changes in channel cross-section.

9.1. THE TISTA

This border river of the study area is one of the greatest Himalayan tributaries of the Ganga-Brahmaputra system (Fig. 2). The Tista originates from the Kanchenjunga massive (8580 m a.s.l.) and drains the mountain area above 8600 km^2. It is deeply cut into the bedrock along its 200 km length and forms a canyon shape at the outlet from the mountains (Photo 1). The river Tista has a typical mixed hydrological regime (Starkel, Basu 2000), fed by snow, ice and groundwater which receives the most energy from extreme continuous rain that repeats every 20–50 years (Starkel 1972; Sarkar 2004b). In the last two centuries such extreme floods were recorded in 1899, 1950 and 1968. Every year at the mountain edge the discharge may reach 3000–5000 m^{3}s^{-1}, the water table rising to 5–6 meters above mean water level. But in October 1968 the water level in Tista Bazar rose to 26 m above normal and discharge was calculated at 18,500 m^{3}s^{-1}. At Jalpaiguri about 50 km downstream of the mountain front, the discharge reached 19,800 m^{3}s^{-1}, and part of the town was flooded.

At present, the river Tista flows on the left margin of the fan taking only 3 tributaries i.e. the Lish, Gish and Chel in its upper portion, which superimpose fine overbank deposits over the bars in the wide Tista channel.

The older fan surface 8–15 m high extending from the mountain margin is dissected by a 4–6 km wide braided channel, which continues above 200 km down to the river Brahmaputra. The present-day Tista fan extends south of Jalpaiguri, which was modelled by the shifting nature of the river. A great flood in 1787 caused the avulsion of the river Tista over the fan surface to the east, causing it to join the Brahmaputra instead of the Ganga (Sen 1968).

Before the 1968 flood, the braided channel was composed of 2–4 river branches, about 80% was occupied by unvegetated bars and only on the right side were vegetated shoals. After the October 1968 flood, the channel pattern inside the widening floodplain zone changed totally. In the uppermost part, the right branch started to be the main channel. However, field observations over the last two decades reveal that new changes in branch channel pattern take place every year. In fact, 5–10 flood waves of various amplitudes are recorded annually.

9.2. THE LISH

The first large left-bank tributary of the Tista in the piedmont zone is the Lish, only 20 km long, and draining a total catchment area of 64 km^2, out of which 48 km^2 is in the hills, where the highest peaks rise to 1820 m a.s.l. The dendritic pattern of deep valleys cuts various geological units from Siwaliks to Darjeeling gneisses of various resistances and is characterised by coal mining and landslides (Basu, Ghatowar 1990; Basu, Ghosh 1993). Between 1930 and the late 1990s forest cover was reduced from 45% to 31%, and at the same time area occupied by agriculture and settlement increased from 16.75% to 45.5%. Data from 2001 reveal that the area affected by landslides increased from 1.5 to 5 km^2.

An alluvial fan spread to about 10 km in length and 3–5 km in width is found on the foreland, which narrows at two bridges, being crossed by railway and a national highway (Photo 2). Its surface descends from 200 to 120 m a.s.l. There are many records of floods and damage, during which the braided channel extended both upstream of the bridge even to 1.5 km wide and again downstream to 1 km wide (Fig. 29). The greatest extension followed between 1930 and 1980, when two major floods (in 1954 and 1968) were recorded. The first caused damage to the road bridge and the second also washed away the bridge and caused considerable damage to the Bagrakote and Washabari tea gardens. Bagrakote T.E. recorded 809 mm of rainfall on 3 consecutive days, while 5th October 1968 alone recorded 499 mm. The comparison of two satellite images from 1990 and 2001 presents the area covered by bars and shoals but does not show any distinct changes in their spatial dimensions (Fig. 30). However, it does reveal a continuous tendency to aggradation. The channel floor of the river was elevated by up to 2.5 m between 1982 and 2000. After Basu and Ghosh (1993), the total area covered by bars and shoals along the

Lish increased between 1930 and 2000 from 11.4 km^2 to about 18 km^2. In the recent past, three floods were recorded again, i.e. in 2002, 2005 and 2007.

In September 2007 a major flood caused breaching of a right-bank embankment between a railway bridge and road bridge, and the national highway was washed away and half of the village with surrounding fields was flooded (Photo 3).

9.3. THE GISH

The Gish river catchment is much larger (at 201 km^2), out of which 160 km^2 is located in the hills. Its length is 41 km (over 30 km in the hills). The dendritic system drains an area built of similar belts of rocks as in the Lish basin. The highest ridge in the headwaters rises to 2370 m a.s.l. This catchment is undergoing deforestation and coal mining, and many large landslides are located in the marginal part of hills especially (Basu, Ghatowar 1988).

Forest cover decreased between 1930 and the late 1990s, from 49 to 37% of total surface and agricultural land including settlement increased from 22.6% to 33.6%. An extension of the braided pattern followed between 1930 and 1980 when three creeks at the outlet from hills starting from 195 m a.s.l. formed an extensive fan 3 km wide (Fig. 29, Photo 4). In 1954 a devastating flood was recorded, during which about 10 km^2 of cultivated land was flooded and a silt layer up to 1 m thick was deposited.

Satellite images from 1990 and 2001 reveal that aggradations have extended upstream and the area of non-vegetated bars and shoals has been reduced (Fig. 30). This is visible especially in the root part of the fan in which hundreds of trees are buried by sandy – gravely bars (Photo 5). Between 1982 and 2000, the channel bottom rose by about 2 m, but many fragments have been revegetated especially downstream of two bridges (up to the junction with the river Tista), due to gradual incision of several branches of the channels. The width of the lowest course of the Gish river channel has thus been reduced from the former 2 km to about 0.5 km.

There were two severe floods (in 2002 and 2005), damaging the railway bridge and necessitating construction of new higher bridges.

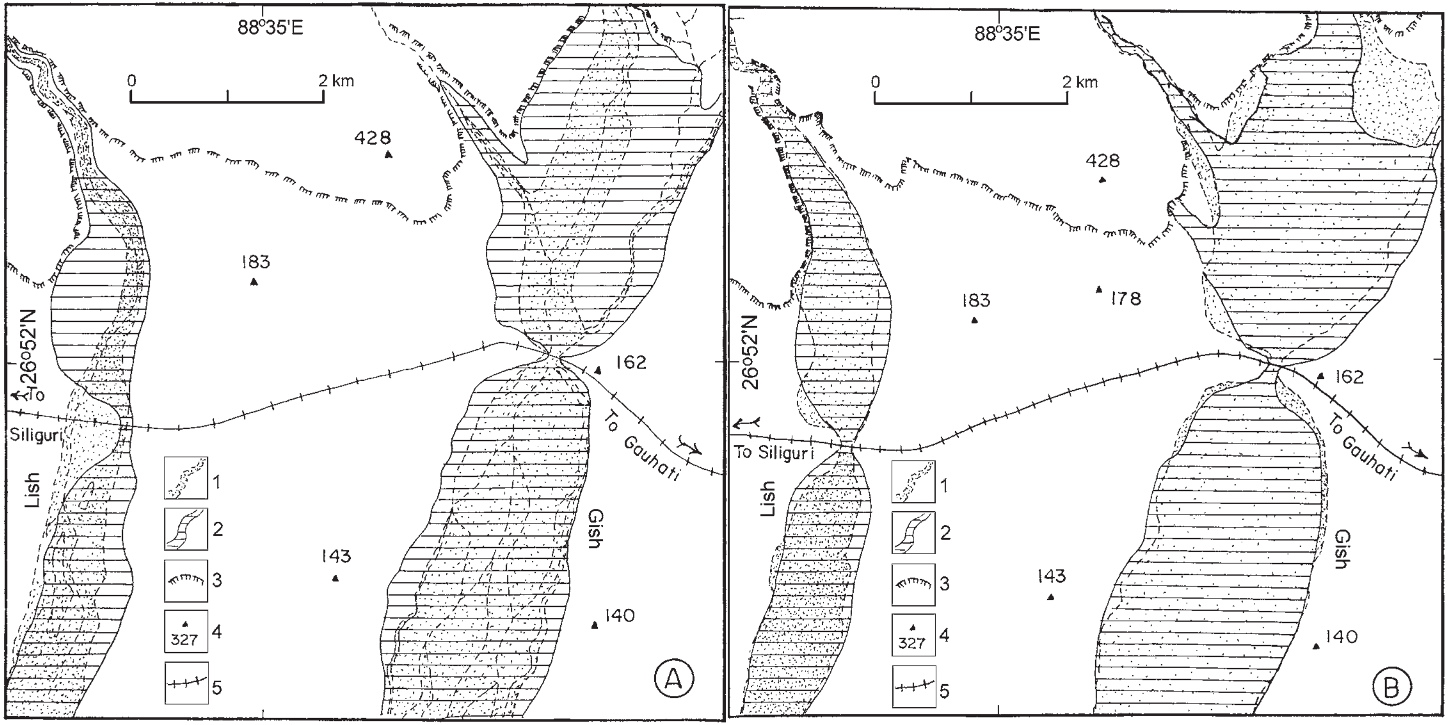


Fig. 29. Changes in alluvial fans of the Lish and Gish rivers (elab. by S. Sarkar)
A – between 1935 and 1964, B – between 1984 and 1998. 1 – extent of braided channel in 1935 (A) and 1984 (B), 2 – extent of braided channel in 1964 (A) and 1998 (B), 3 – margin of the Himalaya 4 – elevations (m a.s.l.), 5 – railway line (with bridges)

Zmiany stożków napływowych rzek Lish i Gish (oprac. S. Sarkar)
A – między latami 1935 i 1964, B – między latami 1984 i 1998. 1 – zasięg koryta roztokowego w 1935 (A) i 1984 (B), 2 – zasięg koryta roztokowego w 1964 (A) i 1998 (B), 3 – brzeg Himalajów, 4 – wysokości (m n.p.m.), 5 – linia kolejowa (z mostami)

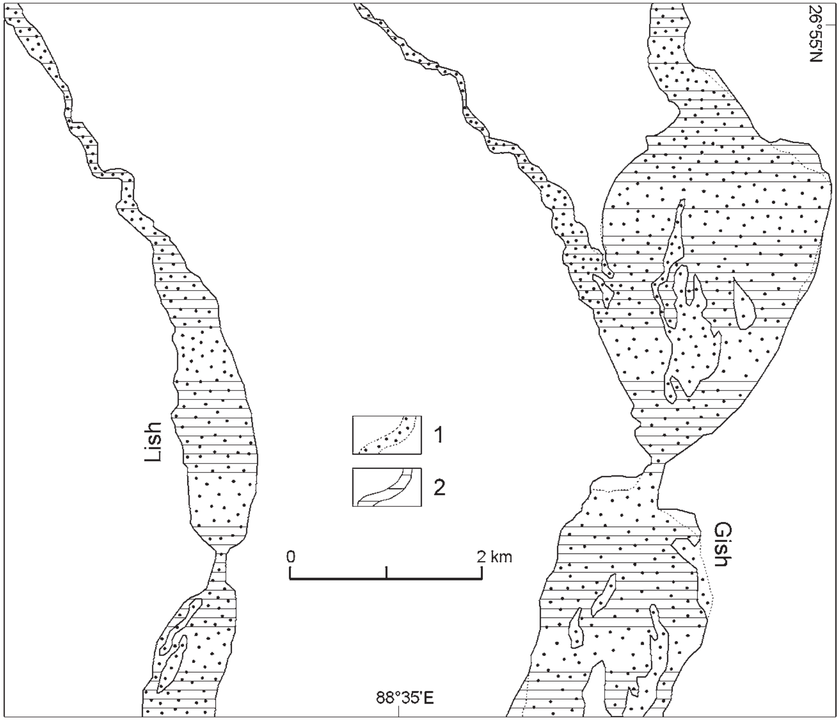


Fig. 30. Changes in alluvial fans of Lish and Gish rivers between 1990 and 2001, on the basis of satellite images (elab. by P. Prokop)
1 – river channel with bars in 1990,
2 – river channel with bars in 2001

Zmiany zasięgu stożków napływowych rzek Lish i Gish w latach 1990-2001 wg zdjęć satelitarnych (oprac. P. Prokop)
1 – koryta rzek z odsypami w 1990 r.,
2 – koryta rzek z odsypami w 2001 r.

9.4. THE CHEL

The river Chel is 16.3 km long in its upper segment. 5 km downstream of the outlet from the mountains it joins two smaller streams, the Mangzing and Sukha Khola. Altogether, the hilly catchment rising to 2400 m a.s.l. has an area of 97.4 km^2. The piedmont part is wide and the lower course up to the Tista some 47 km long. The valley floor with erosion terraces less than 0.4 km wide in the hills spreads rapidly into a large fan with a declining gradient of between 25‰ and less than 15‰ at 7 km distance. The root part of the fan is at an elevation of about 340 m a.s.l. Many small streams start on the plain, being fed by groundwater (Fig. 31). The active channel is found 3–5 m incised along the right margin of the fan, over which there is a distinct paleochannel of about 5 m deep and 600–800 m wide, turning to the SE (Photo 7).

At a distance of about 10 km from the hills, the older fan surface is separated by an E–W aligned scarp about 40 m high. At the base of the scarp, the paleochannel and present Chel channel are accompanied by a lower fan surface, which is bordered by another WNW–ESE fault line that the Chel follows (Fig. 7). The third former fan surface extends and slopes straight to the south, up to the Tista.

Downstream, the Chel meanders, before taking the left-bank tributary, the Mal, which also drains the mountain margin and has a meandering course with distinct point-bars along the next 10 km stretch. Of a similar nature is the lowest Chel segment about 10 km long, running up to the junction with the extensive braided Tista.

The SOI topographic map from 1965 plus the satellite images from 1990 and 2001 were used in making comparisons.

In 1965, the river Chel at the mountain outlet had several vegetated central bars and a total channel width reaching 200–400 m. The Mangzing Khola fan joins the Chel valley downstream, with valley width extending to 400–1100 m (Fig. 31). About 6 km further downstream, the width of the channel is reduced to 600–800 m, and – after narrowing (to <100 m) at two bridges – it widens again and further downstream bifurcates (total width up to 1500 m).

The image from 1990 shows three mountain channels each up to 100 m wide, with a total extension of up to 800 m near the junction and 4 km downstream above 1000 m, with three distinct branches separated by vegetated bars (Fig. 32). This denotes a tendency to stabilise contrasting with those of other rivers, this probably starting in the wake of the major flood hitting the Darjeeling Himalaya in 1968 (Starkel, Basu 2000). Downstream, the channel width is similar (at 200–400 m) both above and below the bridge, though aggradation is continuing (Photo 6).

The last survey from 2001 does not show any great change, except for a slight narrowing of the channel at the junction of the three creeks. But the shape of branches and vegetated bars differs very much, indicating normal fluvial activity but no catastrophic flooding. Indeed the heavy rain events in the Chel basin between 1993 and 2000 fluctuated across the range 200–500 mm only (Fig. 14).

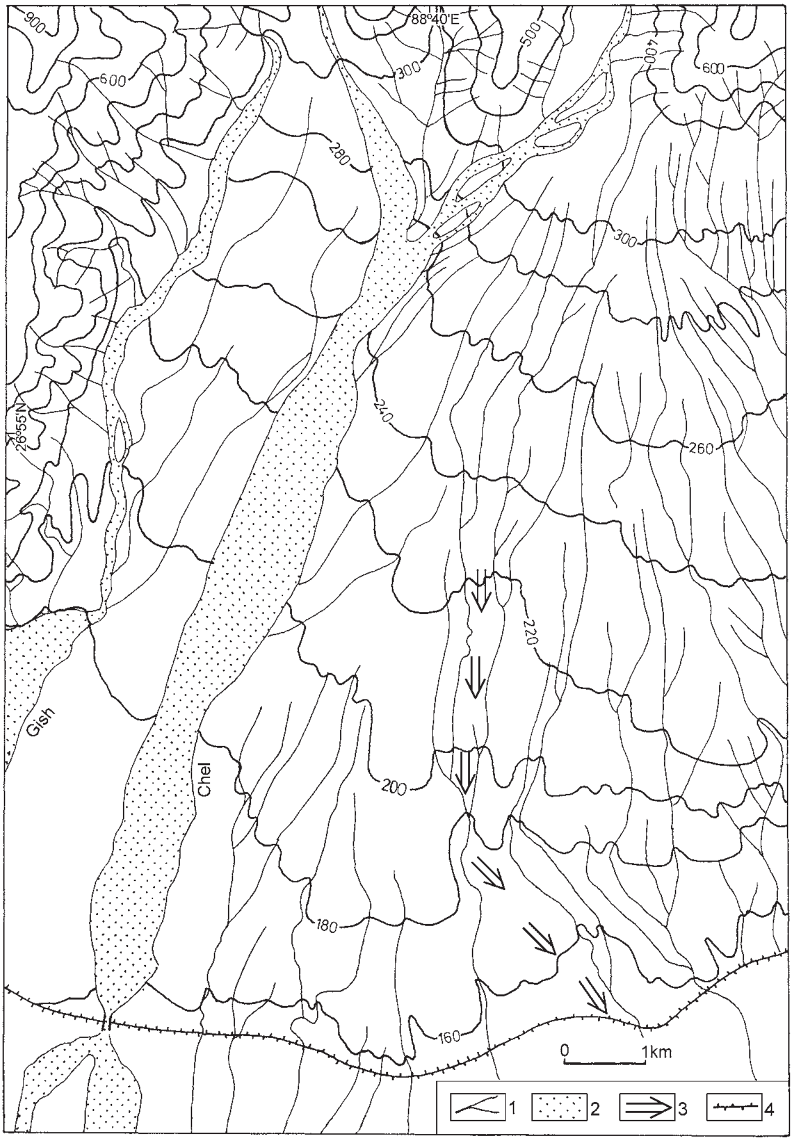


Fig. 31. Upper part of the alluvial fan of Chel river based on a topographic map surveyed in 1965. The wide braided channel did not extend in subsequent decades. 3 km east of the main channel is the visible palaeochannel up to 0.5 km wide.
1 – rivers, 2 – braided channel of the Chel, 3 – paleochannel, 4 – railway

Górna część stożka napływowego rzeki Chel wg mapy topograficznej z 1965 r. Szerokie koryto roztokowe, które później nie zostało poszerzone. 3 km na wschód od obecnego koryta rysuje się paleokoryto o szerokości do 0,5 km.

1 – rzeki, 2 – koryto roztokowe rzeki Chel, 3 – paleokoryto, 4 – linia kolejowa

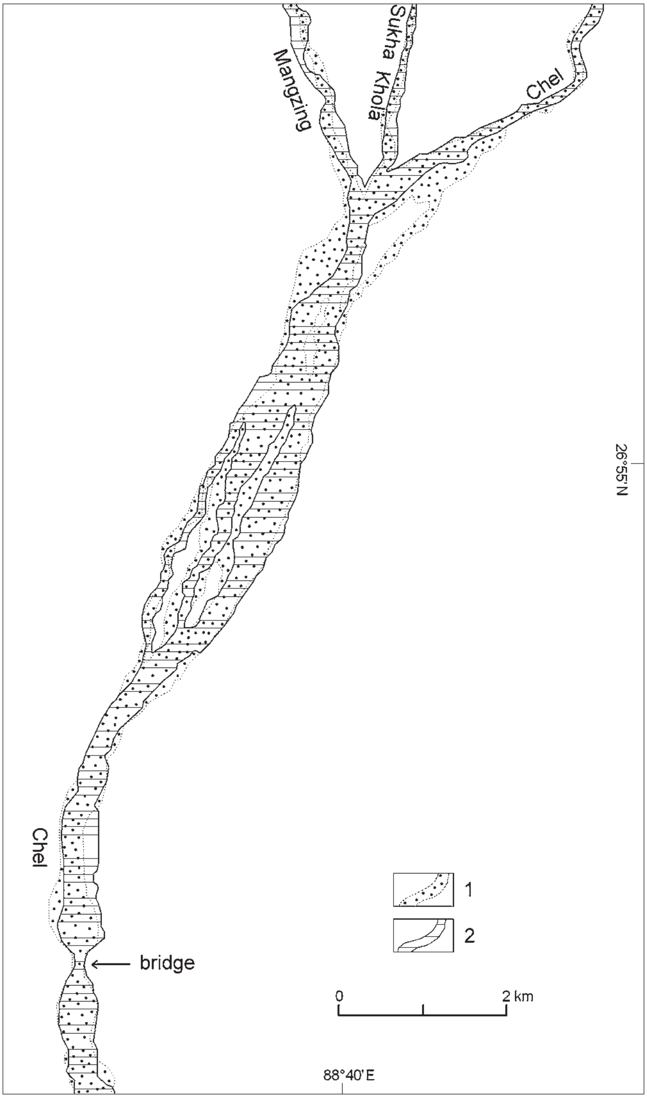


Fig. 32. Fragment of the alluvial fan of Chel river between 1990 and 2001, on the basis of satellite images (elab. by P. Prokop)

1 – river channel with bars in 1990, 2 – river channel with bars in 2001

Fragment stożka napływowego rzeki Chel w latach 1990–2001 wg zdjęć satelitarnych (oprac. P. Prokop)

1 – koryta rzek z odsypami w 1990 r., 2 – koryta rzek z odsypami w 2001 r.

9.5. THE JALDHAKA

The river Jaldhaka is the largest in the study area after the Tista and Torsa. At the outlet from the mountains it is only elevated at about 200 m a.s.l. The 65 km stretch of the river plus tributaries extends over an area of 787 km^2, also draining part of the higher Himalayan ridges rising to 5870 m a.s.l. Among its main tributaries before the junction with river Daina 35 km downstream are the left–bank tributaries like the Ghatia (30 km long, catchment 193 km^2) and the smaller Kuji Daina, as well as the right-bank tributary the Murti (47.5 km long, hilly catchment of 44 km^2).

The piedmont zone in this part differs markedly from others. The mountain front connected with MBF has retreated far to the north, and the gulf-like foreland is formed by several tectonic blocks displaying a tendency towards either uplift or subsidence. Finally, at a distance of 10–12 km from the hills, the river follows the W–E aligned 50 m scarp connected with the HFT fault line. The uplifted blocks preserve fragments of higher Quaternary terraces (Figs. 5 and 9), which after new radiocarbon dating on the Thaljhora North scarp prove to be thrusted parts of alluvial cover dating back to 27210±240 BP (Guha et al. 2007). The main rivers draining the area (the Murti, Jaldhaka and Ghatia) show a marked tendency to incision and are even transporting large big boulders (Photo 13 and 17). Only the Jaldhaka channel is wide. Therefore conditions for aggradation and the formation of young alluvial fans may begin to apply to the south of this tectonic scarp (Photo 14 and 16).

A detailed elaboration has been initiated along the river Jaldhaka near the junction with the Daina (Figs. 33 and 34). Also subject to analysis are the repeated three cross-sections (Fig. 35): (i) at the bridge on the outlet from the rising block (J3), (ii) at the junction with the Daina (J1) and (iii) 20 km downstream (J2) (cf. Fig. 28).

At the junction with the Daina, the braided Jaldhaka was 200–600 m wide in 1930, with a 1‰ gradient and manifesting a tendency towards meandering. At that time, the lowest course of the Daina was narrower, with a more distinct tendency to meander. By 1964, the Jaldhaka had shifted up to 1 km westwards, while its braided channel extended to 500 m and closer to the junction with Daina even to 1200 m. The river Daina river also bifurcated by that time (Fig. 33).

Satellite images from 1990 show that the Jaldhaka-Daina junction has shifted about 6 km upstream. At that time, the Jaldhaka valley expanded to 1.5 km in width, with about 30% being covered by revegetated bars. In wide contrast, the Daina channel at that time was only 200–300 m wide (Fig. 34). The cross-section at the confluence shows a common width of about 2800 m, with several channels incised 1–2 m in the sandy bar surface (Fig. 35).

In 1997, a single major flood caused the channel to extend again, reaching 1.0–2.5 km in width. In turn, the series of floods in 1998 as well in 2000 when the discharge several times exceeded 2000 m^3s^{-1} (and once even 5000 m^3s^{-1}), changed the branches of the Jaldhaka (as well as the lowest-course parts of the Daina) completely, as both the transect from February 2000 and the satellite image from 2001 confirm. The width of the lowest course of the Daina channel was twice as great as in 1990. The area of revegetated bars was reduced to 18% (Fig. 35), while a trend towards aggradation was also observable. Similar changes have been noted at transect J2, 20 km downstream. Only upstream near the bridge in the section with an uplift tendency (profile J3) is the trend towards incision visible between 1991 and 2000. Indeed, the channel bottom of the main stream has been lowered by more than 1 m.

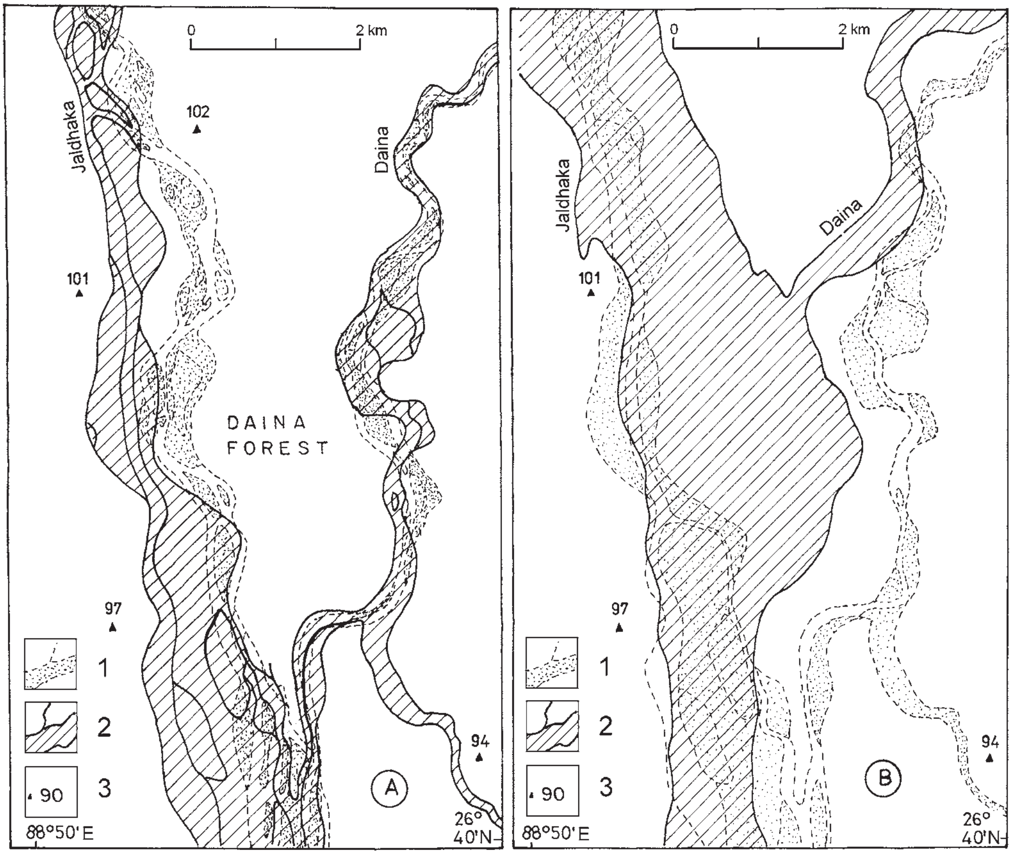


Fig. 33. Changes in river channels at the junction of Jaldhaka and Daina rivers (elab. by S. Sarkar). Note avulsion of junction.

A – between 1937 and 1964, B – between 1964 and 1997

1 – extent of braided channel in 1937 (A) and 1964 (B), 2 – extent of braided channel in 1964 (A) and 1997 (B), 3 – elevations (m a.s.l.)

Zmiany zasięgu koryt u zbiegu rzek Jaldhaka i Daina (oprac. S. Sarkar). Zwraca uwagę awulsja połączenia koryt.

A – między latami 1937 i 1964, B – między latami 1964 i 1997

1 – zasięg koryta roztokowego w 1937 (A) i 1964 (B), 2 – zasięg koryta roztokowego w 1964 (A) i 1997 (B), 3 – wysokości (m n.p.m.)

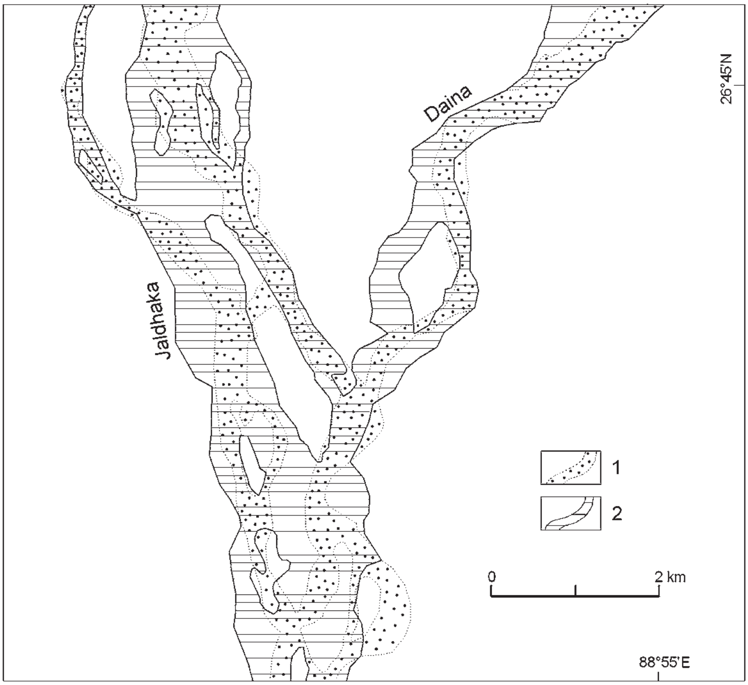


Fig. 34. Changes in river channels at the junction of Jaldhaka and Daina rivers between 1990 and 2001, on the basis of satellite images (elab. by P. Prokop)

1 – river channel with bars in 1990, 2 – river channel with bars in 2001

Zmiany zasięgu koryt u zbiegu rzek Jaldhaka i Daina wg zdjęć satelitarnych w latach 1990-2001 (oprac. P. Prokop)

1 – koryta rzek z odsypami w 1990 r., 2 – koryta rzek z odsypami w 2001 r.

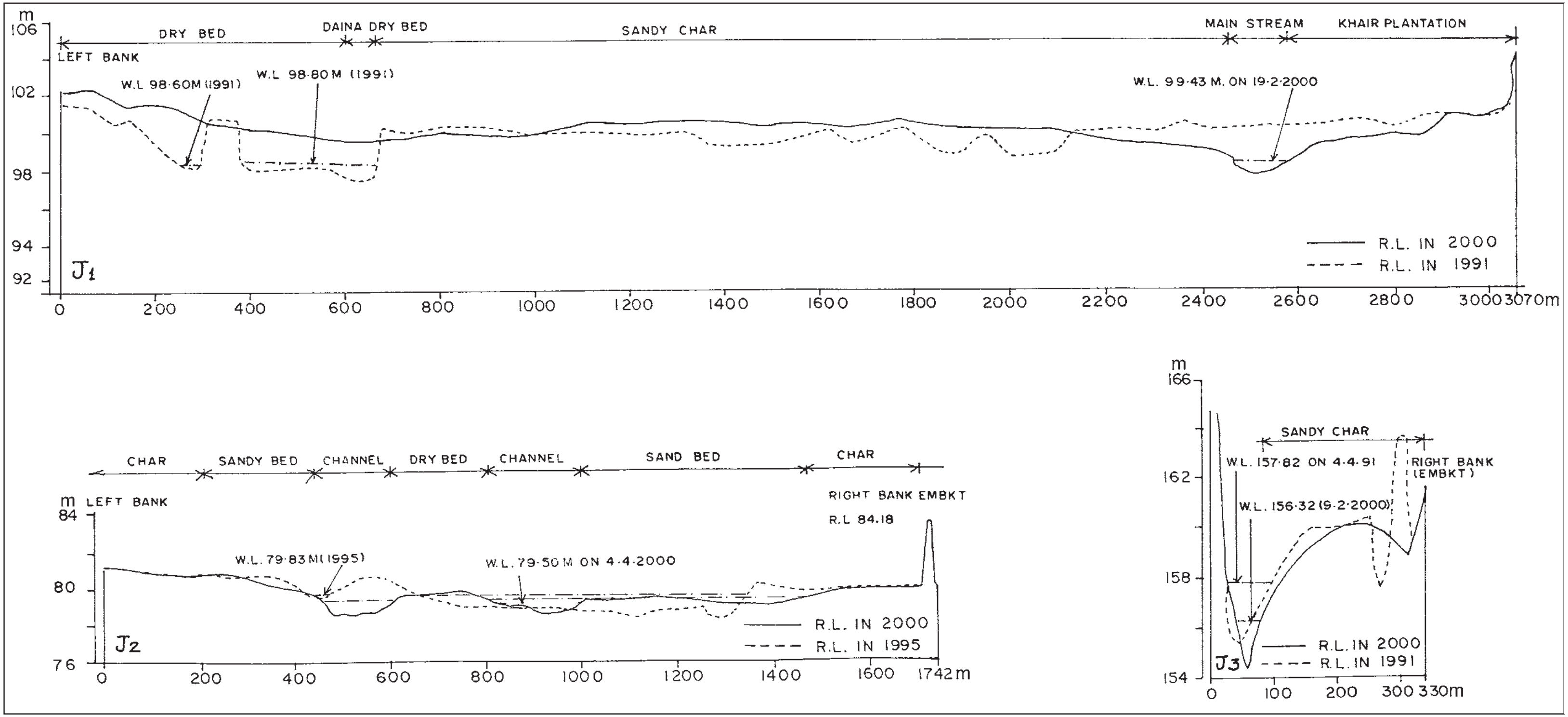


Fig. 35. Changes in channel cross-sections of Jaldhaka river between 1991 and 2000 (elab. by S. Sarkar).
J1, J2 and J3 (for location see Fig. 28) J1 – near junction of the Jaldhaka and Daina, J2 – near Dhupguri, J3 – at Nagrakata, R.L. – year of survey

Zmiany przekrojów koryt rzeki Jaldhaka między latami 1991 i 2000 (oprac. S. Sarkar)
J1, J2 i J3 (położenie jak na ryc. 28) J1 – u zbiegu rzek Jaldhaka i Daina, J2 – koło Dhupguri, J3 – w Nagrakata, R.L. – rok kartowania

9.6. THE DAINA AND CHAMURCHI

These two rivers join at the piedmont, where the steep scarp of the Himalaya rapidly turns south from latitudinal to longitudinal (Fig. 9). The river Daina flows directly from the north and the Chamurchi from the east, separating the marginal southern block of the hills. Both rivers form an extensive combined fan sloping to the SW–S, and with a mountain catchment that is more than 90% forested (Table 4).

The mountain catchment of the Daina occupies 108.6 km^2, the main channel being 17.6 km long and draining a belt 14 km wide. In the headwaters the main watershed rises to 3300 m a.s.l. From the outlet at an elevation of 360 m, two creeks start a 1 km wide fan followed in the west by fragments of terrace 50–150 m high. In its root part, this fan is inclined at about 25‰, this declining downstream to 15‰.

The catchment of the river Chamurchi flowing from the east and undercutting the steep scarp built of (very intensely exploited) dolomite and limestone is slightly smaller (at 93.6 km^2). The floor of the 13.7 km stream has undergone very intensive aggradation. The wide channel floor built of gravels and boulders is bounded on the left by a 12–15 m high scarp (lowering downstream to 5–7 m), this not being subject to flooding, and featuring inclines of between 24‰ and 12‰ downstream. The wide Chamurchi channel floor built of gravels and blocks up to 50 cm in size is only drained by a small creek during the dry season. Along its 8 km channel up to the junction with the Daina, the river Chamurchi descends from an altitude of about 360, to 240 m a.s.l. Beyond the junction, the wide braided channel continues up to the junction with the river Jaldhaka at a distance of 21 km, with just one narrowing at the railway bridge (Fig. 36, Photo 18).

The topographic map from 1930 reveals that the width of the Chamurchi channel fluctuates between 150 and 1000 m, with many vegetated bars. The channel of the Daina is narrow, only exceeding 200 m in width in its lowest part. Beyond the confluence, the width of both the braided channels increases to 500m, locally even to 1000 m.

In the 1960s, the Chamurchi channel was wider along its whole length, with vegetated bars reaching 1200 meters. The Daina channel in its upstream length spreads to 1000 m (including the vegetated parts). Downstream, the width of the Daina channel was of up to 1200 m along the whole length (measurement based on SOI map, 1965, Fig. 36).

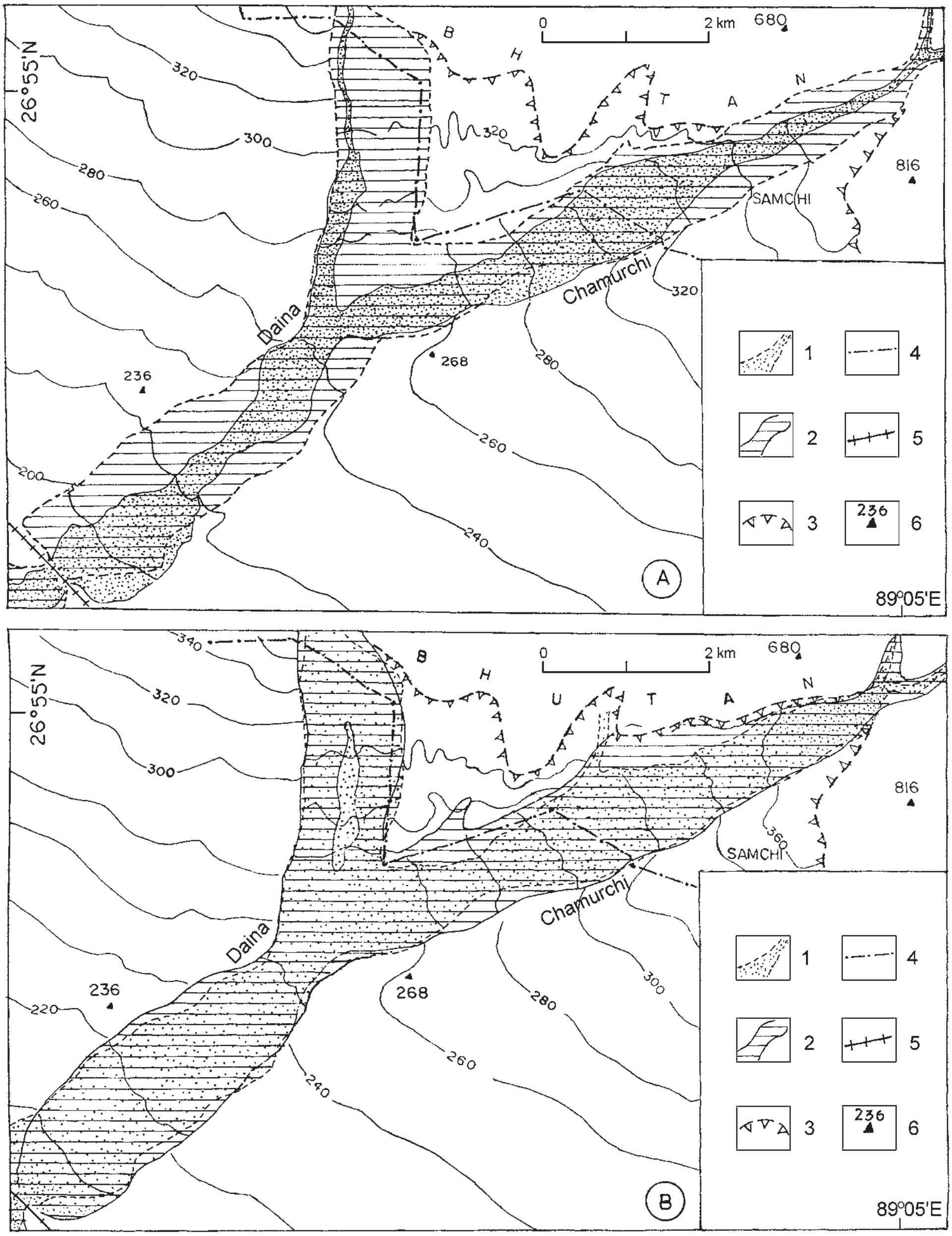


Fig. 36. Changes in the braided channels over the alluvial fan of Daina and Chamurchi rivers (elab. by S. Sarkar). A – between 1925 and 1966, B – between 1966 and 1998; 1 – extent of channel in 1925 (A) and 1966 (B), 2 – extent of channel in 1966 (A) and1998 (B), 3 – margin of the Himalaya, 4 – state border, 5 – railway, 6 – elevations (m a.s.l.)

Zmiany koryt roztokowych w obrębie stożków napływowych rzek Daina i Chamurchi (oprac. S. Sarkar). A – między latami 1925 i 1966, B – między latami 1966 i 1998; 1 – zasięg koryta roztokowego w 1925 (A) i 1966 (B), 2 – zasięg koryta roztokowego w 1966 (A) i 1998 (B), 3 – brzeg Himalajów, 4 – granica stanu, 5 – linia kolejowa, 6 – wysokości (m n.p.m.)

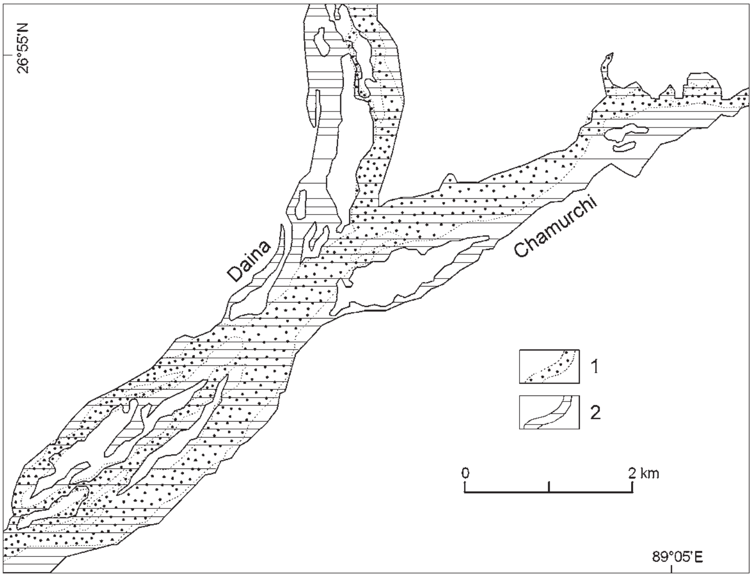


Fig. 37. Changes in the braided channels over the alluvial fans of Daina and Chamurchi between 1990 and 2001, on the basis of satellite images (elab. by P. Prokop)
1 – river channel with bars in 1990, 2 – river channel with bars in 2001
Zmiany koryt roztokowych w obrębie stożków napływowych rzek Daina i Chamurchi wg zdjęć satelitarnych w latach 1990–2001 (oprac. P. Prokop)
1 – koryta rzek z odsypami w 1990 r., 2 – koryta rzek z odsypami w 2001 r.

Table 5. Changes of channel forms of selected river reaches between 1990 and 2001 (see Fig. 28, elab. by P. Prokop)

River	Channel forms	Area (km^2)		Difference (km^2) 1990-2001
		1990 year	2001 year	
Lish (Fig. 30)	braided channel	3.33	3.22	-0.11
	vegetated bars	0.00	0.11	+0.11
	total	3.33	3.33	0.00
Gish (Fig. 30)	braided channel	10.71	9.92	-0.79
	vegetated bars	0.00	0.76	+0.76
	total	10.71	10.68	-0.03
Chel (Fig. 32)	braided channel	7.77	6.66	-1.11
	vegetated bars	0.89	0.98	+0.09
	total	8.66	7.64	-1.02
Jaldhaka (Fig. 34)	braided channel	6.68	10.32	+3.64
	vegetated bars	2.83	2.12	-0.71
	total	2.03	12.44	+10.41
Jaldhaka (Lower Daina) (Fig. 34)	braided channel	2.03	3.67	+1.64
	vegetated bars	0.00	0.54	+0.54
	total	2.03	4.21	+2.18
Chamurchi (Fig. 37)	braided channel	2.41	3.97	+1.56
	vegetated bars	0.06	0.72	+0.66
	total	2.47	4.69	+2.22
Daina (Fig. 39)	braided channel	6.17	10.56	+4.39
	vegetated bars	1.97	2.60	+0.63
	total	8.14	13.16	+5.02
Rehti (Fig. 39)	braided channel	4.80	6.44	+1.64
	vegetated bars	0.00	1.23	+1.23
	total	4.80	7.67	+2.87
Torsa upper (Fig. 46)	braided channel	16.44	22.32	+5.88
	vegetated bars	1.22	4.26	+3.04
	total	17.66	26.58	+8.92
Torsa lower (Fig. 49)	braided channel	9.01	12.46	+3.45
	vegetated bars	1.37	0.97	-0.40
	total	10.38	13.43	+3.05
Gabur-Basra (Fig. 51)	braided channel	5.29	10.22	+4.93
	vegetated bars	0.39	1.15	+0.76
	total	5.68	11.37	+5.69
Pana (Fig. 51)	braided channel	2.18	5.78	+3.6
	vegetated bars	0.10	0.26	+0.16
	total	2.28	6.04	+3.76
Bala (Fig. 55)	braided channel	3.00	2.27	-0.73
	vegetated bars	0.04	0.04	-0.00
	total	3.04	2.31	-0.73
Jainti (Fig. 55)	braided channel	6.80	4.22	-2.58
	vegetated bars	0.11	0.14	+0.03
	total	6.91	4.36	-2.55

The satellite image from 1990 again shows a minor extension of channels, as well as the presence of several vegetated bars. In contrast, satellite imagery from 1996 reveals that channel width had extended, with the disappearance of the elevated fragments, probably through vertical aggradation (Fig. 37).

The satellite image from 2001 shows an extension of river channels similar to that which was present in 1990, though the percentage of vegetated islands has changed in comparison with 1990 (Fig. 37, Table 5). Extension of vegetation-free channels downstream beyond the confluence was clearly visible, this being connected with continued aggradation in the course of the series of floods arising in the 1990s.

9.7. THE REHTI

The shape of the catchment and course of the river Rehti is special in character. The Rehti drains a 65.6 km^2 area in a marginal part of totally forested hills rising to 1800 m a.s.l. Flowing westwards, it leaves the mountains at an elevation of about 260 m a.s.l. (Fig. 9). At this place the Rehti rapidly turns south, following the edge of the mountains and receiving a small tributary, the Sukreti Khola, from the north. This creek also follows the mountain front along 4 km of its length, draining 8 km^2 in the hills (Photo 19), and having on its right side the large, older fan of the river Chamurchi (described above). The flat channel floor of the Rehti, consisting of sand, gravel and boulders of up to 0.5 m in diameter is totally dry in the winter season (Photo 20). At the turn south, channel width increases rapidly above 1 km, while the gradient declines gradually from 15 to 10‰. At about 6 km downstream, the fan surface is wider, but channel width is in decline. At a distance of 15 km from the mountain front, the Rehti joins the Dimdima, the channel narrowing at the road bridge 2 km further south. In this part, the channel has filled up with fine sand and silt, and is accompanied by a 3–5 m higher terrace surface built of a thick silt-clay deposit that is exploited by many brickyards (Photo 21). The presence of such fine alluvial deposits so close to the Himalayan foothills is probably connected with the weathering of schists and marls accompanying dolomite beds.

The Rehti preserves its braided character further downstream, joining the Jaldhaka after a further 28 km.

The first map of the river Rehti from 1930 shows a braided character and aggradations entering into the mountains. At the turn south, the channel widens from 400 to 600 m, even to 900 m further downstream (Fig. 38). The width of the channel decreases to 200 m at 6 km downstream. 35 years later the channel width was double with two branches, the left one being 600 m wide. At 3–4 km downstream, the two branches met together again and the whole channel width gradually declined from 900 m to 300 m.

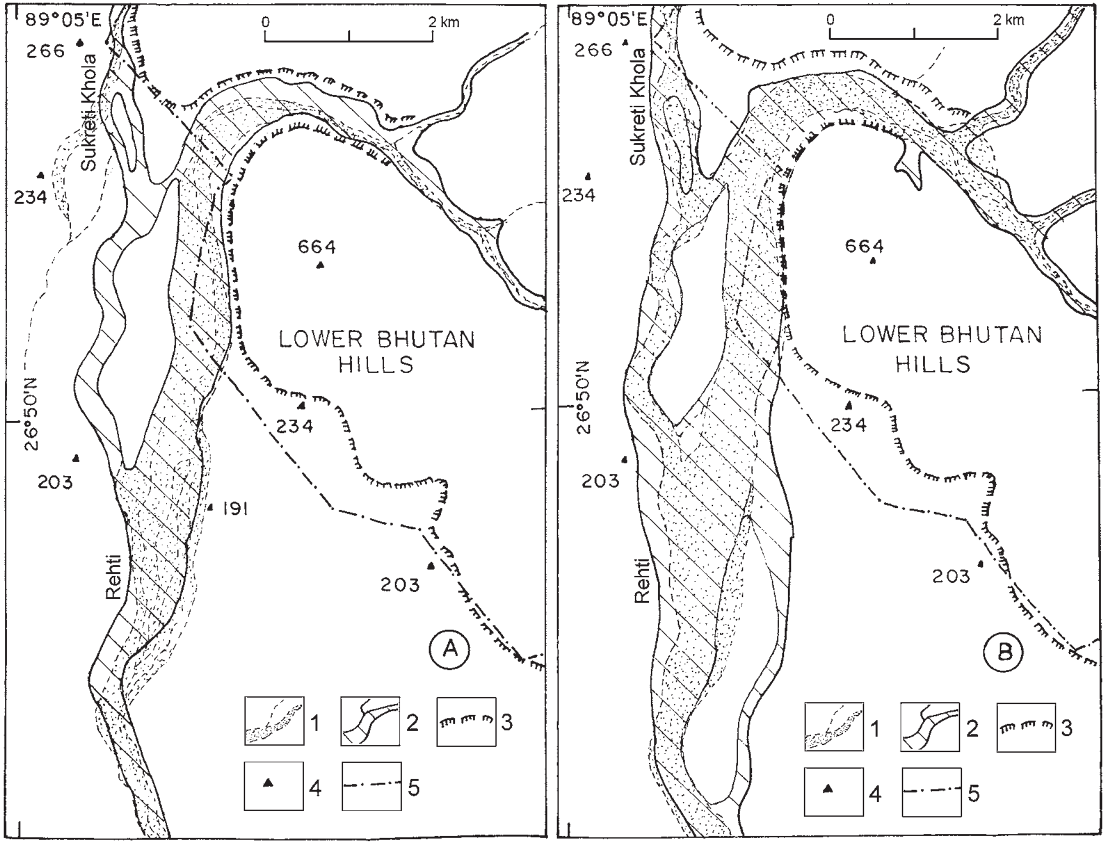


Fig. 38. Changes in the braided channel over the alluvial fan of Rehti river (elab. by S. Sarkar)

A – between 1929 and 1964, B – between 1964 and 1996

1 – extent of channel in 1929 (A) and 1964 (B), 2 – extent of channel in 1964 (A) and 1996 (B), 3 – margin of the Himalaya, 4 – elevations (m a.s.l.), 5 – state border

Zmiany koryta roztokowego w obrębie stożka napływowego rzeki Rehti (oprac. S. Sarkar)

A – między latami 1929 i 1964, B – między latami 1964 i 1996

1 – zasięg koryta roztokowego w 1929 (A) i 1964 (B), 2 – zasięg koryta roztokowego w 1964 (A) i 1996 (B), 3 – brzeg Himalajów, 4 – wysokości (m n.p.m.), 5 – granica państwa

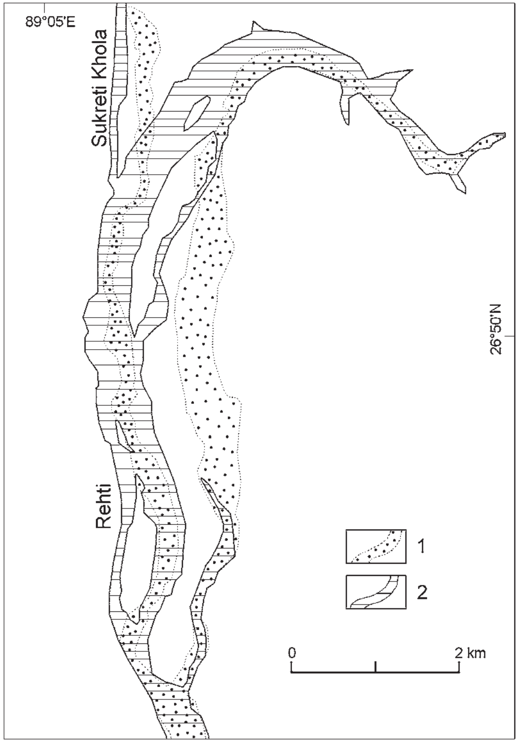


Fig. 39. Changes of the alluvial fan of Rehti river between 1990 and 2001, on the basis of satellite images (elab. by P. Prokop)
1 – river channel with bars in 1990, 2 – river channel with bars in 2001

Zmiany stożka napływowego rzeki Rehti wg zdjęć satelitarnych w latach 1990-2001 (oprac. P. Prokop)
1 – koryta rzek z odsypami w 1990 r., 2 – koryta rzek z odsypami w 2001 r.

On the satellite image from 1990 the river Rehti is seen to be wide, but no longer with two branches. At 2–3 km downstream, a new vegetated central bar appeared. The image from 1996 shows great extension of aggradation, both upstream into the mountains and in the foreland, where the width reached 1500 m (Fig. 38). The satellite image from 2001 presents the retreat of aggradations after a series of floods, reflected in a slight narrowing of the active channel. Nevertheless, a comparison of the two images from 1990 and 2001 shows a c. 50% extension of channel area in the surveyed section (Fig. 39, Table 4).

9.8. THE PAGLI, SUKTI AND DIMDIMA

These three rivers have their headwater area in the marginal part of the Himalaya and their catchments are forested by above 90%. But in the mean time this area has been heavily damaged by many landslides and debris flows in the course of several episodes of heavy rain in the 1990s (Starkel, Sarkar 2002). The W–E aligned mountain edge is dissected by several river valleys each at 2–4 km distance, these having a NE–SW alignment probably connected with the uplift of the eastern part along N–S directed fault lines. The marginal part has a character of foothills rising above 1500 m a.s.l. The hilly catchments are very small, covering 15.9, 16.6 and 4.8 km^2 respectively in the cases of the three described rivers. When the zone of degradation is compared with the system of alluvial fans, the last extensive piedmont area is seen to be disproportionally large. It slopes towards the SW (in the upper part). Downstream, the river courses turn south (Photo 23–25, Fig. 40), and at a distance of 40 km from the Himalayan front the river meets the Jaldhaka. The root parts of these fans are located at various elevations on the mountain edge i.e., the Pagli at 400 m a.s.l., the Sukti at 310 m and the Dimdima at only 240–260 m a.s.l. (Fig. 9).

The largest fan is connected with the easternmost Pagli river, the fan root part of which follows its western margin, undercutting the steep slopes dissected by dozens of gullies with debris flows (Photo 24). The fan extends rapidly from the root part elevated 400 m a.s.l. to about 5 km wide at a distance of 6 km from the hills and joins with neighbouring fans. The Pagli fan has very steep gradients, ranging from about 30‰ in the root part to below 20‰ 6–8 km downstream.

The SOI topographic map from 1930 shows that the Pagli channel was only 100 m wide at the mountain edge, while over the fan, only the central branch had a braided channel, though some water used lateral channels across the jungle or tea gardens (Fig. 40, Photo 23 and 25). The 1966 topographic map shows the width of the unvegetated channel which was 500 m in the root zone, undercutting a steep mountain slope with the channel bifurcating further downstream. The central branch of the Pagli channel was 300 m wide downstream below 200 m, while the right branch was only 50 m wide.

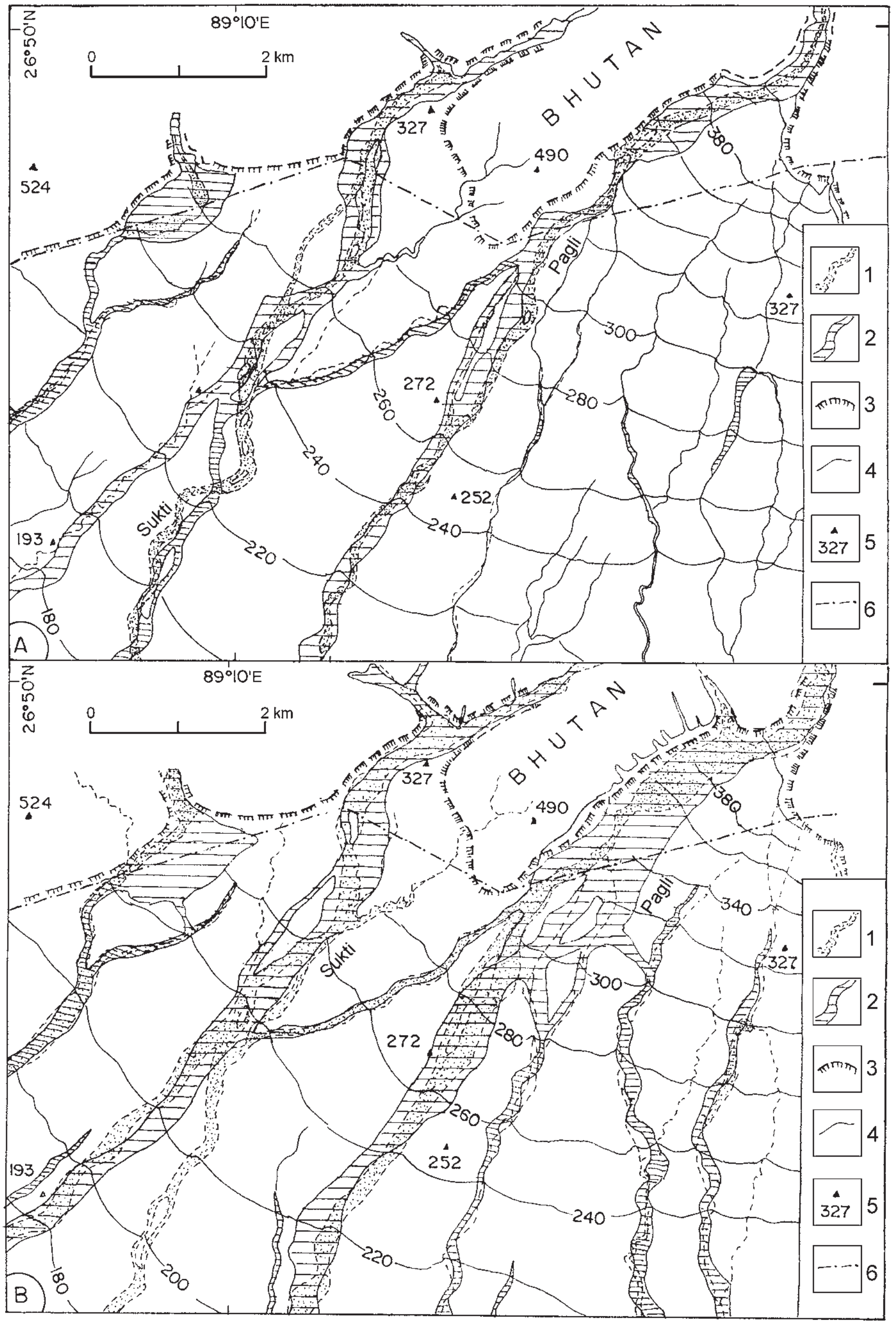
The satellite image from 1990 (Figs. 41 and 42) shows a similar pattern, though distinct lateral expansion up to 900 m is noticeable. The existence of vegetated bars in the zone of bifurcation indicates a tendency for aggradation to take place. A satellite image from 1996 following the two flood events of 1993 and 1996 records the continuation of this tendency and aggradation in the two left channels. Especially distinct is the impact of the 1998 flood (Fig. 43). Prior to the bifurcation, the channel width extends to 1200 m. The width of the central branch fluctuates between 250 and 600 m. The satellite image from 2001 (after the 1998 floods) indicates local extension, but a gradual narrowing downstream. The trend to aggradation is documented by a 2.54 m rise in the channel bed over the seven years 1993–2000.

In 1930, the river Sukti at the fan root zone had two branches of 1.5 km length, while its braided channel with small central bars had started meandering further downstream (Fig. 41). By 1966, the aggradation had proceeded upstream into the mountains. At the outlet channel it expands to 600 m in width. The former bifurcation is cut off, while a new right-hand channel 200 m wide had formed downstream after the confluence with the Pagli (Photo 23). The former channel has shifted laterally, but still exists.

The satellite image of 1990 shows a similar channel pattern, but downstream to the junction with the Pagli branch, the left channel is totally revegetated (Fig. 40). The next image from 1996 reveals an extension of the channel at the mountain outlet up to 500 m, and the existence of one wide channel further downstream. The image from 2001 presents continuous aggradation in the fan root zone of 3 branches and at 2.5 km downstream the channel is separated by two vegetated islands. The total width of the river increases to 1200 m. This demonstrates the probable effect of floods in 1998 and 2000. Downstream the river channel is of a shape and width similar to those pertaining in 1996.

The third small creek, the Dimdima, drains only 4.8 km^2 of a hilly area rising to about 1000 m a.s.l. There are only two gullies above 200 m deep cutting the southern edge of the hills, which turns rapidly to the north, where another small creek, the Bahune Khola, drains the west-facing scarp and joins the Dimdima at a 7 km distance.

Later, the Dimdima heads south before joining the right main branch of the river Sukti 1.5 km downstream, and flowing southwards to become known as the Dimdima. The main headwater gully, called the Khagra Jhora on the


26°50'N
89°10'E
0
2 km
BHUTAN
327
490
524
380
Pagli
300
327
272
280
260
240
252
240
Sukti
193
220
180
A
1
2
3
4
327
5
6
26°50'N
89°10'E
0
2 km
BHUTAN
327
524
490
380
340
Pagli
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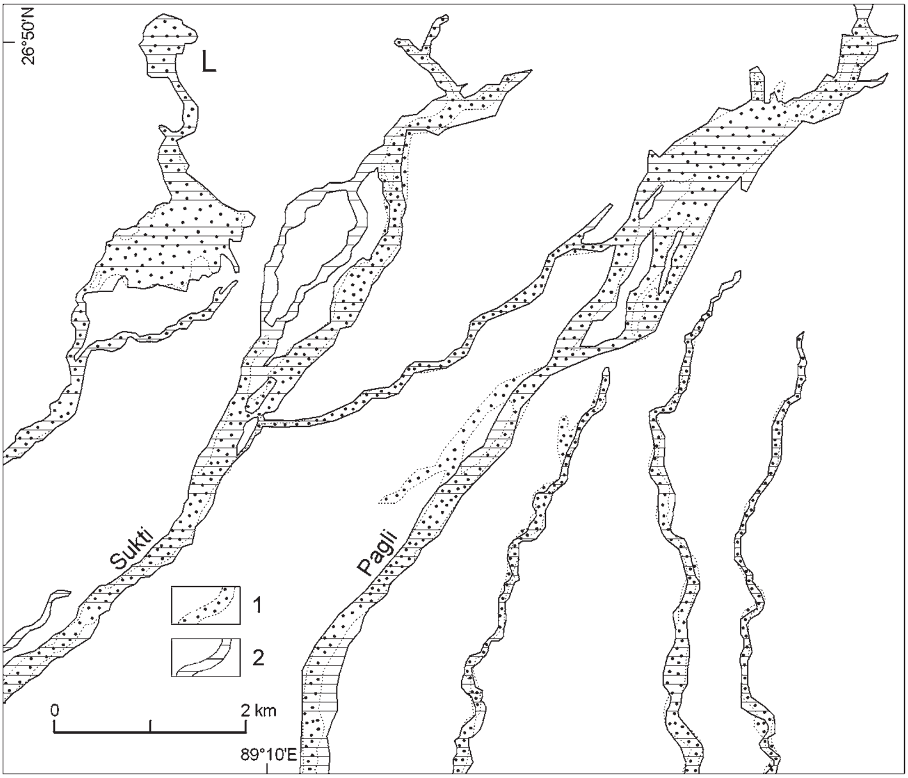


Fig. 41. Changes in river channels over alluvial fans of the Pagli-Sukti river system between 1990 and 2001, on the basis of satellite images (elab. by P. Prokop)
1 – river channel with bars in 1990, 2 – river channel with bars in 2001, L – Khagra Jhora valley

Zmiany koryt w obrębie stożka napływowego rzek Pagli-Sukti wg zdjęć satelitarnych w latach 1990-2001 (oprac. P. Prokop)

1 – koryta rzek z odsypami w 1990 r., 2 – koryta rzek z odsypami w 2001 r., L – dolina Khagra Jhora

Fig. 40. Changes in channels over alluvial fans of the Pagli-Sukti river system (elab. by S. Sarkar)
A – between 1930 and 1966, B – between 1966 and 1996
1 – extent of channel in 1930 (A) and 1966 (B), 2 – extent of channel in 1966 (A) and 1996 (B), 3 – margin of the Himalaya, 4 – contours (m a.s.l.), 5- elevations (m a.s.l.), 6 – state border

Zmiany koryt w obrębie stożka napływowego rzek Pagli-Sukti (oprac. S. Sarkar)

A – między latami 1930 i 1966, B – między latami 1966 i 1996

1 – zasięg koryta roztokowego w 1930 (A) i 1966 (B), 2 – zasięg koryta roztokowego w 1966 (A) i 1996 (B), 3 – brzeg Himalajów, 4 – poziomice (m n.p.m.), 5 – wysokości (m n.p.m.), 6 – granica państwa

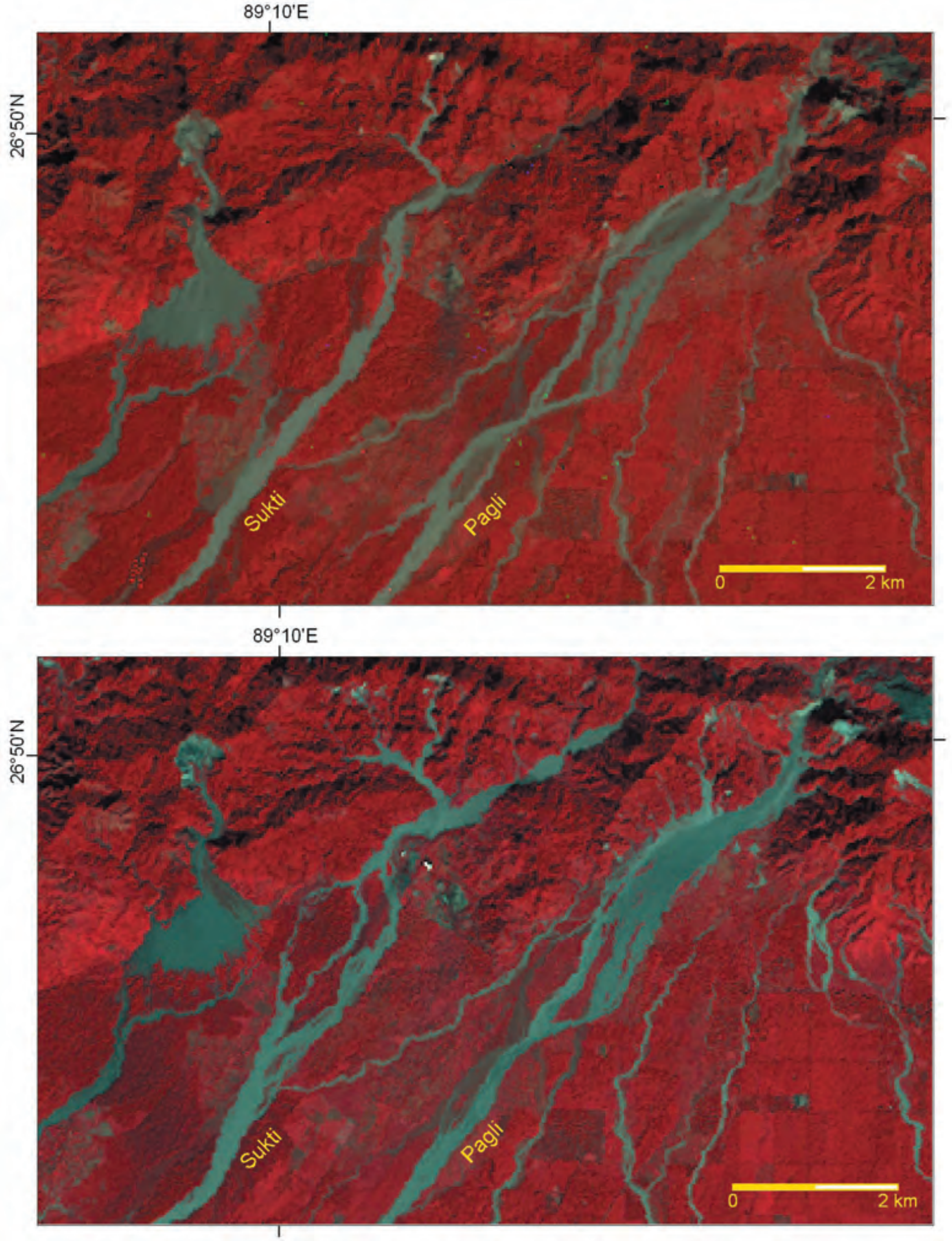


Fig. 42. Satellite images (FCC) of the Pagli-Sukti alluvial fans in 1990 (upper) and 2001 (lower). Note avulsions and extension of river channels after several floods between 1993 and 2000. River branches after avulsion have mainly been revegetated. New branches frequently use old paleochannels.

Zdjęcia satelitarne (FCC) stożków napływowych rzek Pagli-Sukti w 1990 (górne) i 2001 r. (dolne). Zwraca uwagę awulsja i poszerzenie koryt rzecznych po kilku powodziach w latach 1993–2000. Ramiona rzek po awulsji na ogół porosła roślinność. Nowe ramiona często wykorzystują stare koryta.

Fig. 43. Comparison of two satellite images from December 1996 and November 1998 in the catchments of Pagli and Titi river (after Starkel and Sarkar 2002)

1 – landslides and braided channels recorded in 1996, 2 – extension of landslides and braided channels after 2 years

Porównanie dwóch zdjęć satelitarnych z grudnia 1996 r. i listopada 1998 r. w zlewniach rzek Pagli i Titi (za Starkel, Sarkar 2002)

1 – osuwiska i koryta roztokowe zanotowane w 1996 r., 2 – wzrost zasięgu osuwisk i koryt roztokowych po 2 latach

SOI map of 1930, does not show any colluvial fan over the piedmont surface. The 1966 SOI map shows an incision in the upper part of the Khola and an unvegetated fan about 0.5 km long and 0.9 km wide spreading in the jungle. The satellite image of 1990 shows a large fan 1 km long and 1.8 km wide, this being further expanded in subsequent years, and drained by a small marginal stream at the base of a fan, as is depicted in the images from 1996 and 2001. Field observations made in 2000 and later prove conclusively that this fresh fan is connected with a large landslide about 3 km long and with a steep active niche (Photo 22). This landslide is the best example of chronic mass movements supplying the fans in the foreland, helping us to understand the relationship between the narrow mountain frontal belt and the widely spread fans of the piedmont zone.

9.9. THE SYSTEM OF RIVERS DISSECTING THE HIGH TERRACE

Counting from the west, the river Titi is the last to dissect more deeply the marginal part of the Himalaya, and to have a braided channel 500 m wide extending after the floods of the 1990s (Starkel, Sarkar 2002;, Fig. 43). The edge of the mountains rising from 300 to 1000 m a.s.l. turns to the NE and reaches the Torsa valley to the east (Fig. 7). The slope of the scarp is not deeply dissected, but is the source area for streams draining the 3–5 km wide piedmont bench, elevated to 200–300 m a.s.l. and separated by a distinct fault line from the valley floor of the Torsa. This flat bench is built of gravels and sands of the older Pleistocene terrace, and the straight-line, 50 m-high scarp suggests very active uplift. The terrace surface is covered by jungle and is drained by more than ten parallel seasonal streams incised 20–40 m. During the heavy rains of the last 15 years, these have aggraded so much that buried trees have also been noted during field observation (Fig. 44, Photo 26). Alluvial-colluvial fans 100–500 m long have been identified at the front of every creek, these having very steep slopes of between 5^{o} to 10^{o}, making these steeper than the gradient of valley bottoms upstream. It seems that the bottoms of seasonal streams hang over the base of the uplifted terrace. Fine material is spread over the bottom of a marginal depression of the wide Torsa floor, floodwater following this depression and draining it as a meandering tributary of the Torsa (Photo 28).

The satellite image from 1998 shows very clearly that the valley floors and fans are covered by fresh alluvia (Fig. 44). However, the image from 2001 reveals large-scale revegetation on the fresh alluvia. This tendency was well observed during the field visit in 2003.

Among these parallel creeks the only exception is the seasonal Najtri Nadi, the last to the north-east. Its flat floor built of gravels is 200–300 m wide, be-

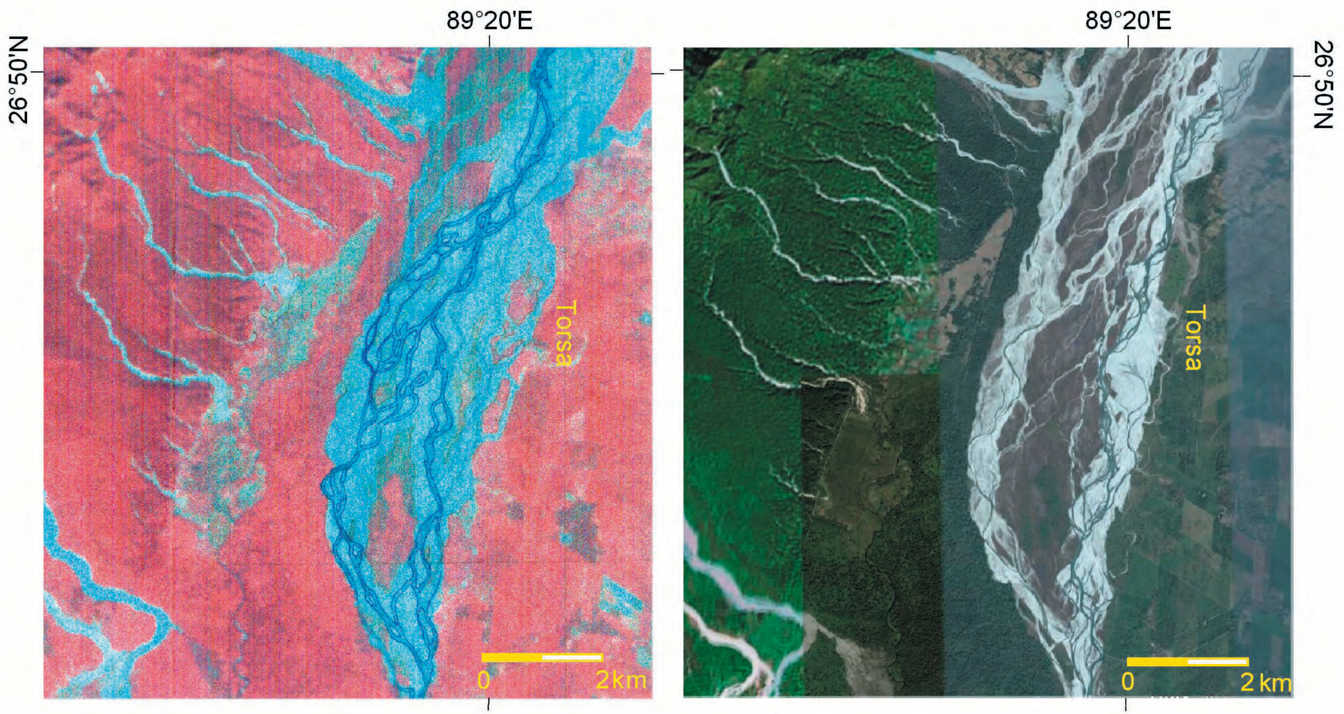


Fig. 44. Satellite images (FCC – left in 1998, GoogleEarth – right in 2004) of valleys dissecting the uplifted high terrace west of the Torsa river (see no. 7 on Fig. 28). Note the gradual revegetation of small alluvial fans. Along the Torsa there are distinct visible changes in river branches, as well as revegetation of bars.

Zdjęcia satelitarne (FCC – lewe z 1998 r., GoogleEarth – prawe z 2004 r.) dolin rozcinających podniesioną terasę na zachód od rzeki Torsa (zob. nr 7 na ryc. 28). Zwraca uwagę stopniowe porastanie roślinnością małych stożków napływowych. Na rzece Torsa widać wyraźne zmiany ramion rzecznych, a także porośnięte przez roślinność odsypy.

ing in the nature of an active debris flow filling the wide valley such that the older terrace plateau only rises 3–5 m above the floor (Fig. 44). The lack of vegetation and fresh features are connected with the extensive niche of a landslide at the mountain scarp which supplies fresh debris every year. This valley floor also has a steep gradient in its lower portion, before the spreading of the extensive fan on the bottom of the Torsa valley. That steeper part is just at the crossing of a SW–NE aligned fault line.

The described area is a good example of relief transformation in the piedmont zone without the influence of transit Himalayan river both by heavy rains extending not only over the mountain front and by differentiated tectonic movements.

9.10. THE TORSA (MIDDLE COURSE)

The Torsa river catchment is one of the largest in the Sikkimese-Bhutanese Himalaya. It drains the highest range rising to 7065 m a.s.l. Its mountain catchment up to Phuntsholing covers more than 3800 km^2. On the 172 km-long mountain reach, the Torsa is deeply cut into various metamorphic rocks, partly meandering and with a tendency to aggrade in the marginal part of the mountains supplied by debris flows (Photo 27). Fed by rains, but also by meltwaters from glaciers and snow cover, the Torsa resembles the Tista in being a perennial river. During extreme floods its highest discharge has reached 12230 m^{3}s^{-1} (specific discharge 3.02 m^{3}s^{-1}km^{-2}). At the mountain foreland till the junction with Jaldhaka near Cooch Behar on its way to 193 km long journey the river Torsa forms a narrow fan (about 5 km wide), which at a distance of 15 km from the hill margin expands to 10–15 km, with distinct avulsions (Figs. 7 and 48). The river gradient declines downstream, from about 6‰ at the mountain front to 3–2‰, the braided channel with gravel bars finally turning into a meandering pattern with point bars.

The reasons for such an unusual shape of the fan are twofold, reflecting: (i) the presence of a small, active tributary, the Gabur Jetia from the east, with a gravely – sandy fan pushing the Torsa valley westwards and (ii) the NNE–SSW aligned faultline- elevated old terrace reaching 100 m, which forms a shelf several km wide at the foreland of the mountain front to the west of the Torsa.

Along the river Torsa two segments each about 11 km long were selected for detail recognition of channel changes during last century.

9.10.A. The upper one is located between the outlets of the left-bank tributary, the Gabur Jetia creek, but upstream of the bridge on the national highway. The floodplain is elevated to between 165 and 125 m a.s.l., and the gradient declines from about 6‰ to 3‰. In 1930, the straight braided channel with several branches was 900–1200 m wide. Later, in the 1960s, the analogous channel was wider, at even above 1500 m. After several floods in the 1990s, the width extended further to 2–2.5 km, with several vegetated islands between channel branches. Probably the greatest transformation took place in the flood of 1996 (when Phuntsholing recorded 793 mm of rain in four days and the water level was about 3 m above its maximum during drier years) (Figs. 45 and 21).

Comparison of the two satellite images from 1990 and 2001 (as separated by four major floods) reveals distinct expansion of the braided channel and the entry of aggradation into the distributary channels over a floodplain (Fig. 46). The width increases by 50% and the area of unvegetated bars by only 36% but of vegetated islands by 250%. The comparison of channel patterns between 1998 and 2001 does not show any distinct changes (revegetation), probably because of yet a further flood in the year 2000 (Figs. 44, 46 and 47).

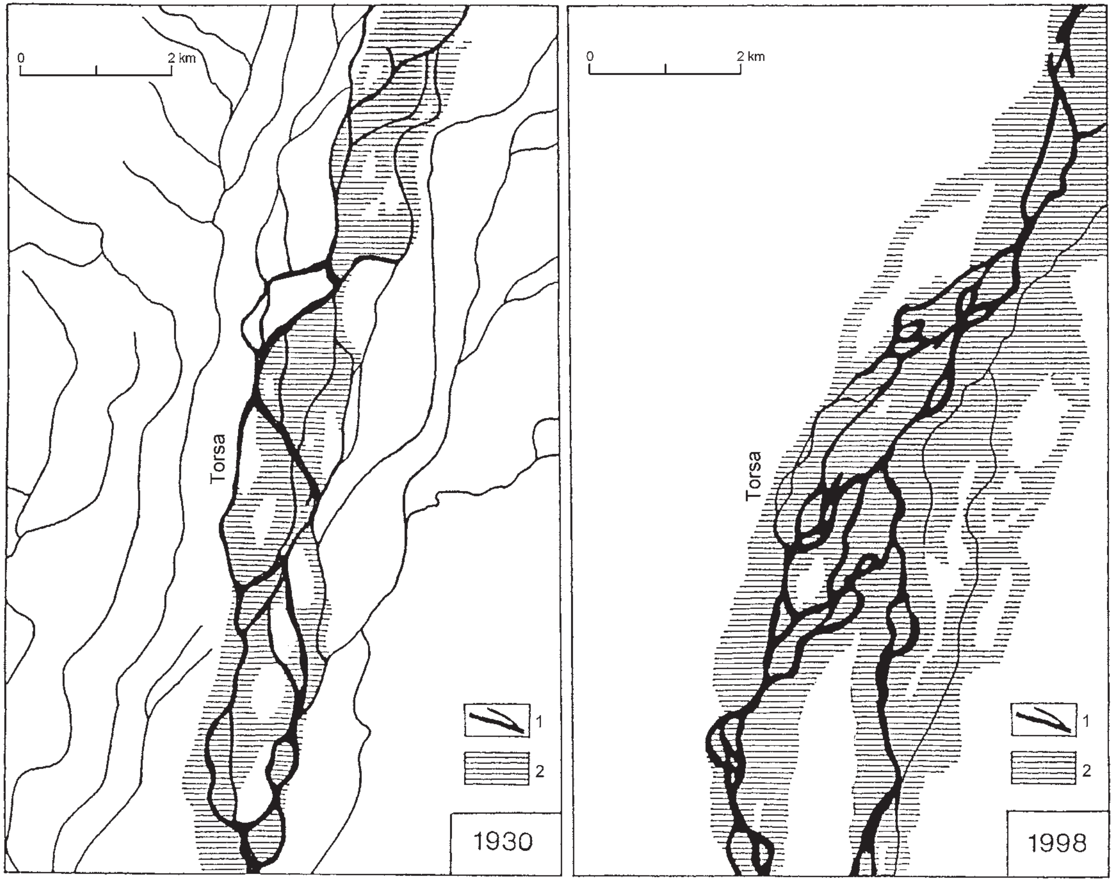


Fig. 45. Change in the braided channel pattern in the upper fragment of the Torsa's middle course (area 8 on Fig. 28), on the basis of the topographic map from 1930 and satellite imagery from 1998 (after Starkel and Sarkar 2002)

1 – branches of the Torsa and other streams, 2 – unvegetated bars

Zmiany koryta roztokowego górnego fragmentu rzeki Torsa w jej środkowym biegu (obszar 8 na ryc. 28) na podstawie mapy topograficznej z 1930 r. i zdjęcia satelitarnego z 1998 r. (za Starkel, Sarkar 2002).

1 – ramiona rzeki Torsa i inne cieki, 2 – świeże odsypy

Fig. 46. Changes in the braided channel pattern in the upper fragment of the Torsa's middle course between 1990 and 2001, on the basis of satellite images (elab. by P. Prokop)

1 – river channel with bars in 1990, 2 – river channel with bars in 2001

Zmiany koryta roztokowego górnego fragmentu rzeki Torsa w jej środkowym biegu wg zdjęć satelitarnych w latach 1990–2001 (oprac. P. Prokop)

1 – koryta rzek z odsypami w 1990 r., 2 – koryta rzek z odsypami w 2001 r.

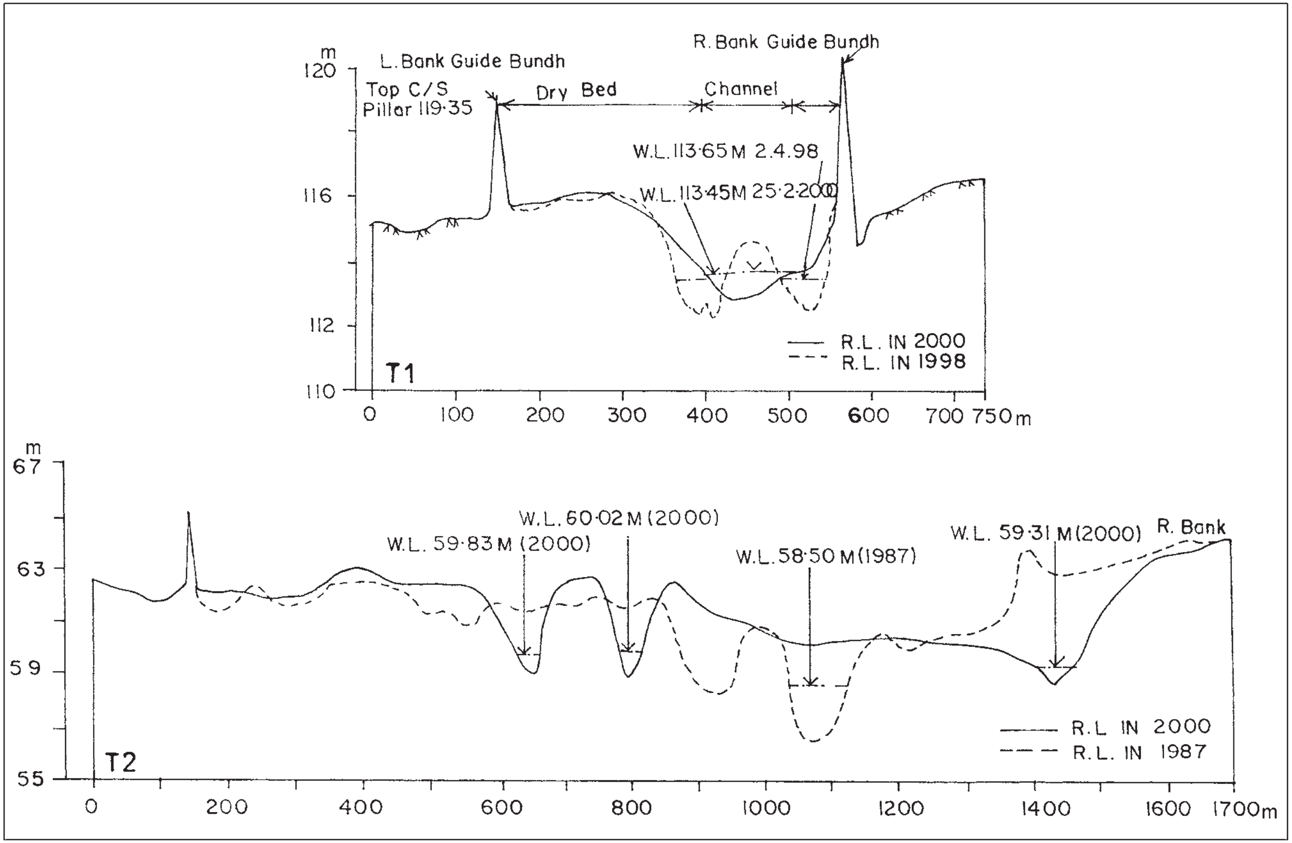


Fig. 47. Channel cross-sections T1 and T2 of the Torsa river, between 1987 or 1998 and 2000 (elab. by S. Sarkar)
T1 – at Hashimara, T2 – at Ghughumari, R.L. – year of survey

Przekroje T1 i T2 koryta rzeki Torsa między 1987 r. lub 1998 i 2000 r. (oprac. S. Sarkar)
T1 – w Hashimara, T2 – w Ghughumari, R.L. – rok kartowania

9.10.B. The second selected reach of the river Torsa is located south of the main road bridge, where the Jaldapara natural forest extends over a floodplain with an incline of 2–3‰ and wide paleochannels.

In the early 20th century there were two parallel rivers here. Later, the Torsa shifted into the right (western) channel now called the Buri Torsa. This former channel about 1 km wide had a braided pattern which is still reflected in relief as swampy depressions or widening streams in the higher root zone covered by forest (Fig. 48, Photo 31 and 32). The SOI map from 1965 illustrates a new location for the river Torsa called the Sil Torsa, which made an eastwards avulsion of 1–4 km. The satellite image from late 1998 shows a double extension of a braided channel to about 2 km wide, with distinct lateral erosion of the right bank that is still continuing (Photo 29 and 30).

The comparison of images from 1990 and 2001 (Fig. 49) reveals a gradual (now 30%) extension of the braided channel (with lateral shift westwards), a 38% increase in gravely–sandy bars (which now occupy c. 93% of the entire area) and a distinct reduction of vegetated islands.

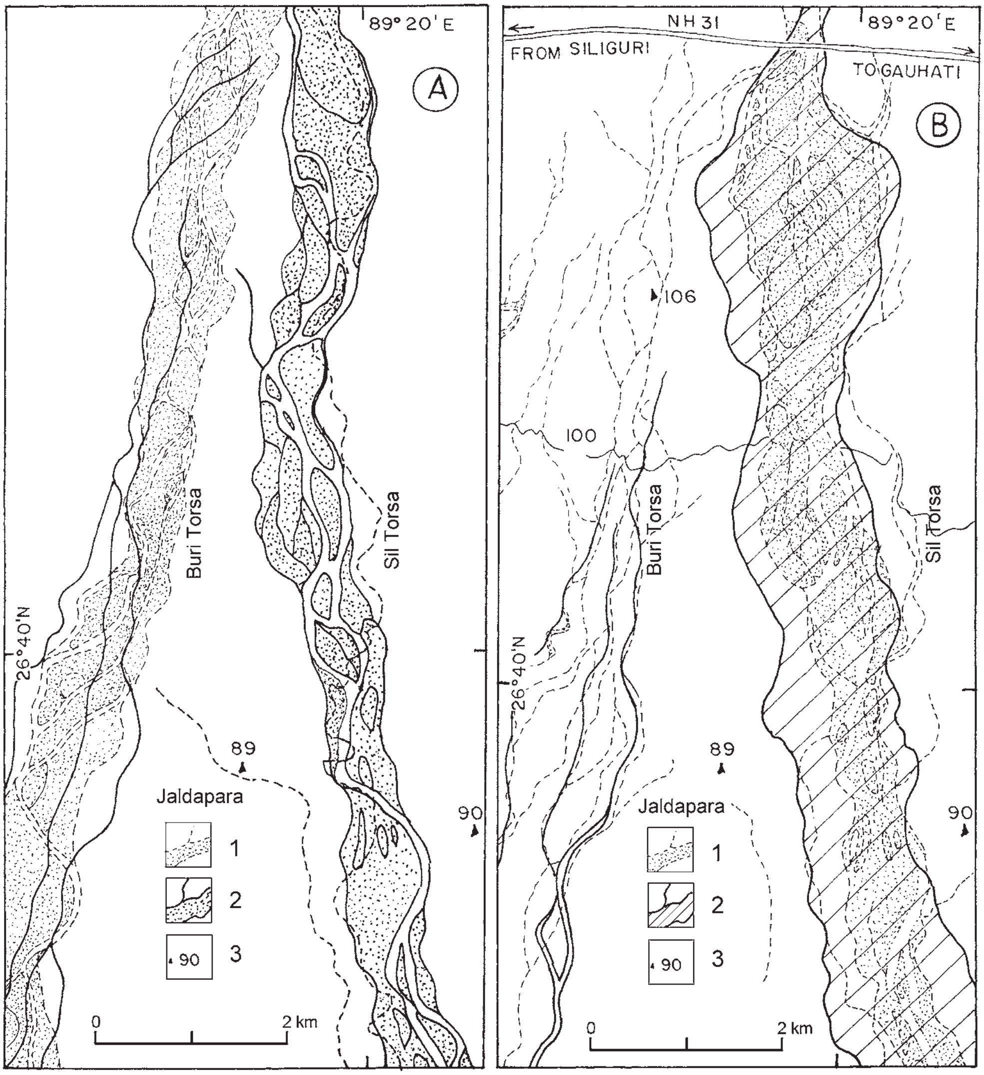


Fig. 48. Changes in the braided channel in the lower fragment of the Torsa's middle course (area 9 on Fig. 28) (elab. by S.Sarkar)

A – between 1929 and 1971, B – between 1971 and 1998

1 – channel pattern with bars in 1929 (A) and 1971 (B), 2 – channel pattern with bars in 1971 (A) and 1998 (B), 3 – elevations (m a.s.l.)

Zmiany koryta roztokowego dolnego fragmentu rzeki Torsa w jej środkowym biegu (obszar 9 na ryc. 28) (oprac. S. Sarkar)

A – między latami 1929 i 1971, B – między latami 1971 i 1998

1 – zasięg koryta roztokowego w 1929 (A) i 1971 (B), 2 – zasięg koryta roztokowego w 1971 (A) i 1998 (B), 3 – wysokości (m n.p.m.)

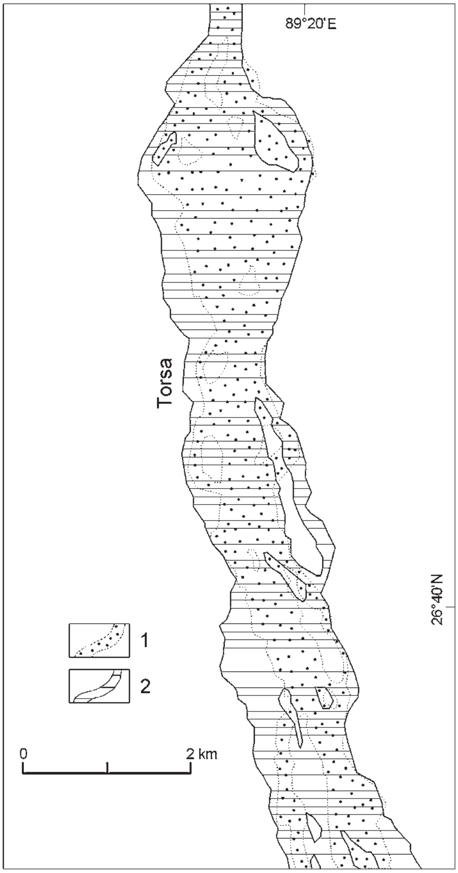


Fig. 49. Change in the braided channel pattern in the lower fragment of the Torsa's middle course (area 9 on Fig. 28), between 1990 and 2001, on the basis of satellite images (elab. by P. Prokop)

1 – river channel with bars in 1990, 2 – river channel with bars in 2001

Zmiany koryta roztokowego dolnego fragmentu rzeki Torsa w jej środkowym biegu wg zdjęć satelitarnych w latach 1990–2001 (oprac. P. Prokop)

1 – koryta rzek z odsypami w 1990 r., 2 – koryta rzek z odsypami w 2001 r.

9.11. PANA AND GABUR-BASRA (KALJANI)

Two rivers, i.e. the Gabur-Basra with its tributary the Kala Jhora, and to the east the Pana, drain the margin of the Himalaya at a distance of only 7 km. The mountain catchment of the Gabur-Basra (14.3 km long) extends over 96.7 km^2, while its highest ridge rises to 2350 m a.s.l. (Table 1). The Kala Jhora drains only 6.8 km^2 of a 2.5 km-wide front scarp rising from 220 to 780 m a.s.l. The catchment of the Pana in turn covers about 33.8 km^2, drains a 10 km-wide belt and has a watershed rising to 2100 m a.s.l. Steep slopes are mostly covered by dense forest, but in the lower elevations are partly deforested and dissected by dozens of landslides (Figs. 7, 9 and 26, Photo 33).

A complex fan surface extends on the mountain foreland, where the main rivers join together at a distance of 10 km from the hill margin. The Gabur-Basra starts at the junction of 3 mountain creeks at an elevation of ca. 260 m a.s.l. and, at a distance of 6 km, has a mean gradient equal to 10‰. However, downstream (at an elevation of about 120 m), the mean gradient has declined to just 6‰. The Pana river fan is shorter and its upper part is steeper, with a gradient of 22‰. 5–6 km away from the mountain front, the width of the two fans together exceeds 10 km, this being a belt of lateral shifting and avulsions of both the main rivers, and especially the Pana.

As of 1930, the river Gabur-Basra had a braided channel with vegetated higher bars and channel width reaching 200–600 m (Fig. 50). However, the 1966 SOI map shows a partly shifted channel of width extended to 500–1100 m. After the floods in the 1990s, the channel extended still further along several sections, especially (to more than 1 km) after the junction with the Kala Jhora and the two branches of the Pana. In November 2004 and 2006, the Gabur-Basra in the upper part of its fan carried water via 2–3 small branches cut in gravely bars (Photo 33). Comparison of satellite images from 1990 and 2001 shows an increase in braided channel area from 5 to 10.6 km^2, this being the effect of several major flood events between 1993 and 2000 (Fig. 51). There was equally a distinct decline between 1966 and 1990, this perhaps being attributable to the less frequent flooding and consequent revegetation of the former channel. This revegetation is also visible in the narrowing of the braided channel when the width from 1998 is compared with that in the 2001 satellite image (Figs. 50 and 51).

In contrast, the Pana shows very distinct avulsions. In 1930, the river used a 200–350 m wide right branch in the upper part of the fan. The river then turned to the left used the left branch and its width along with revegetated bars extended to 500–650 m. The 1966 SOI map shows that the Pana had expanded at the mountain foreland, reaching a width of 1200–1500 m and downstream concentrating its flow on the left side and narrowing to 500 m. The survey made after the 1998 flood shows a distinct separation of the two branches, both reaching the Gabur-Basra at about 1 km distance (Fig. 50).

The comparison of the two surveys from 1990 and 2001 again shows that the right branch formed after 1966 existed before 1990 along the whole length, probably being formed after the major regional flood in 1968 (Figs. 51 and 52). The left branch was formed after 1990 and is still frequently flooded, as was observed in 2005 when part of Chuapara T.E. was damaged (Photo 34). During the winter the gravel-bed channel is totally dry. The right branch of the Pana is undergoing gradual revegetation, though still being partly used during flooding (Photo 35). The unvegetated branches of the Pana occupy an area of about 5.5 km^2 along a 9 km stretch.

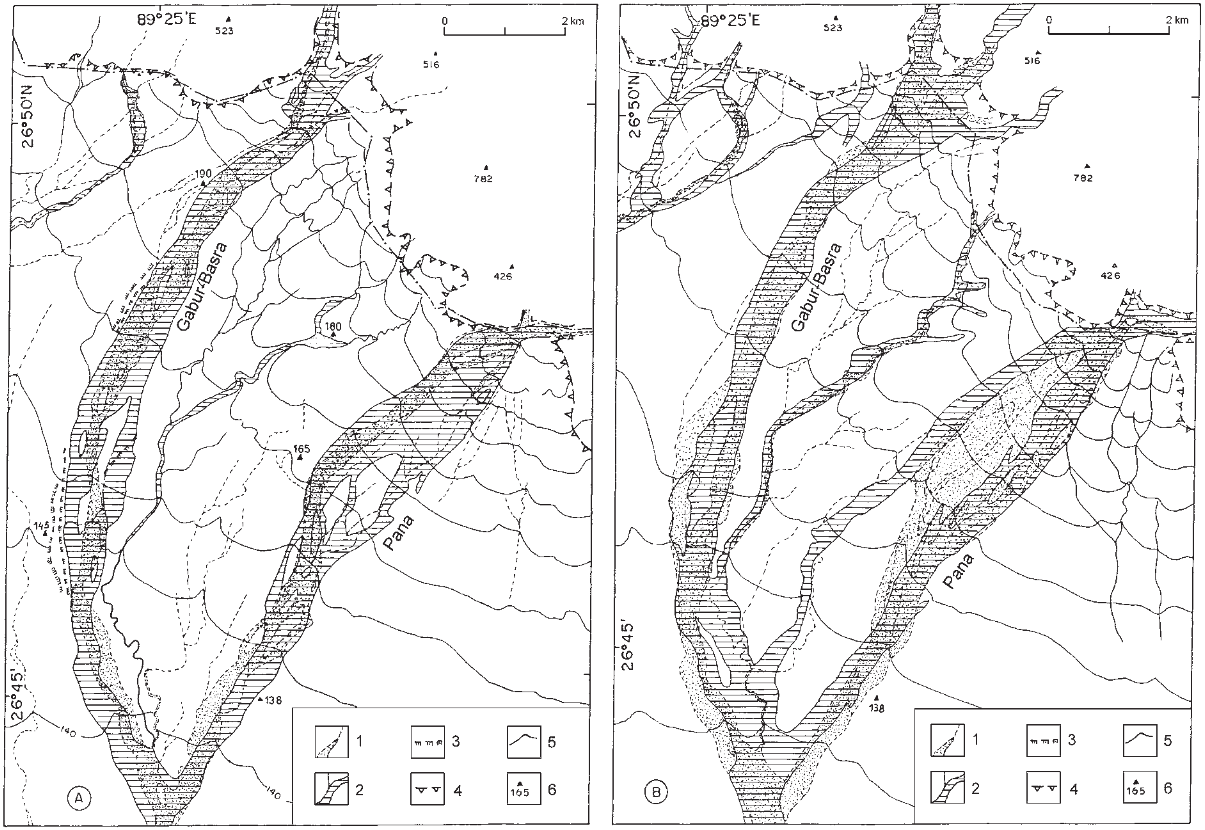


Fig. 50. Channel changes over alluvial fans of the rivers Gabur-Basra and Pana (elab. S. Sarkar)

A – between 1930 and 1966: 1 – channel in 1930, 2 – channel in 1966, 3 – scarps, 4 – margin of the Himalaya, 5 – contours (m a.s.l.), 6 – elevations (m a.s.l.)

B – between 1966 and 1998: 1 – channel in 1966, 2 – channel in 1998, 3 – margin of the Himalaya, 4 – contours (m a.s.l.), 5 – elevations (m a.s.l.)

Zmiany koryt w obrębie stożków napływowych rzek Gabur-Basra i Pana (oprac. S. Sarkar)

A – między latami 1930 i 1966: 1 – koryto w 1930, 2 – koryto w 1966, 3 – skarpy, 4 – brzeg Himalajów, 5 – poziomice (m n.p.m.), 6 – wysokości (m n.p.m.)

B – między latami 1966 i 1998: 1 – koryto w 1966 r., 2 – koryto w 1998 r., 3 – brzeg Himalajów, 4 – poziomice (m n.p.m.), 5 – wysokości (m n.p.m.)

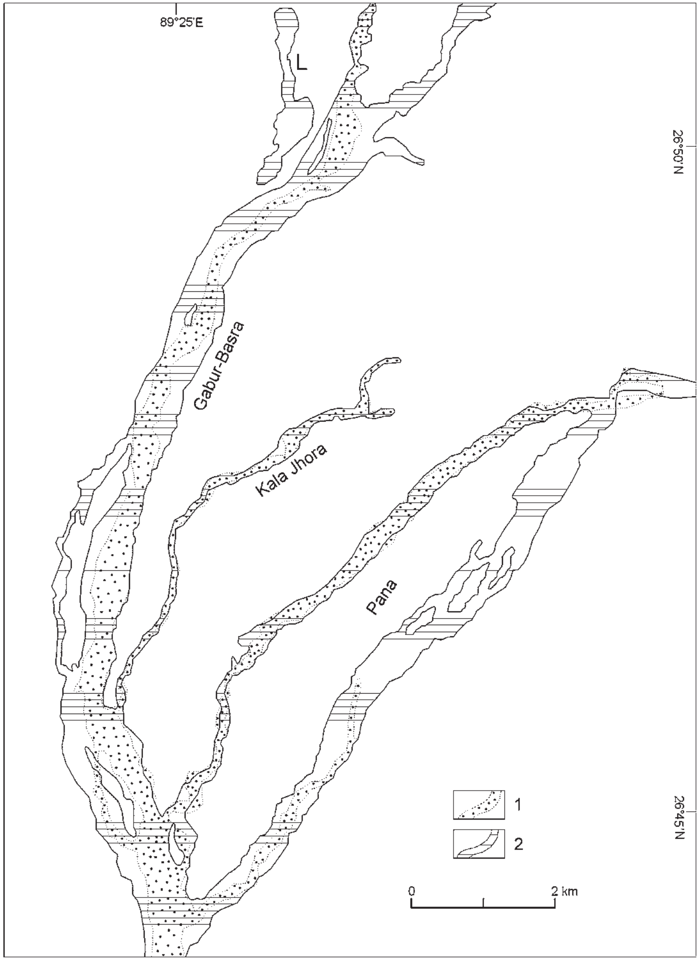
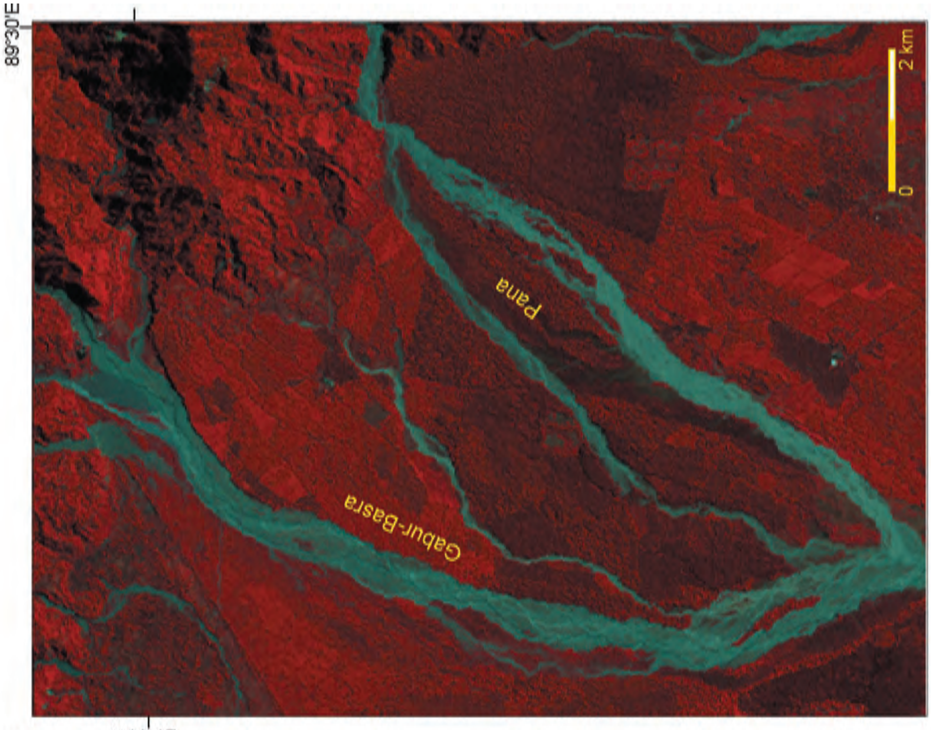


Fig. 51. Channel changes over alluvial fans of the Gabur-Basra and Pana rivers between 1990 and 2001, based on satellite images (elab. by P. Prokop)

1 – river channel with bars in 1990, 2 – river channel with bars in 2001, L – landslide

Zmiany koryt w obrębie stożków napływowych rzek Gabur-Basra i Pana wg zdjęć satelitarnych w latach 1990-2001 (oprac. P. Prokop)

1 – koryta rzek z odsypami w 1990 r., 2 – koryta rzek z odsypami w 2001 r., L – osuwisko


89°30'E
26°50'N
Pana
Gabur-Basra
0
2 km

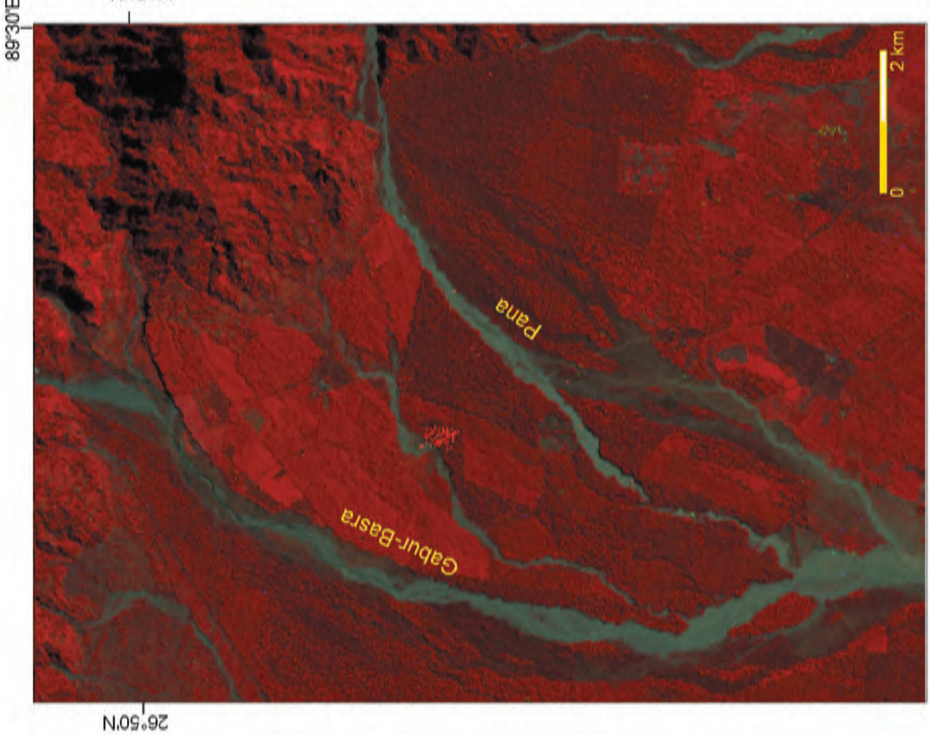

89°30'E
26°50'N
Pana
Gabur-Basra
0
2 km

Fig. 52. Satellite images (FCC) of the Gabur-Basra and Pana alluvial fans in 1990 (left) and 2001 (right). Note avulsions and extension of river channels after several floods between 1993 and 2000. River branches after avulsion have mainly been revegetated. New branches frequently use old paleochannels.

Zdjęcie satelitarne (FCC) stożków napływowych rzek Gabur Basra i Pana w 1990 r. i 2001 r. Zwraca uwagę awulsja i poszerzenie koryta po kilku powodziach między 1993 r. i 2000 r. Ramiona rzek po przerzutach koryt na ogół porosła roślinność. Nowe ramiona często wykorzystują stare koryta.

9.12. THE RAIMATANG AND THE DIMA

The two rivers drain the southern slope of the ridge rising to about 1895 m a.s.l. and have similar length up to their confluence point, though the upper mountain course is shorter in the case of the Raimatang (4 km), and longer in the Dima catchment (7 km). In contrast, the Raimatang and its several tributaries drain the mountain front at about 7 km wide, while the Dima with its one tributary drains only the mountain front 3 km wide.

Along a 10km length of the Raimatang, the flat piedmont surface slopes down from 225 to 100 m a.s.l (equating to an inclination of 20 to 9‰). The river then joins the Dima, which has a fan reach only 8 km long with an apex elevated at only 200 m a.s.l. At about 150 m a.s.l., several small tributaries fed by groundwater start on the flat fan surface. In the lower course of about 20 km, beyond the junction with the Dima, the river assumes a meandering pattern, before finally reaching the river Kaljani, as followed on both sides by parallel rivers issuing on the fan.

The SOI map of 1929 shows only one tributary of the Raimatang with a braided pattern, 100 m wide but narrowed downstream and with a distinct meandering pattern. The Dima channel is shown as straight but braided. Beyond the confluence point, the dry channel widens to 200–400 m (Fig. 53).

In the late 1990s both rivers changed their parameters. In the Raimatang system the active bars extended to 900 m. Downstream it was to 300–500 m wide with avulsion to the former channel of the left-bank tributary called the Gangutia (Fig. 53). In the Dima river system aggradation entered upstream into the mountain reach of both creeks, and over the fan surface the braided belt widens to 400–500 m. Below the junction the 50–100 m wide river changes to a meandering pattern with a meander radius of about 500 m and bars to 200 m wide.

To both the west and east of the main channel there are streams commencing on the flat alluvial plain and exhibiting a meandering pattern from the source onwards, with distinct fresh point bars.

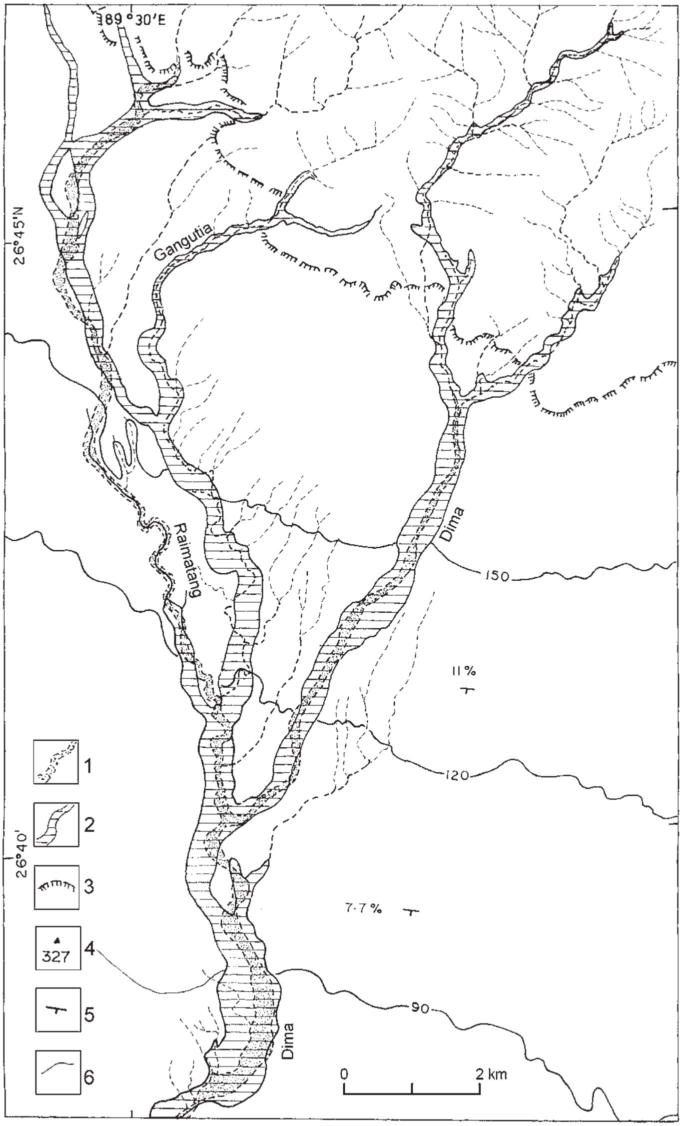


Fig. 53. Channel changes over alluvial fan of Raimatang and Dima rivers between 1929 and 1998 (elab. by S. Sarkar)
1 – channel in 1929, 2 – channel in 1998, 3 – margin of the Himalaya, 4 – elevations (m a.s.l.), 5 – gradient of fan surface, 6 – contours (m a.s.l.)

Zmiany koryta w obrębie stożka napływowego rzek Raimatang i Dima między latami 1929 i 1998 (oprac. S. Sarkar)
1 – koryto w 1929 r., 2 – koryto w 1998 r., 3 – brzeg Himalajów, 4 – wysokości (m n.p.m.), 5 – nachylenie powierzchni stożka, 6 – poziomice (m n.p.m.)

9.13. THE BALA

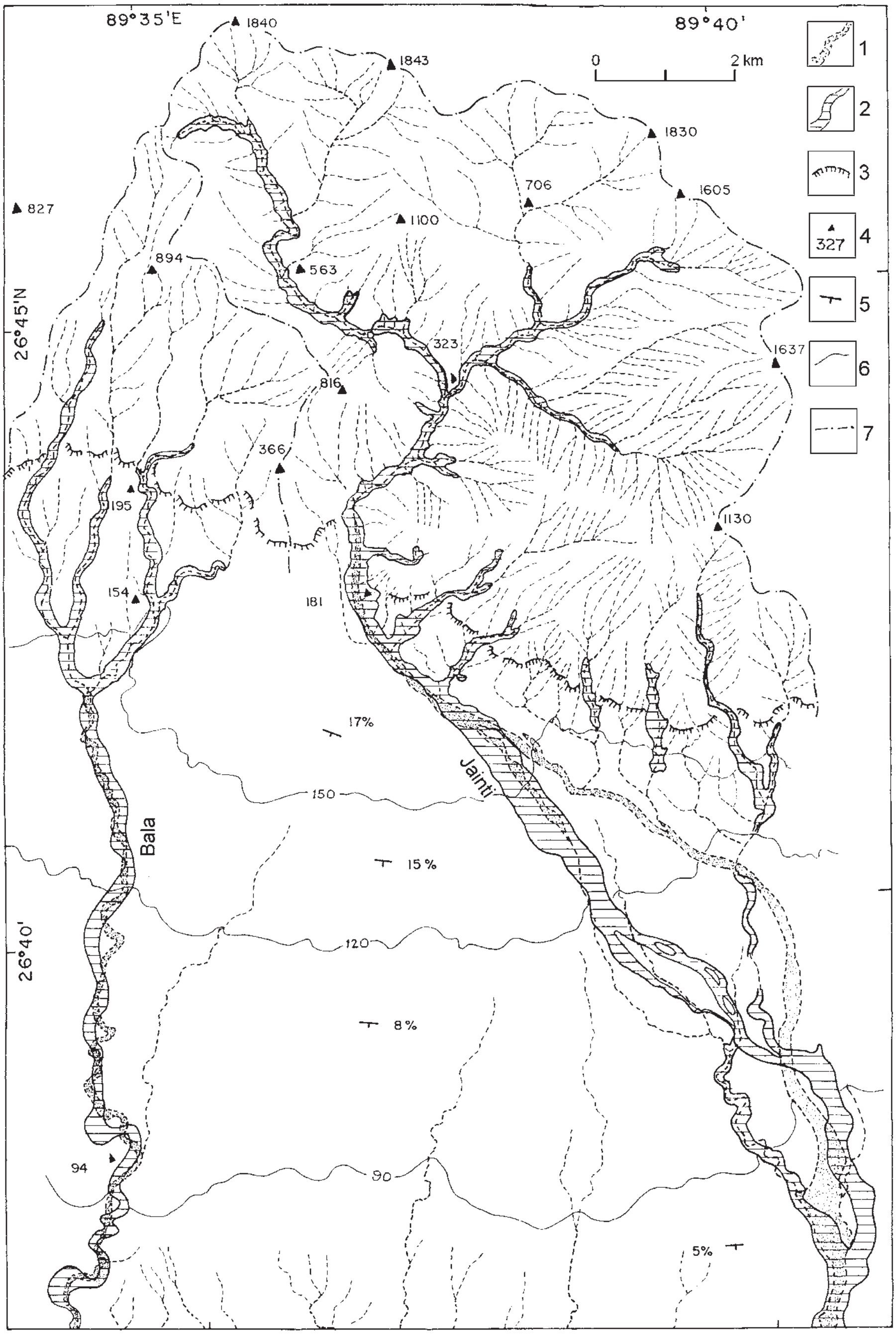
The river Bala is one of the smallest of the 4 creeks draining the margin of the Himalaya at a distance of 4 km. Here, hills with dense forests only partly deforested rise from 200 to 1300 m a.s.l. The creeks in question have built complex fan surfaces, which join together at an elevation of ca 150 m a.s.l. The surface is mainly covered by forest (in the Buxa Tiger Reserve). At about 15 km from the mountain front the river changes its character to a meandering one, at an elevation of ca 120 m. After a further 15 km it joins with the Kaljani. The gradients of the fan surface decline from about 20‰ to less than 8‰ at a distance of 10 km.

The SOI topographical map of 1929 reveals the wide dry channel indicated only downstream of the junction of all creeks. It was 50–100 m wide and has a distinct meandering pattern. It is in this part that there appears the line of springs giving rise to several perennial rivers (Fig. 54).

The satellite image from 1998 reveals a distinct change at the mountain front up to the upper reaches (300 m a.s.l.), in the form of extending wide gravel bars. The channels are not incised in the main flat fan surface, whereas in the forest several years ago we observed fresh humps of gravels and boulders. Downstream of the junction, the width of the braided channel declines from 300–400 m to 100–250 m, and the former meandering channel has been transformed into a widening one.

The comparison of two satellite images from 1990 and 2001 shows extension of the unvegetated channel surface by about 30% (Fig. 55).

Along the Bala there are no avulsions or distinct lateral shifts to be observed, since this river flows at the margin separating two larger fans – of the Dima to the west and the Jainti to the east.


89°35'E
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327
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6
7
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827
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894
563
26°45'N
323
1637
816
366
195
1130
154
181
17%
Jainti
150
Bala
15 %
26°40'
120
8%
94
90
5%

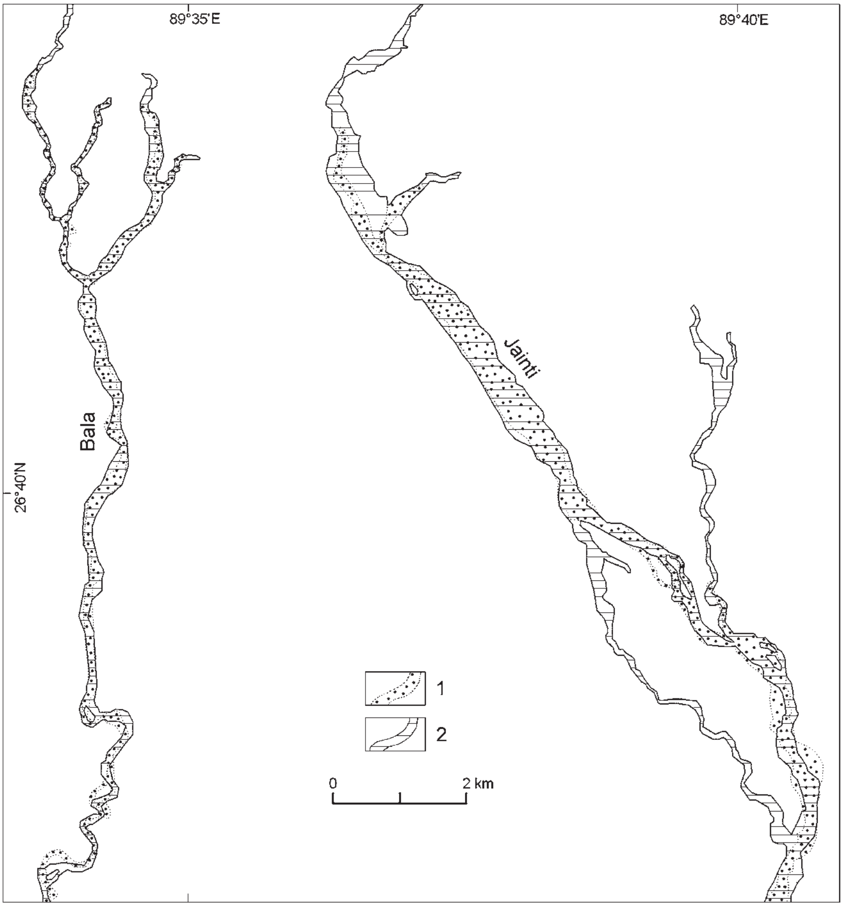

Fig. 55. Channel changes over alluvial fans of Bala and Jainti rivers, between 1990 and 2001, on the basis of satellite images (elab. by P. Prokop)

1 – river channel with bars in 1990, 2 – river channel with bars in 2001

Zmiany koryta w obrębie stożka napływowego rzek Bala i Jainti wg zdjęć satelitarnych w latach 1990–2001 (oprac. P. Prokop)

1 – koryta rzek z odsypami w 1990 r., 2 – koryta rzek z odsypami w 2001 r.

Fig. 54. Channel changes over alluvial fans of Bala and Jainti rivers between 1929 and 1998 (elab. by S. Sarkar)

1 – extent of channel in 1929, 2 – extent of channel in 1998, 3 – margin of the Himalaya, 4 – elevations (m a.s.l.), 5 – gradient of fan surface, 6 – contours (m a.s.l.), 7 – watershed

Zmiany koryta w obrębie stożka napływowego rzek Bala i Jainti między latami 1929 i 1998 (oprac. S. Sarkar)

1 – zasięg koryta w 1929, 2 zasięg koryta w 1998, 3 – brzeg Himalajów, 4 – wysokości (m n.p.m.), 5 - nachylenie powierzchni stożka, 6 – poziomice (m n.p.m.), 7 – granica zlewni

9.14. THE JAINTI

The Jainti river is among the longest left–bank tributaries of the Torsa, joining it 60 km from the Himalayan margin. The Jainti may be divided into three courses. Its upper reach only 10 km long drains a mountain frontal zone 7 km wide, which rises from 200 to 1840 m a.s.l. and is highly dissected by deep valleys (density 6.9 km km^{-2}). This belt is built of metamorphic rocks of the Daling series (gneisses, slates, quartzite, etc.) with a narrow marginal zone of dolomite and limestone. This part is still mostly covered by natural forest, though the last few decades have seen the appearance of cultivated enclaves on the hills, as well as an initiation of dolomite working (Photo 39).

An extensive alluvial fan 20 km long and 10 km wide descending from 240 m to about 80 m a.s.l. is formed at the mountain foreland (Photo 38). The Jainti in this section has a braided channel with many prints of paleochannels (Fig. 54). Downstream the river starts meandering on the extensive alluvial plain, joining the Torsa after a further 40 km journey.

The studied section is partly still under natural forest cover (in the Buxa Tiger Reserve), but is also partly deforested and used for cultivation and settlement. This section was examined by Sarkar (2004a) after the 1993 flood, and visited several times subsequently. The right bank of the river has a wide fan covered by forest and inclined between 15 and 10‰. A comparison on the basis of the SOI topographic map of 1928 and satellite images from 1990 and 2001 has been attempted (Figs. 54 and 55).

The SOI map of 1928 shows that the width of the braided channel at the mountain outlet fluctuated between 50 and 100 m. 5 km downstream the wider channel divided into two branches – the left active and widening down up to 200–500 m and the right with aggradation reaching only to 2 km downstream. The small left–bank tributaries from the mountain front have not shown aggradation.

A great flash flood recorded on the 20th July 1993 was connected with 4 days of rain (at Hasimara T.E. 792 mm), with the last day alone recording 450 mm (Sarkar 2004a). The calculated discharge exceeded 1000 m^3s^{-2}. The road bridge at Jainti village was taken away and large pieces of construction and blocks were carried up to 700 m downstream (Photo 38). It was possible to observe, not only scouring and the formation of new bars, but also bank erosion to 165 m along a 690 m section (Fig. 56), destruction of forest patches and revegetated bars formed during the previous large flood of 1968, and the formation of a large central bar downstream. We do not know the records from subsequent floods in 1996, 1998 and later, but a tendency for the channel floor to rise is being maintained and is also visible at the tributary outlets, where trees are buried by coarse gravels and boulders. On the picture from 1998 we

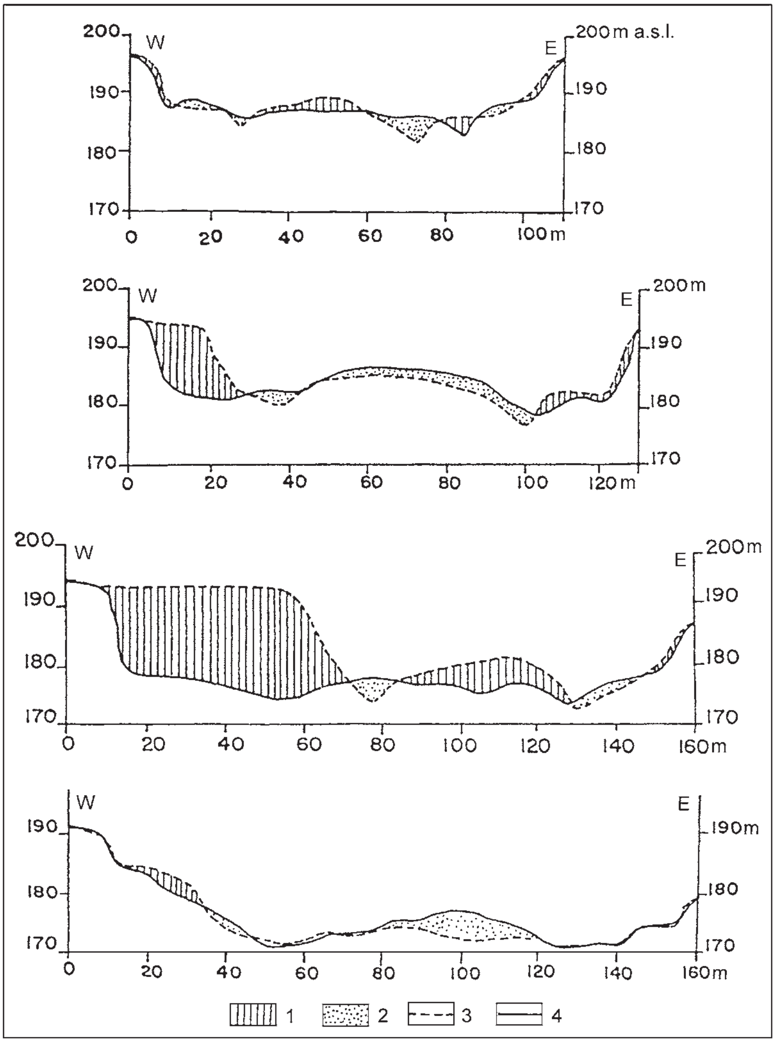

Fig. 56. Channel cross-sections of Jainti river (each at about 0.5 km distance) before and after 1993 flooding, showing extent of erosion and aggradation during one event (surveyed by S.Sarkar)
1 – erosion, 2 – deposition, 3 – 1993 (pre-flood), 4 – 1995
Przekroje koryta rzeki Jainti (każdy w odległości ok. 0,5 km) przed i po powodzi z 1993 r. pokazujące zasięg erozji i agradacji podczas pojedynczego zdarzenia (kartowanie S. Sarkar)
1 – erozja, 2 – depozycja, 3 – 1993 r. (przed powodzią), 4 – 1995 r.

see an extension of the braided reach (Fig. 54), which entered upstream into the mountains, while downstream over the fan the river uses the right branch 200–700 m wide and bifurcating again downstream. Small left-side gullies up to 2 km long dissect the mountain edge and have formed fans of a debris-flow character, only some of them reaching the Jainti Valley. The overall effect of several floods between 1993 and 2000 was to up-build the channel floor by about 3 meters. The zone of braided channel also expanded about 10 km downstream, entering the zone of meandering (Fig. 57).

The comparison of two satellite image from 1990 and 2001 (Fig. 55) shows an extension of the braided channel at the outlet from the mountains (aggradation shifting upstream) from 2.2 km^2 to 3.6 km^2 as well downstream the formation of a new branch different from that visible on the 1998 satellite picture. This is probably the product of a flood in 2000. Its small width and meandering pattern indicate that only a small part of the flood discharge actually used that branch.

9.15. CONCLUSIONS

Detailed analysis of changes in the channel pattern and area occupied by braided channels with unvegetated bars – as surveyed from 1930 and especially between 1990 and 2001 – shows very distinct changes. In large river channels like those of the Tista and Torsa, there has been continuous change in the braided pattern , with the Torsa making an avulsion to the east along the Jaldapara Forest reach in the wake of the major flood. In the catchments of the Lish, Gish and Chel, the expansion of alluvial fans followed several decades ago, in the course of intensive deforestation and mining activities (Fig. 29). Since 1990, the area occupied by fans is expanding, not only by way of vertical aggradations but also through horizontal progression in both upstream and downstream directions (Table 4).

In the smaller catchments to the east large expansion of fans is observed, and explained by reference to the cluster of floods occurring since 1993 (Starkel, Sarkar 2002). The comparison of two satellite images from 1996 and 1998 has shown the role of the 1998 events played in extending braided channels and forming new debris flows and landslides (Fig. 43). A 50–60% increase in the area occupied by unvegetated channels was recorded between 1990 and 2001 in the studied sections, as well frequent avulsions. The most limited expansion (of just 30%) was that observed for the forest-covered Bala catchment, this contrasting with the 100%+ increase affecting such seasonal rivers as the Pagli, Gabur-Basra and Pana. In smaller catchments, the braided sectors end at the narrowings connected with bridges. In the braided channels of small seasonal streams west of the Torsa, which developed after the extreme events of the 1990s, revegetation and stabilization tended to occur in subsequent years.

Reactivation of periodic streams and debris flows also caused a shift some 5–15 km further downstream in the beginnings of stable meandering channel reaches. This is especially visible along the lower course of the Daina channel, as well as along the rivers Dimdima, Gabur-Basra and Jainti (Fig. 57). The phenomenon is connected with the high frequency with which flooding was recorded after 1993, as well as probably – in the case of the Daina and Dimdima – with the exploitation of dolomite at the mountain front on the Bhutanese side.

All the facts presented above indicate that the growing and up-building of the piedmont surface have very complicated spatial and temporal patterns. The present study has recognised a very distinct acceleration of changes occurring in the last decade of the 20th century.

10. TRENDS IN THE EVOLUTION OF THE SIKKIMESE-BHUTANESE HIMALAYAN PIEDMONT

Leszek Starkel

10.1. TYPES OF RELIEF IN THE PIEDMONT ZONE

The nature of the forms and processes presented above helps in the distinguishing of several types of relief in the piedmont of the Sikkimese-Bhutanese Himalaya. While some of these are modelled by present-day fluvial processes, and others are not active, all are still subject to faster or slower neo-tectonic deformations. The differential of relief types is controlled jointly in relation to the sizes of river valleys dissecting the margin of the Himalaya, the type and rate of tectonic deformations, as well as the rainfall-runoff regime of rivers (Fig. 7).

The most characteristic feature of the piedmont are the alluvial fans. The older fans are dissected to 10–20 m or more, and the active fans are still under the process of up-building by braided streams. Among them are the two mega-fans of the major rivers, the Tista and Torsa, as well as a series of smaller fans forming a steeper marginal belt similar to Bhabar zone at the margin of the Ganga Plain (Singh 1992; Shukla, Bora 2003). The third type of relief is represented by the raised blocks of uplifted Quaternary alluvial terraces sometime up to 100 m high, bounded by linear scarps following fault lines. The alluvial plain with two steps of the floodplain extends to the south down to the Brahmaputra (Goswami 1998), these being modelled by the lower courses of meandering or braided rivers (in the case of large transient rivers), as well as by many meandering streams starting at the foot of the fans (see Chapters 5 and 7).

10.2. THE GENERAL MODEL OF THE PIEDMONT CROSS-SECTION

Studies carried out in recent decades in this part of the Himalayan piedmont, mainly in Darjeeling district, have helped in the elucidation of a generalised model for the piedmont transect, this distinguishing two types in relation to the rate of uplift and the anthropogenic aggradation progressing upstream into the mountains (Froehlich, Starkel 1993; Starkel, Basu 2000; Starkel, Sarkar 2002; Starkel 2005). The general model published in 2002 and 2005 (Fig. 58), distinguished the root part of the fan with a braided shifted channel inclined at 10–4‰, built of boulders and gravels; then a middle part inclined at 3–2‰,

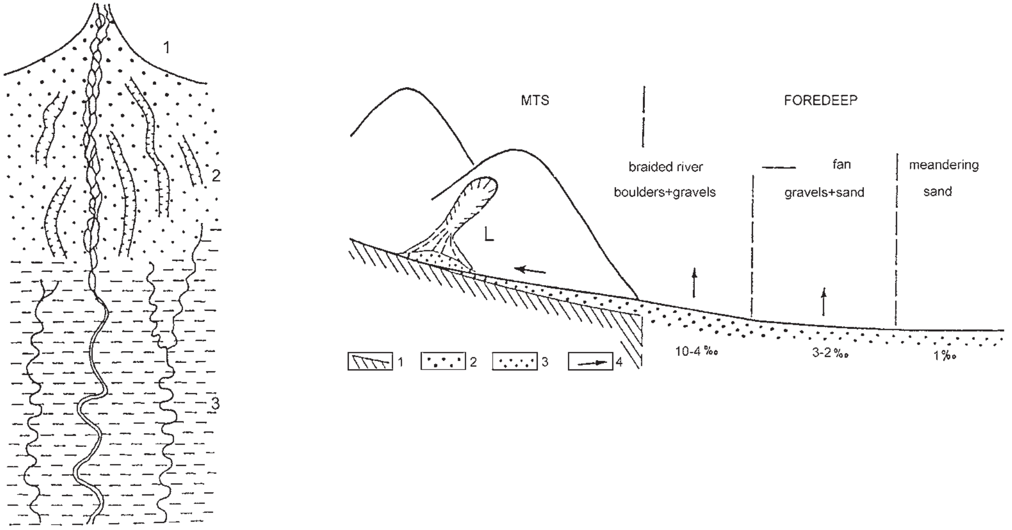

Fig. 58. Old general models of alluvial fans in the piedmont of the Sikkimese-Bhutanese Himalaya On the left spatial model (Starkel 2005): 1 – steep root section, 2 – middle section with braided pattern and paleochannels, 3 – flat lower section with meandering channel and new rivers. On the right longitudinal profile (Starkel, Sarkar 2002): 1 – bedrock, 2 – gravels and boulders, 3 – sands, 4 – tendency for aggradation (vertical and progressing upstream), L – landslide supplying river with colluvia.

Stary ogólny model stożków napływowych na przedpolu Sikkimsko-Bhutańskich Himalajów. Po lewej model przestrzenny (Starkel 2004): 1 – stromy odcinek korzeniowy, 2 – odcinek środkowy z korytem roztokowym i paleokorytami, 3 – płaski odcinek dolny z korytem meandrowym i nowymi rzekami. Po prawej profil podłużny stożka (Starkel, Sarkar 2002): 1 – cokół skalny, 2 – żwiry i głazy, 3 – piaski, 4 – postępująca agradacja (pionowa i w górę biegu rzek), L – osuwisko zasilające rzekę koluwiami built of gravels and sand; and finally the lowest portion with a meandering channel and a gradient below 1–2‰, built of sandy overbank deposits.

Various data presented in the present study have made possible the more detailed development of this general concept, as well as a greater ability to account for the way in which deviations from this model have arisen. As the general model has been constructed, special consideration has been given to some regularities connected with changes in size of river, channel pattern, elevation at the mountain margin and the character of alluvial fans. The two main types of piedmont to be distinguished (Fig. 59) are:

A. the great Himalayan rivers carrying high discharges (like the Tista and Torsa).

B. the small rivers draining the margin of the Lesser Himalaya and building smaller, steep fans.

Type A is characterised by the mountain river deeply incised into the bedrock and by fan building starting from the sharp edge of the Himalaya. In some cases, the fan root part may even enter upstream into the mountains (as with the Torsa). Downstream, the fan is subject to gradual spread, to the point where it may attain a width of several tens of kilometres. While of reducing gradient, it maintains its braided character either up to the junction with the Brahmaputra (as in the case of the Tista) or up to a distance of 50 km from the mountains, when it assumes a meandering character (as with the Torsa). Meandering streams appear over the fan surface fed by groundwater.

Type B is formed by smaller streams draining only the frontal zone of the mountains, which is densely dissected and in receipt of the heaviest rainfall (up to 6000–7000 mm per year). Frequent flood waves carry a heavy bed load supplied by landslides and debris flows. The gradient of these fans in their root part is thus rather steep, at 20–30‰. Water infiltrates into the alluvia (for 6–8 months of the year most of these streams are totally dry) and reappears in the channels about 10–20 km downstream. These fans frequently form an inclined shelf at the base of the mountain scarp. With gradually reduced gradient and finer overbank deposits, the streams change their channel pattern to a meandering one.

10.3. VARIOUS DEVIATIONS FROM THE GENERAL RULES

Different local factors connected with relief, valley pattern, bedrock lithology, tectonic activity, rainfall-runoff regime and human impact give rise to various modifications of, or deviations from, the general form model.

a) Piedmont features connected with relief and river network

a1. The deeply-incised river Tista flows down from the High Himalaya. Its alluvial fan starts at the outlet from a narrow canyon at an elevation of about 150 m a.s.l. Its extensive older fan is dissected (to about 10m) by the 3–6 km wide braided Tista channel with a gradient of 3–1‰ accompanied by two steps of the floodplain. The floodplain spreads out further downstream, forming a 50 km-wide younger fan (Fig. 59A, Photo 1).

a2. The river Torsa, the other trans-Himalayan river, is elevated 190 m a.s.l. at the outlet from the mountains and has a braided channel with aggradation progressing upstream. The alluvial fan in its upper part has a gradient of 5–7‰ and is 3–5 km wide, though farther downstream the width extends to 15–18 km with palaeochannels formed by avulsions.

a3. The 2–4 neighbouring streams at the dissected mountain front form coalescing alluvial fans with a gradient of 30–20‰ declining to 10–6‰ with

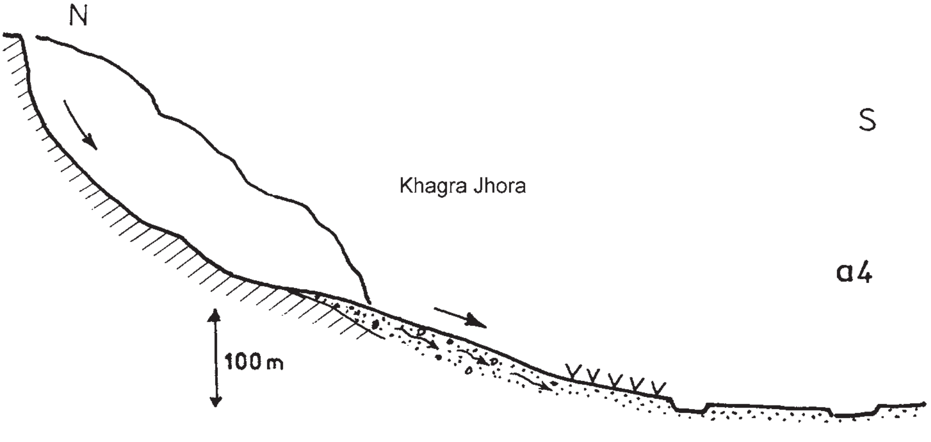

Fig. 60. Debris flow fan of the small Khagra Jhora landslide valley dissecting the edge of the Lesser Himalaya and upbuilding an extensive alluvial fan (elab. by L. Starkel)
Stożek spływu gruzowego u wylotu małej doliny osuwiskowej Khagra Jhora, rozcinającej krawędź Niskich Himalajów. Nadbudowuje on rozległy stożek napływowy (oprac. L. Starkel).

frequent shifting channels and avulsions (like the Upper Gish, Daina and Chamurchi, the Gabur-Basra and the Pana) (Photo 4 and 23, Figs. 36 and 50).

a4. A characteristic anomaly is exemplified by the small landslide valley of the Khagra Jhora, situated at the base of the uplifting mountain front with a retreating niche, forming a large expanding debris flow fan (of about 1.5 km^2), as superimposed on the alluvial fan of larger streams (in the Sukti and Dimdima system) (Fig. 60, Photo 22).

b) Deviations from the piedmont model connected with young tectonic activity

b1. The undeveloped overthrusts of the Himalaya in the section between the Chel and Torsa have caused, not only a distinct withdrawal of the steep edge of the Lesser Himalaya, but also the formation of uplifted horsts and tectonic scarps restricting aggradation. The Himalayan streams cross this elevated part, creating antecedent sections, while they built small fans downstream of the tectonic scarps (Fig. 61–b1, Photo 9, 10, 12, 13, 16 and 17).

b2. The alluvial fan of the river Chel is composed of at least three fills intersected by latitudinal fault lines, creating a staircase topography (Fig. 61–b2).

b3. In the sections along which the mountain front takes a longitudinal (N–S) direction, there are young fans up-building over an older fan surface (as with the Rehti – Fig. 62–b3, Photo 20). The complex of high-elevated fans of the Sukti and Pagli is also probably connected with buried older fans (Fig. 40).

b4. The high terrace elevated along the SW-NE fault line located on the foreland between the Pagli and Torsa (Fig. 62–b4) is dissected by several parallel gullies (Photo 26), forming small fans and being drained by a stream following the fault line.

c) Anomalies and deviations in piedmont formation connected with climatic and hydrological factors

c1. The mountain margin and neighbouring part of the piedmont receive the highest rainfall, which causes flash floods and frequent avulsions, as well as expansion and up-building of torrential fans in both directions (upstream and downstream – Fig. 59). The clustering of heavy rain events since the 1990s is in particular reflected in a widening of braided channels, their avulsion and the shifting of braided sections by even 10–15 km downstream (as compared with maps from the 1960s – Fig. 57). The stable meandering channel as recorded in old SOI maps (1930) is replaced by braided channels, as in the cases of the rivers Daina, Rehti, Gabur-Basra, Jainti, and so on.

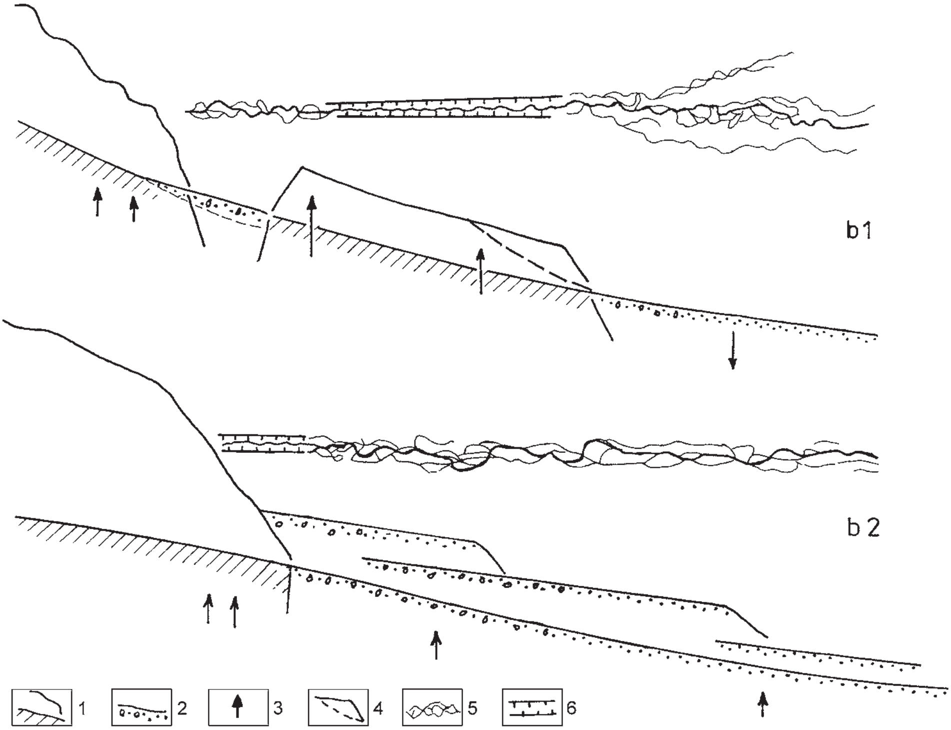

Fig. 61. Examples of young uplift in the piedmont zone (elab. by L. Starkel)
b1 – rivers crossing uplifted block between the Chel and Daina, b2 – sequence of incised fans of the Chel connected with the uplift tendency
1 – bedrock in channel dissecting rised hills, 2 – alluvia, 3 – uplift tendency, 4 – valleys dissecting tectonic scarp, 5 – braided channel, 6 – deeply incised valley (antecedent)
Przykłady młodej tektoniki w strefie piedmontu (oprac. L. Starkel)
b1 – rzeki rozcinające podnoszony blok między rzekami Chel i Daina, b2 – szereg włożonych stożków rzeki Chel, związanych z ruchami podnoszącymi
1 – cokół skalny w korytach rzeki rozcinającej brzeg gór, 2 – aluwia, 3 – tendencja podnosząca, 4 – dolinki rozcinające krawędź tektoniczną, 5 – koryto roztokowe, 6 – głęboko wcięta dolina (antecendentna)

c2. Meandering streams fed by groundwater and local heavy rain have developed over the lower segments of extensive fans, dissecting them and gradually displaying downstream the limit of the piedmont zone (Fig. 59, Photo 40, 41 and 42).

d) Anthropogenic acceleration of sediment loading and aggradation in the piedmont zone

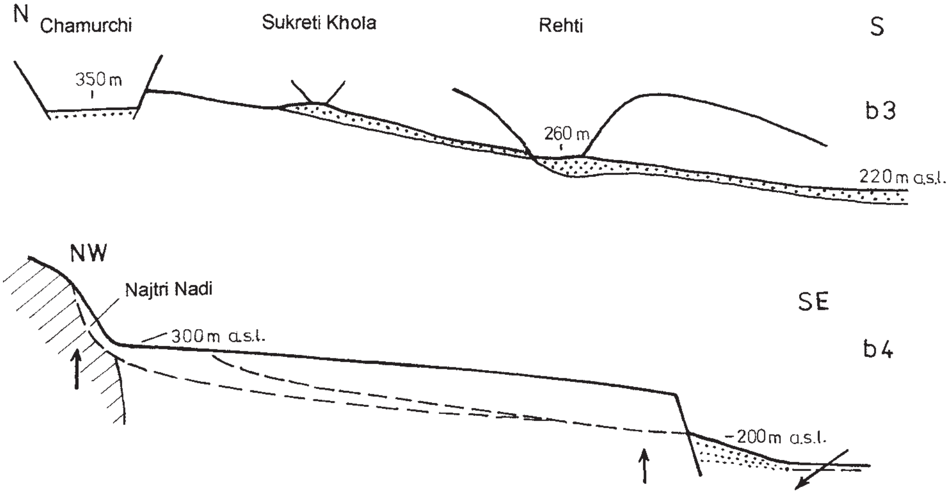

Fig. 62. Examples of young uplift in the piedmont zone (elab. by L. Starkel)
b3 – longitudinal fragment of mountain front dissected by Chamurchi and Rehti river. Young fans are incised or superimposed on older piedmont surface,
b4 – streams dissecting uplifted block on the Himalayan foreland west of the Torsa valley. For explanation see Fig. 61.
Przykłady młodej tektoniki w strefie piedmontu (oprac. L. Starkel)
b3 – południkowy odcinek brzegu gór rozciętego przez rzeki Chamurchi i Rehti. Młode stożki są włożone lub nałożone na starszą powierzchnię piedmontową.
b4 – rzeki rozcinające podniesiony blok na przedpolu Himalajów za zachód od doliny Torsy. Objaśnienia jak na ryc. 61.

d1. The fast-growing aggradation along the mountain margin is essentially a natural phenomenon. But in the western part of the Himalayan margin, we find a contrast between parallel river valleys. Comparing river channels draining forested catchments (like those of the Neora or Jaldhaka) with deforested ones featuring agricultural or mining activity (like those of the Lish, Gish, Chamurchi, Pagli, etc.), we observe a distinct trend towards rising of the channel floor and expansion of braided channels in the second group, as is recorded on satellite images (Fig. 8, Photo 2, 4 and 23).

d2. The construction of bridges over the main railway line and national highway to Assam was accompanied by a narrowing of channels and the construction of embankments blocking high discharges and heavy bed load. Braided channel patterns were observed to end above bridges over many rivers, the channel floor then being raised by some 2–3 metres in just 10–15 years, forcing the construction of a new bridge in the aftermath of the 1993 flood (Figs. 8, 29 and 36, Photo 6, 16 and 18).

10.4. TRENDS IN THE EVOLUTION OF THE SIKKIMESE-BHUTANESE HIMALAYAN PIEDMONT

The tectonic instability of the investigated piedmont part combine with the great variety of river patterns to necessitate the introduction of two distinct corrections to the evolutionary model of the Sikkimese-Bhutanese piedmont sloping down to the Brahmaputra valley (Fig. 2).

The first of these concerns the presence of rising fault scarps and horsts between the Chel and the Rehti, these now gradually being dissected by rivers, with the zone of aggradation shifting 15–20 km to the south to the zone of elevation 200–100 m a.s.l., (Figs. 7 and 9, Photo 16).

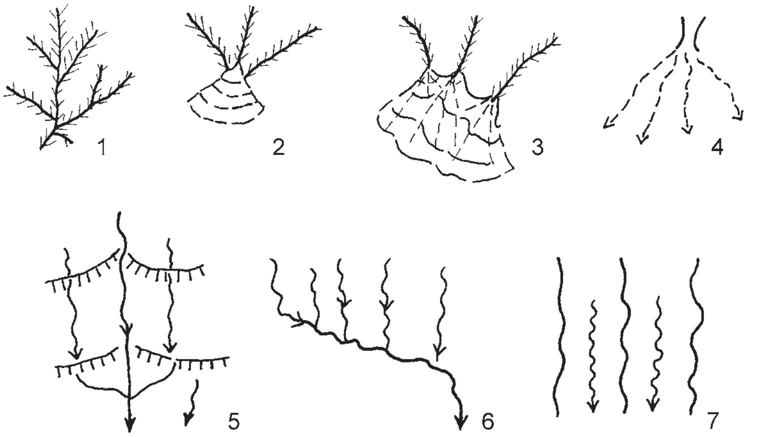

Fig. 63. Various types of drainage pattern in the Himalayan piedmont (elab. by L. Starkel)

1 – convergence of streams in foothill zone, 2 – convergence of streams at mountain scarp forming one fan, 3 – several fans forming piedmont bench, 4 – divergence of channels over active fan, 5 – parallel streams draining staircase of uplifted blocks, 6 – junction of several parallel streams following fault line, 7 – parallel streams in lower part of piedmont separated by meandering local rivers fed by groundwater

Różne rodzaje układu koryt na terenie piedmontu Himalajów (oprac. L. Starkel)

1 – konwergencja potoków w obrębie gór, 2 – zbieg potoków u czoła gór, tworzących wspólny stożek, 3 – połączone stożki tworzące półkę piedmontową u brzegu gór, 4 – dywergencja koryt w obrębie stożka, 5 – równoległe potoki drenujące stopnie podniesionych bloków, 6 – łączenie kilku równoległych potoków przez główny, biegnący wzdłuż uskoku, 7 – równoległe rzeki w dolnej części piedmontu, przegradzane rzekami meandrowymi zasilanymi przez wody gruntowe

The second specific feature is the presence of alternate belts (zones) with a tendency for river networks to either converge or diverge, modifying the general trend towards convergence in the evolution of the piedmont's longitudinal profile (Fig. 63). Convergence dominates in the foothills zone drained by larger streams. Divergence is characteristic for root parts of the torrential fans which expand out to 10–20 km from the mountain front (Fig. 42). Only in the Jaldhaka catchment does convergence still dominate. In the lower belt of the piedmont (100–50 m a.s.l.), only two mega-fans (of the Tista and Torsa) show a trend towards widening. Smaller streams, frequently running parallel to one another, nevertheless have a tendency to join what is partly facilitated by the presence of latitudinal fault lines (Fig. 6), as well as the shifting of the Tista mega-fan in a SSE direction.

10.5. SPECIFIC FEATURES OF THE SIKKIMESE-BHUTANESE PIEDMONT IN RELATION TO THE WHOLE GANGA-BRAHMAPUTRA DEPRESSION

Comparing the studied part of the Himalayan piedmont with the whole Ganga-Brahmaputra Plain we may note major differences connected with such varied factors as the presence or absence of diverse young tectonic movements, type of drainage pattern, size of catchment basin and the gradual decline in precipitation towards the west (cf. Chapter 1.1.). The western part has a mature and more gentle mountain front with the wide Siwalik Belt (Gansser 1964; Valdiya 1998), as well as the uplift tendency in the foredeep reflected in the incised river channels of the main Himalayan rivers (Singh 1992; Jain, Sinha 2003). The number of great Himalayan rivers is larger and their channels run parallel to one another, forming a complex system of mega-fans separated by plain-fed rivers.

Only from the River Kosi to the east does there begin the system of mega-fans of rivers (the Tista, Torsa, etc.) transversal to the main latitudinal axis of the lower courses of the Ganga and Brahmaputra.

In the west, there is exposure of the narrow belt of small steeper fans of streams draining the marginal Siwaliks zone (cf. Shukla, Bora 2003), but east of the Tista – where much more precipitation is received and there is active rise it is more distinct, with small and steep fans showing much more rapid extension and changes in drainage pattern.

The studied part of the subsiding Ganga-Brahmaputra Lowland is among the most actively transforming parts of the whole Himalayan foredeep. The rising Himalaya in Jaldhaka basin represents a 50 km long sector a partly undeveloped mountain front, being at present "in statu nascendi", because the Quaternary overthrust is still in propagation (cf. Guha et al. 2007). A high gradient of the river channels of parallel running streams is another indicator of this (Fig. 9).

Simultaneously, this fragment of Himalayan margin and its foreland is located directly north of the Bay of Bengal, and of the wide gap between the Deccan and Meghalaya Uplands. This area records the highest annual rainfall and probably the highest frequency of extreme rains along the whole length. The clustering of floods in the last 15 years is well expressed in the expansion of braided rivers and frequent avulsions (Starkel, Sarkar 2002). Downstream of the fast-growing fans, which act as a sponge during flash floods, is the second belt of streams fed by groundwater and still by heavy rainfall. These rivers play a role in the levelling of contrasts between the fan zone and extensive floodplains along the Brahmaputra (Fig. 59).

The studied fragment of Himalayan piedmont between the rivers Tista and Jainti still hide unsolved questions. The rates of uplift and subsidence were not recorded in this sector. The age of the Quaternary terraces is not known, though some new light was thrown on the issue only last year, when elevated terraces in the Jaldhaka Valley were radiocarbon dated at 20–40 thousand years BP (Guha et al. 2007). Detail sedimentological study is also lacking. Nevertheless, the present work shows the great complexity and spatial diversity to the processes modelling the piedmont zone at the border between the intensively rising Himalaya and the subsiding foredeep. The high rates of change are explained by the character of the rainfall regime acting in an area of intense tectonic activity. The human impact can not be taken as the main factor underpinning the degradation taking place throughout the Himalaya, as well as the catastrophic flooding taking place in the plains, as is accepted in many circles. Anthropogenic factors merely accelerate the sediment loading and aggradation.

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WSPÓŁCZESNA EWOLUCJA PIEDMONTU SIKKIMSKO-BHUTAŃSKICH HIMALAJÓW

Streszczenie

Monograficzne opracowanie współczesnej ewolucji piedmontu Sikkimsko-Bhutańskich Himalajów dotyczy fragmentu rowu przedgórskiego Himalajów między doliną Tisty i Jainti (ryc. 1, 2). Trwała subsydencja na nizinie odwadnianej przez Ganges i Brahmaputrę na przedpolu podnoszonych Himalajów doprowadziła do utworzenia strefy przejściowej – nachylonego piedmontu, którego podstawową częścią składową są większe i mniejsze stożki napływowe rzek rozcinających Himalaje. Przedpole Sikkimsko-Bhutańskich Himalajów wznoszących się do 7000 m n.p.m. opada na długości 100–150 km od około 350–300 m n.p.m. do poniżej 50 m n.p.m. Strefę brzegu gór na tym odcinku charakteryzują wysokie opady przekraczające 5000 mm co wiąże się z brakiem wyższych barier na ich przedpolu.

Celem pracy było danie odpowiedzi na pytanie jaką rolę we współczesnej ewolucji piedmontu Sikkimsko-Bhutańskich Himalajów odgrywa wielkość i położenie zlewni górskich, aktywność tektoniczna, ekstremalne opady i powodzie (i ich zgrupowanie w czasie) jak również zróżnicowana działalność człowieka. Analiza tych czynników stała się podstawą opracowania modeli zróżnicowanej przestrzennie ewolucji piedmontu Himalajów.

Obszar zainteresowania badany był dawniej fragmentarycznie zarówno przez geologów jak i geomorfologów (m.in. Nakata 1972). W latach 1980. szczegółowe badania głównie osuwisk i stożków w dorzeczach Lish i Gish prowadził S. Basu z North Bengal University z zespołem i równolegle rozpoczął w Dardżylińskich Himalajach zespół polski. Studia te zainicjował jeszcze po powodzi w 1968 roku L. Starkel (Starkel 1972; Froehlich, Starkel 1993 i in.). Z nowszych badań geologicznych szczególną wagę mają datowania aluwiów wysoko podniesionych teras w dorzeczu Jaldhaki na 22–34 tys. lat BP (Guha i in. 2007).

Zespół autorów niniejszej rozprawy prowadził badania w ciągu ostatniego 10-lecia. Obejmowały one analizę map topograficznych z lat 1929–30 i 1960. i zdjęć satelitarnych z lat 1990 i 2001 (oraz fragmentarycznie z innych lat) w celu rozpoznania związku zmian w przebiegu i zasięgu koryt rzecznych a także w mniejszym stopniu rozmiarów osuwisk i zmian w użytkowaniu ziemi. Dane opadowe (w tym dobowe) głównie z lat 1993–2001 uzyskiwano przede wszystkim z plantacji herbaty, a także ze stacji sieci państwowej Indii jak i brzeżnej części Bhutanu. Fragmentaryczne dane o przepływach głównie Torsy i Jaldhaki, a także o wahaniach stanów wody i transporcie zawiesiny i zmianach przekroju koryt rzecznych zostały udostępnione przez różne służby. W analizie użytkowania oparto się na zdjęciach satelitarnych i publikowanych danych statystycznych.

W czasie kilkudniowych objazdów terenowych w latach 2000–2007 dokonywano rejestracji kartograficznej i fotograficznej typów rzeźby, a zwłaszcza typów koryt rzecznych, zmian ramion koryt, osuwisk, tempa zarastania łach, konfrontując obserwacje ze zdjęciami topograficznymi i satelitarnymi. Na plantacjach herbaty zbierano szczegółowe informacje o przebiegu i skutkach ulew. Szczególnie skupiono się na kilkunastu odcinkach dolin (ryc. 28) dla których zrekonstruowano zmiany w ciągu ostatnich 70 lat.

Sikkimsko-Bhutański odcinek górotworu Himalajów składa się z kilku nasunięć, z których najbardziej brzeżne, obejmujące neogeńsko-plejstoceńskie utwory molasowe Siwalików zanika na części odcinka (ryc. 1, 4) i stroma, 500–1500 m wysoka krawędź gór cofnięta jest do kilkunastu kilometrów ku północy między rzekami Chel i Ghatia. W tej części rejestrujemy liczne równoleżnikowe i południkowe linie tektoniczne wzdłuż których poszczególne bloki przesunięte są w pionie o dziesiątki metrów (ryc. 5, 6, 7). Pierwsze datowania radiowęglowe wskazują, że stosowane wcześniej kryterium hipsometryczne nie może być główną podstawą wydzielania kilku różnowiekowych stopni terasowych. Dlatego na przeglądowej mapie geomorfologicznej (ryc. 7) wydzielono jedynie 2–3 generacje stożków i teras.

W analizie rzeźby szczególną uwagę zwrócono na przebieg krawędzi gór i wysokość nad poziomem morza wierzchołków stożków i koryt rzecznych u wylotu z gór (ryc. 9). Okazuje się, że są one warunkowane zarówno młodą tektoniką jak i wielkością rzek (reżimem hydrologicznym). Duże rzeki są głęboko wcięte (Tista, Torsa), małe zaś, drenujące brzeg gór o wysokich opadach sypią stożki, których nie są w stanie uprzątnąć okresowe potoki stale zmieniające bieg. Do tego dźwigane bloki sprawiają, że różnice położenia wylotów dolin himalajskich przekraczają 200 m (ryc. 9). Niektóre z mniejszych rzek himalajskich przecinają podnoszone bloki antecedentymi przełomami (np. Neora, Murti, Kurti i in.) i sypią stożki poniżej (ryc. 8). Generalnie, stożki mniejszych potoków o większych nachyleniach (do 20–30‰) tworzą charakterystyczną listwę u brzegu gór szeroką do 10 i więcej kilometrów, poniżej spadki maleją i frakcja niesionego rumowiska. W odróżnieniu od nich duże, głębiej wcięte roztokowe rzeki rozlewają się szerzej i przerzucają koryta dopiero w większej odległości od gór. Na odcinku 30–40 km aż po Brahmaputrę rozciągają się rozległe równiny, w obrębie których przeważają rzeki meandrowe. Liczne z nich mają swe źródła dopiero w dolnych partiach stożków i żłobią płytkie rynny rozcięte do 2–3 m.

Opady skoncentrowane w 4 miesiącach letnich (ryc. 10) osiągają najwyższe wartości roczne rzędu 4000–6000 mm zarówno na krawędzi gór jak i w brzeżnej części piedmontu (ryc. 11–14). W głąb gór opady szybko maleją spadając poniżej 2000 mm na około 25 km, mniejszy gradient rejestrowany jest na przedpolu gór. W szczególnie wilgotnych latach (1998) opady sięgają nawet 8000 mm. Średnio w ciągu roku zdarza się 5–10 dni z opadem wyższym od 100 mm. Analiza opadów rozlewnych w latach 1993–2001 (ryc. 15) pokazuje, że rejestrowane są serie opadów przekraczające 1000–1500 mm. Opad w dniach 19–21 lipca 1993 sięgał w Makrapara 1606 mm (maksymalny dobowy 838 mm). Natomiast w 1998 roku wystąpiły 3 serie opadów rozlewnych. Pierwsza fala miała miejsce 8–13 czerwca 950–1200 mm, druga 15–18 czerwca 500–900 mm i trzecia 20–24 lipca 700–1000 mm. Charakterystyczne jest zgrupowanie ekstremalnych opadów w odstępach co dwa lata, aczkolwiek w ciągu 40 lat obserwuje się wyraźną tendencję do zmniejszenia wysokości opadów (ryc. 16).

W strefie piedmontu można wydzielić cztery typy rzek o różnym reżimie hydrologicznym:

1. Duże rzeki tranzytowe (Tista, Torsa) płynące z wysokich Himalajów zasilane są nie tylko przez opady, ale topniejące lodowce i śniegi oraz wody gruntowe (ryc. 3, 17). W latach 1998–2000 najwyższy rejestrowany przepływ wynosił 3800 m^3s^{-1} (ok. 1 $m^3s^{-1}km^{-2}$), zaś najniższy poniżej 20 m^3s^{-1}. W 1998 roku zarejestrowano 7 odrębnych wezbrań. Transport zawiesiny był wówczas 5-krotnie wyższy niż gdy było jedno większe wezbranie w 2000 roku (ryc. 25).
2. Rzeki himalajskie niższych pięter (Jaldhaka) zasilane przez opady i wody gruntowe cechuje większa dynamika przepływów (ryc. 21). Maksymalny przepływ sięgnął 5000 m^3s^{-1} przy spływie jednostkowym 3145 $m^3s^{-1}km^{-2}$ (ryc. 22, 23). Można te różnice w stosunku do Torsy tłumaczyć innymi warunkami infiltracji, a zwłaszcza większym obszarem objętym przez ekstremalne opady.
3. Małe rzeki odwadniające brzeżną część Himalajów (Lish, Gish, Daina, Rehti, Pana i in., ryc. 3). Są to rzeki zwykle okresowe (tab. 2), niosące wielkie ilości rumowiska w roztokowych korytach. W zlewniach w znacznym stopniu wylesionych współczynnik nieregularności przepływów sięga 1000–7000. Natomiast w zalesionej zlewni Neora spada do 400.
4. Rzeki meandrowe zasilane przez wody gruntowe wypływające w obrębie stożków, o wyrównanym przepływie, jednak wyraźnie wzbierające w czasie opadów letnich.

Struktura użytkowania terenu odzwierciedla zróżnicowaną rzeźbę, klimat, litologię i gleby gór, stożków napływowych i równin aluwialnych, jak też jest wynikiem procesu kolonizacji. Najwcześniej objął on równiny aluwialne, a od połowy XIX w. szczególnie intensywnie przebiegał na bezpośrednim przedpolu i brzegu Himalajów. Zagospodarowaniu nowych terenów sprzyjały ruchy migracyjne

Nepalczyków i ludności południowego Bengalu na teren zakładanych plantacji herbaty, a także eksplozja demograficzna w drugiej połowie XX w. Obecnie badany obszar zamieszkuje ok. 2,7 mln ludzi, z czego tylko 8,8% mieszka w miastach.

Góry w większości są porośnięte naturalnym lasem (ryc. 26). Najmniejszy udział powierzchni leśnych przy równocześnie największej gęstości zaludnienia ok. 200 os./km^2 występuje w dorzeczach Lish i Gish wykorzystywanych pod uprawę i odkrywkową eksploatację węgla kamiennego. Strefy wylesień obserwuje się także wzdłuż głównych dolin. Gęstość zaludnienia spada w kierunku wschodnim. Na brzegu Bhutańskich Himalajów, gdzie położone są miasto Phuntsholing i odkrywkowe kopalnie dolomitów, gęstość zaludnienia wynosi tylko 40 os./km^2. Górskie zlewnie w tym obszarze są porośnięte lasem nawet w ponad 90%.

Strefę piedmontu gór budują stożki napływowe (ryc. 7, 9), których południowy zasięg ogranicza w przybliżeniu poziomica 100 m n.p.m. Podczas powodzi rzeki często zmieniają swoje koryta roztokowe zajmujące ok. 10% powierzchni piedmontu. Gęstość zaludnienia sięga tutaj 300–500 os./km^2. Zachodnia część aż po dorzecze Pany zajęta jest pod plantacje herbaty, chronione obwałowaniami przed powodziami. W kierunku wschodnim udział lasów objętych ochroną wzrasta do ponad 75% powierzchni zlewni (ryc. 26).

W odległości 20–30 km od brzegu Himalajów rozciągają się płaskie równiny aluwialne. Meandrowe koryta rzek zajmują tylko 4% powierzchni równin. Jest to obszar niemal w całości wylesiony. Większość terenu zajęta jest pod osiadłe rolnictwo z dominującą uprawą ryżu. Gęstość zaludnienia przekracza miejscami 1000 os./km^2.

Szczegółowa analiza koryt i powierzchni przez nie zajętych na wybranych kilkunastu odcinkach (ryc. 28) szeregu dolin strefy piedmontu w ciągu 70 lat (1930–2000) oparta o dwa zdjęcia topograficzne i dwa zdjęcia satelitarne pozwoliła wykazać skalę zmian zarówno gdy chodzi o zmiany układu roztokowego, przerzuty koryt jak i zmiany ich szerokości. Koryta dużych rzek himalajskich Tisty i Torsy stale zmieniały układy ramion rzeki w systemie roztokowym, a Torsa w obrębie stożka dokonała w połowie XX w. przerzutu z zachodu na wschód. Koryta na stożkach zachodnich rzek Lish, Gish i Chel rozszerzyły swą powierzchnię już przed 30–40 laty w związku z wylesieniem i eksploatacją węgla. Ku wschodowi ekspansja koryt na stożkach była szczególnie wyraźna od 1993 r. gdy nastąpiła seria opadów rozlewnych, które wywołały wielkie powodzie, osuwiska i spływy gruzowe, a także bifurkacje okresowych potoków i przerzuty koryt (ryc. 41, 51, 55). Porównanie zdjęć satelitarnych z lat 1990 i 2001 wykazało często ponad 2-krotny wzrost powierzchni koryt roztokowych (tab. 5), jedynie w zlewniach zalesionych nie przekraczał on 30%. Szczególną rolę odegrały 2–3 ekstremalne opady w 1998 r. (por. ryc. 43). Równocześnie zarejestrowano w latach następnych stopniowe zarastanie nieczynnych ramion (fot. 35). Wzmożony transport rumowiska dennego w latach 1993–2000 doprowadził do wkraczania agradacji w góry jak też do przesunięcia odcinków roztokowych w dół biegu rzek o 5–15 km. Dawne koryta meandrowe np. dolnej Dainy, czy środkowej Gabur-Basry i Jainti uległy wyprostowaniu i poszerzeniu (ryc. 57). Jedynie w odcinkach antecedentnych rzek przecinających podnoszone bloki między dolinami Chel, Jaldhaki i Ghati nie nastąpiły istotniejsze zmiany w szerokości koryt.

Przeprowadzone badania pozwalają wydzielić w obrębie piedmontu Sikkimsko-Bhutańskich Himalajów cztery podstawowe typy rzeźby: megastożki dużych rzek, stożki mniejszych rzek tworzących stromą listwę u brzegu gór, strefę podniesionych bloków z odcinkami antecedentnych dolin i dalej od gór płaskie równiny aluwialne schodzące aż do Brahmaputry.

Opracowano nowy model podłużnego i poprzecznego profilu piedmontu nawiązujący do poprzednich (ryc. 58), podkreślający jednak różnice między stożkami dużych rzek i małych (ryc. 59A i B) i wyjaśniający mechanizm zmian z koryt roztokowych na meandrowe (związanych z facją niesionego materiału i spadkiem koryt). Od tych dwóch modeli występuje szereg odchyleń, związanych głównie z młodymi ruchami tektonicznymi w obrębie piedmontu, które warunkują obecność odcinków antecedentnych i przesuwają strefę maksymalnej depozycji w dół biegu rzek (ryc. 61, 62). W rozwoju stożków, a szczególnie w przerzutach i przesuwaniu odcinków roztokowych w dół biegu rzek szczególną rolę odgrywają zgrupowania wysokich opadów i powodzi (por. ryc. 15), zarejestrowane m.in. w latach 1990. Również działalność gospodarcza człowieka jest przyczyną wzmożonej agradacji w niektórych dolinach rzecznych np. Lish i Gish (por. ryc. 28). Modyfikacje w rozwoju i rozmiarach stożków wprowadzane są również w przez układy koryt m.in. ich konwergencję lub dywergencję (ryc. 63).

Analizowany odcinek piedmontu obok cech wspólnych dla całego piedmontu Himalajów wykazuje odrębności związane zarówno z opóźnieniem czy niedorozwojem brzeżnego nasunięcia strefy Siwalików, jak też z przyspieszeniem w nadbudowie stożków napływowych małych potoków w wyniku wzrostu częstotliwości opadów ekstremalnych. Rola człowieka nie wydaje się być pierwszoplanowa w przebiegu agradacji na tym odcinku brzegu Himalajów.

Wiele problemów jest nadal nierozwiązanych, wymaga dalszych szczegółowych badań m.in. rozpoziomowanie wiekowe aluwiów, zróżnicowanie sedymentologiczne osadów czy też mechanizm transportu rumowiska dennego w czasie gwałtownych powodzi.

Adres of Authors:
Leszek Starkel, Subir Sarkar, Roman Soja, Paweł Prokop
Department of Geomorphology and Hydrology of Mountains and Uplands
Institute of Geography and Spatial Organization
ul. Sw. Jana 22, 31-018 Krakow, Poland

Photo 1. Outlet of Tista river from the Himalaya. Rapid change from channel cut in Siwalik beds to root part of great alluvial fan, November 2007 (by P. Prokop). Arrow indicates flow direction of river

Photo 2. Alluvial fan of Lish river with tendency to aggradation. In spring time totally dry, November 2005 (by L. Starkel)

Photo 3. Deposition of gravels and boulders during summer flood over Lish river after breaking of right embankment, November 2007 (by L. Starkel)

Photo 4. Extensive fan of Gish river bordered by embankment with distinct aggradation tendency, November 2006 (by L. Starkel)

Photo 5. Burried trees in root part of Gish alluvial fans, March 2006, (by R. Soja)

Photo 6. Remains of old bridge over Chel river dammaged during flood and replaced due to rising of channel floor, November 2007 (by L. Starkel)

Photo 7. Old wide paleochannel of Chel river with rise fields crossing the uplifted part of older alluvial fan, November 2005 (by L. Starkel)

Photo 8. Mal river (tributary of Chel) channel with wide bars incised in uplifted block, November 2005 (by L. Starkel)

Photo 9. Terrace steps incised in marginal part of rising block east of Mal river, which is never drying, November 2005 (by L. Starkel)

Photo 10. Outlet of Neora river (tributary of Chel) from rising block in the piedmont zone. River is carrying big boulders, November 2005 (by L. Starkel)

Photo 11. 30 meters high terrace with erosional rocky socle at the outlet of Chel river from the hills near Upper Phagu TE, February 2003 (by L. Starkel)

Photo 12. Kurti river (tributary of Chel) leaving antecedent narrow section incised in upper Quaternary terrace gravels and underlying bedrock, November 2007 (by L. Starkel)

Photo 13. Murti river (tributary of Jaldhaka) with wide boulder bars in the channel incised in uplifted block, November 2005 (by L. Starkel)

Photo 14. Jaldhaka river leaving the Lesser Himalaya. Meandering channel accompanied by high terraces, November 2007 (by P. Prokop)

Photo 15. Palaeochannel of Jaldhaka over uplifted piedmont block to the east of present-day river November 2005 (by L. Starkel)

Photo 16. Jaldhaka river with extensive braided channel downstream of uplifted block, November 2005 (by L. Starkel)

Photo 17. Ghatia river carrying big boulders in tectonically active part of piedmont, November 2005 (by L. Starkel)

Photo 18. Wide braided channel of Daina river, November 2007 (by L. Starkel)

Photo 19. Small fans along the densily dissected N-S directed mountain front between Chamurchi and Rehti rivers, November 2007 (by L. Starkel)

Photo 20. Dry braided channel of Rehti river. Aggradation is progressing upstream into the mountains, November 2007 (by L. Starkel)

Photo 21. Braided channel of Rehti river overloaded by fine sandy-silty deposits. On the higher floodplain are visible many brickyards, November 2007 (by P. Prokop)

Photo 22. Khagra Jhora landslide valley dissecting steep edge of the mountains with great niche in headwaters and extensive fan modelled by debris flows, November 2007 (by L. Starkel)

Photo 23. System of Pagli-Sukti alluvial fans intensively growing in last 15 years, November 2000 (by L. Starkel)

Photo 24. Dissected mountain front along right bank of Pagli river, November 2000 (by L. Starkel)

Photo 25. One of dry branches of Pagli river over extensive fan, carrying water only during heavy rain, November 2007 (by L. Starkel)

Photo 26. Outlet of Ojha Jhora dissecting elevated high terrace west of Torsa valley. Aggradation after series of floods in 1993-2000, March 2003 (by L. Starkel)

Photo 27. Debris flow in Torsa tributary valley in Phuntsholing after heavy rain in 1998 or 2000, November 2000 (by L. Starkel)

Photo 28. Mazina river with meandering pattern draining piedmont zone west of Torsa river near Jaldapara, March 2003 (by L.Starkel)

Photo 29. Lateral migration of Torsa river near Jaldapara, March 2003 (by L. Starkel)

Photo 30. Braided channel of Torsa river with vegetated bar, November 2007 (by L. Starkel)

Photo 31. Old channel of Torsa river left several decades ago now swampy with several rivulets, March 2003 (by L. Starkel)

Photo 32. One of perennial streams in the zone of former paleochannel of Torsa river, November 2006 (by L. Starkel)

Photo 33. Great landslide with extensive fan at the edge of Himalaya in the Gabur-Basra river valley, November 2006 (by P. Prokop)

Photo 34. Dry active left channel of Pana river with embankment protecting Chuapara Tea Estate, November 2005 (by L. Starkel)

Photo 35. Abandoned dry right channel of Pana river. During flood in summer 2005 some water was flowing in axis of that channel, November 2005 (by L. Starkel)

Photo 36. Extensive braided channel of Kaljani river carrying sand and fine gravel with 1–2 m high floodplain, November 2005 (by L. Starkel)

Photo 37. Footplain of Kaljani river built of alternate layers of silt and sand of overbank facies, flooded probably every year or every second year, November 2005 (by L. Starkel)

Photo 38. Braided channel in root part of alluvial fan of Jainti river with remains of bridge dammaged during flood in 1993 (by R. Soja)

Photo 39. Outlet of Jainti river from Himalaya. On the right forest partly buried by debris flow from small tributary (by R. Soja)

Photo 40. Spring zone of one of meandering streams feeded by groundwaters in the lower part of old alluvial fan between Rehti and Torsa rivers, November 2006 (by P. Prokop)

Photo 41. Meandering creek south of Hasimara over alluvial fan of Kaljani river, March 2004 (by L. Starkel)

Photo 42. Eleti river, one of greatest meandering streams starting in the piedmont zone. Active point bars and lateral erosion are connected with floods caused by heavy rains in the piedmont zone, November 2005 (by L. Starkel)

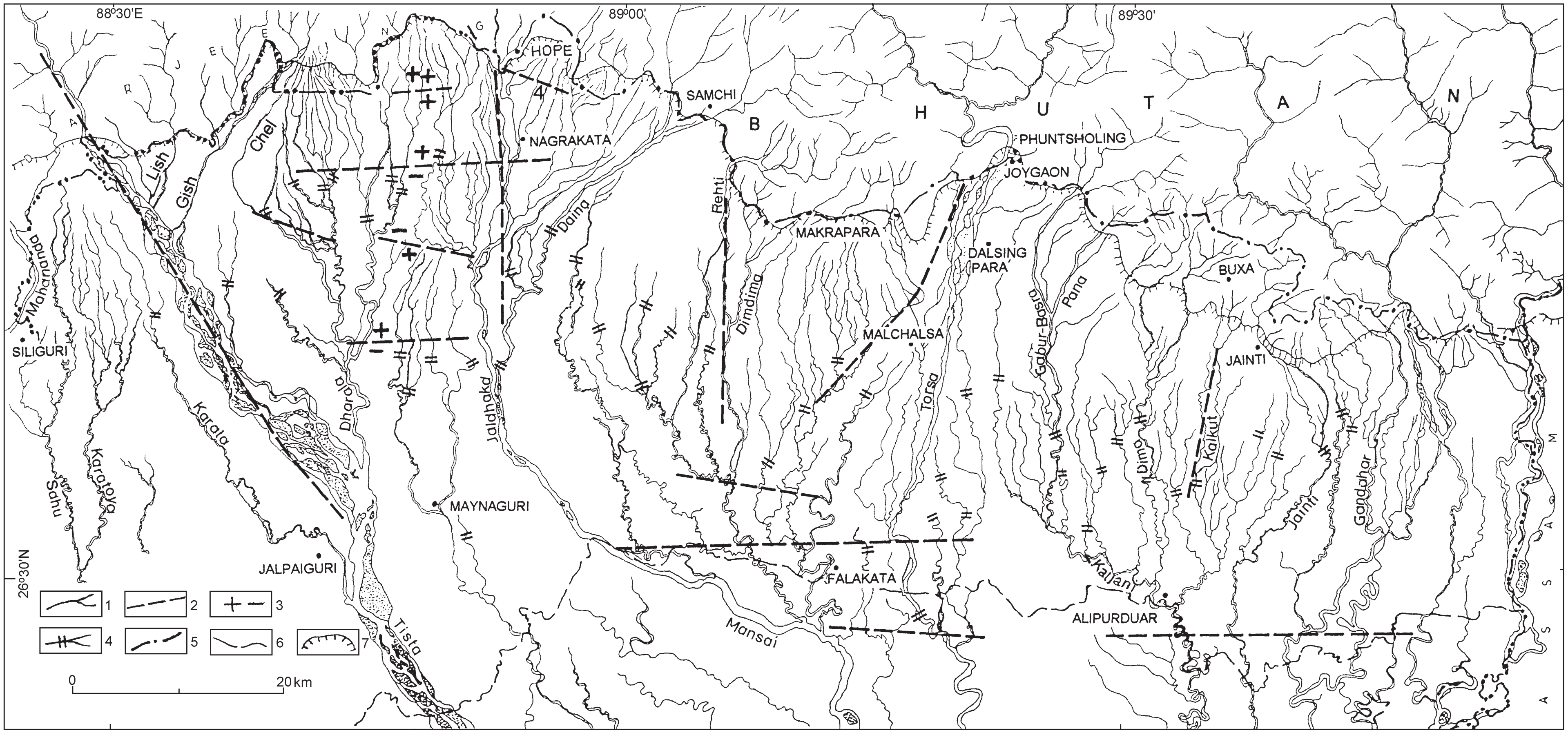


Fig. 6. River network, main fault lines and beginning of meandering channels (compiled by L. Starkel)

1 – drainage pattern after topographic map from 1930, 2 – fault lines (based on Nakata 1972, Chattopadhyay, Das 1972, Guha et al. 2007 and our observations), 3 – rising and subsiding side of active fault lines, 4 – start of meandering sections after topographic map from 1930, 5 – state border, 6 – district boundary, 7 – front of the Himalaya

Sieć rzeczna, główne linie uskoków i początek odcinków meandrowych (oprac. L. Starkel)

1 – rzeki wg starych map topograficznych z 1930 r., 2 – linie uskoków wg map różnych autorów (Nakata 1972, Chattopadhyay, Das 1992, Guha et. al. 2007 i obserwacji własnych), 3 – podniesione i obniżone skrzydło linii uskoku, 4 – początek odcinków koryt meandrowych wg mapy topograficznej z 1930 r., 5 – granica satnu, 6 – granica dystryktu, 7 – brzeg Himalajów

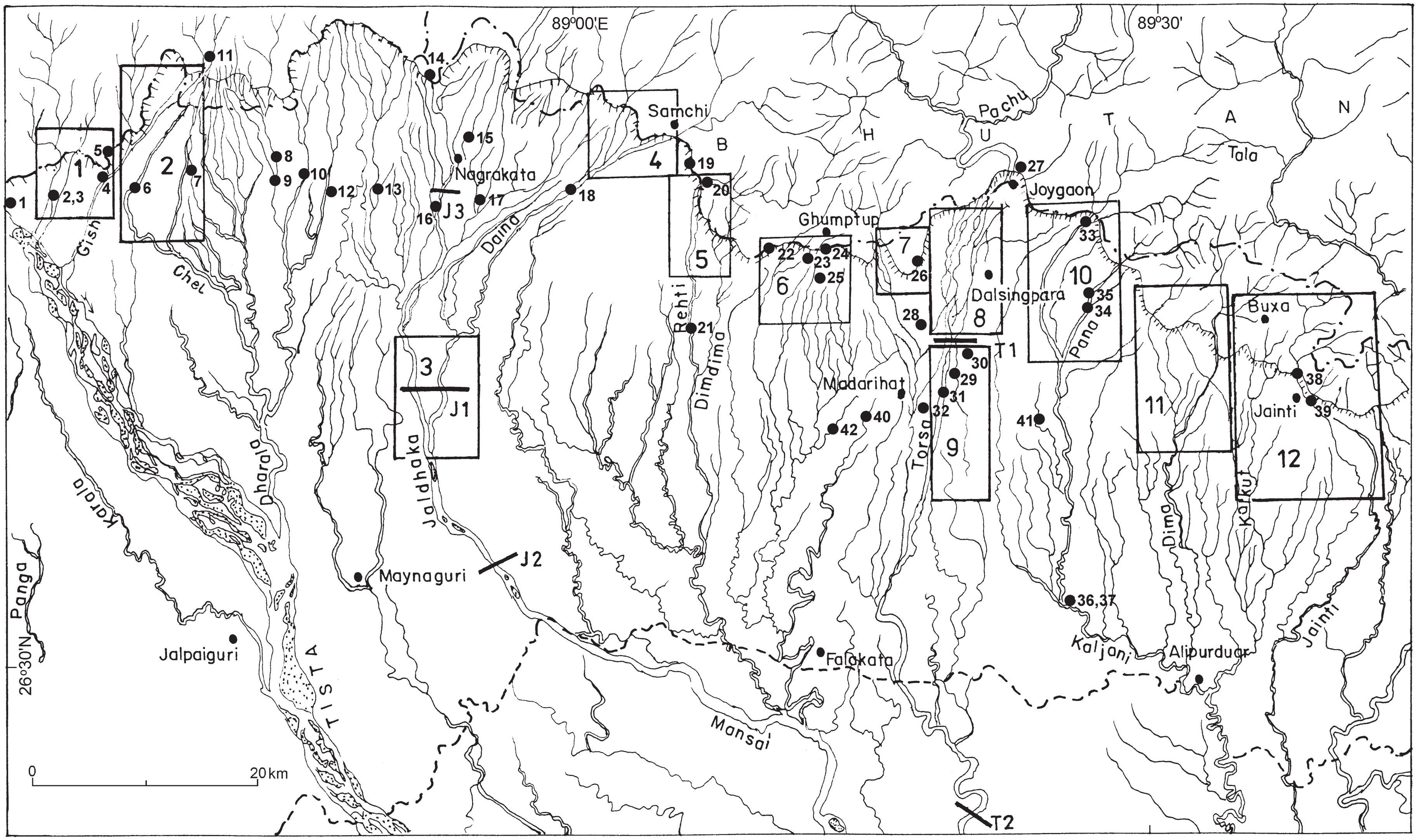


Fig. 28. Location of selected river reaches and channel cross-sections studied in detail. Drainage pattern after map from 1930

1 – Lish and Gish, 2 – Chel, 3 – Jaldhaka, 4 – upper Daina, 5 – Rehti, 6 – Pagli-Sukti, 7 – uplifted terrace west of Torsa, 8 – upper Torsa, 9 – lower Torsa, 10 – Gabur-Basra and Pana, 11 – Raimatang and Dima, 12 – Jainti and Bala, J1-3 – Jaldhaka channel cross-sections, T1-2 – Torsa channel cross-sections

Położenie szczegółowo badanych odcinków dolin i przekrojów koryt. Sieć rzeczna wg mapy z 1930 r.

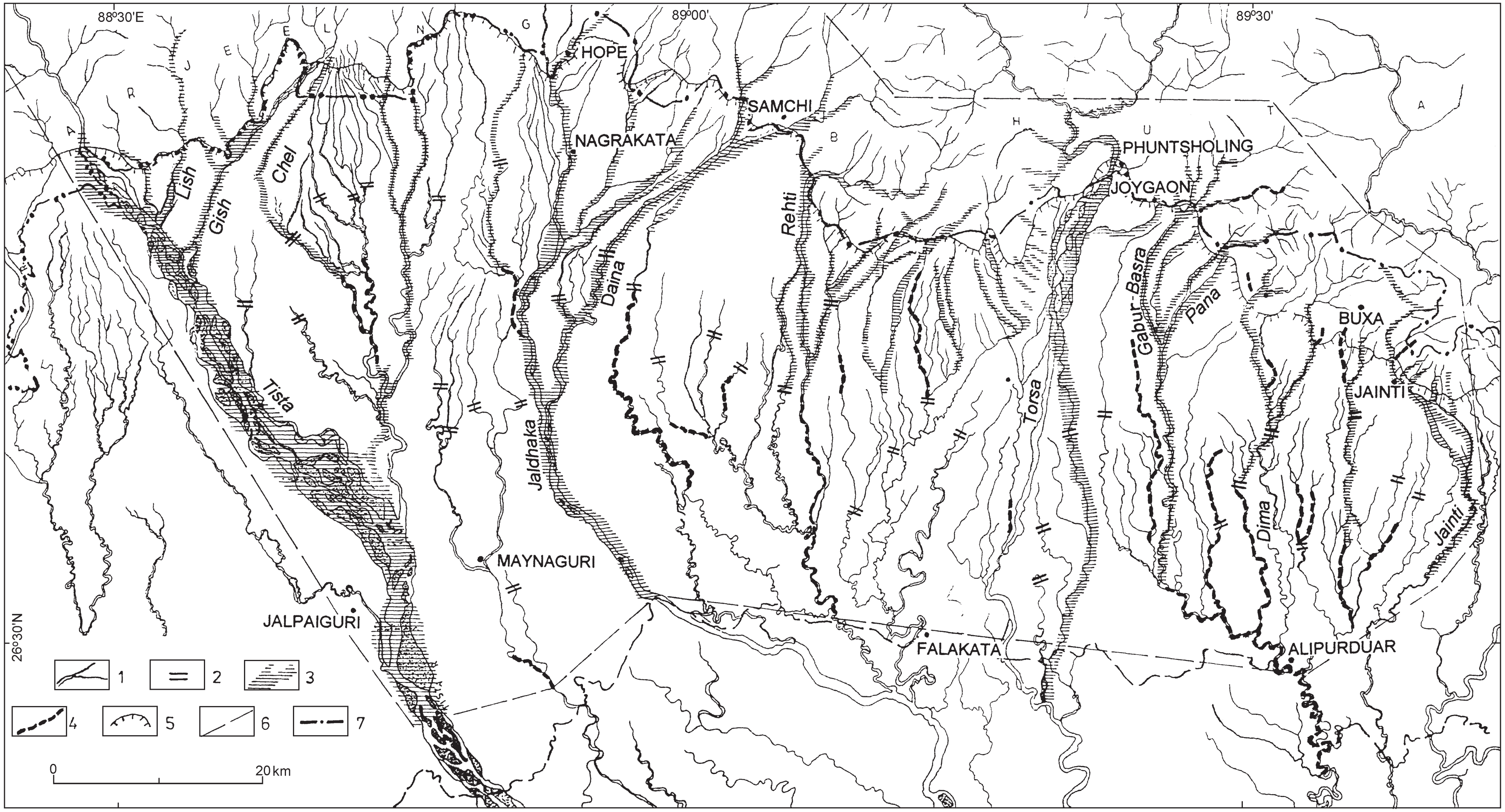
1 – Lish i Gish, 2 – Chel, 3 – Jaldhaka, 4 – górna Daina, 5 – Rehti, 6 – Pagli-Sukti, 7 – podniesiona terasa na zachód od Torsy, 8 – górny fragment Torsy, 9 – dolny fragment Torsy, 10 – Gabur-Basra i Pana, 11 – Raimatang i Dima, 12 – Jainti i Bala, J1-3 – przekroje koryta Jaldhaki, T1-2 – przekroje koryta Torsy

Table 4. Land use in various river catchments in 2001 (cf. Fig. 26, elab. by P. Prokop)

Geomorphic unit	Land use		Lish	Gish	Chel		Jaldhaka					Rehti						Torsa		Kaljani		Raimatang		Bala	Jainti
					Chel	Neora and Mal	Jaldhaka (upper)	Jaldhaka (margin)	Jiti and Ghatia	Daina	Chamurchi	Sukreti Khola	Rehti	Dimdima	Sukti	Pagli	Titi et al.	Amo, Torsa (upper)	Torsa (margin)	Gabur-Basra	Pana	Raimatang	Dima		
Mountains	forest	km^2	24.9	113.4	66.4	98.3	313.0	239.8	144.7	99.0	86.2	5.8	62.3	3.8	14.7	14.3	19.2	1508.2	432.9	90.2	27.4	20.0	26.0	10.4	58.1
		%	49.2	72.2	68.2	88.6	71.0	69.1	74.7	91.1	92.1	73.4	94.8	79.2	88.6	89.9	89.3	45.7	85.2	87.1	80.8	99.0	93.9	98.1	93.0
	other	km^2	23.5	40.9	29.4	12.7	127.4	103.6	46.4	5.8	6.5	1.7	1.9	-	0.8	0.6	0.9	1788.1	62.9	11.6	5.3	0.1	1.2	0.1	2.2
		%	46.4	26.0	30.2	11.4	28,9	29.9	24.0	5.3	6.9	21.5	2.9	-	4.8	3.8	4.2	54.2	12.4	11.2	15.6	0.5	4.3	0.9	3.5
	river	km^2	2.2	2.8	1.5	0.3	0,3	3.4	2.3	3.9	0.9	0.4	1.5	1.0	1.1	1.0	1.4	0.6	12.1	1.7	1.2	0.1	0.5	0.1	2.2
		%	4.3	1.8	1.5	0.1	0.1	1.0	1.2	3.6	1.0	5.1	2.3	20.8	6.6	6.3	6.5	0.0	2.4	1.6	3.5	0.5	1.8	0.9	3.5
	total	km^2	50.6	157.1	97.3	111.0	440.7	346.8	193.4	108.7	93.6	7.9	65.7	4.8	16.6	15.9	21.5	3296.9	507.9	103.5	33.9	20.2	27.7	10.6	62.5
		%	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Alluvial fans or Duars	forest	km^2	-	27.9	72.9		179.9					93.5						164.6		27.2		54.7		79.0	36.1
		%	-	32.7	15.0		30.3					17.3						33.1		12.7		76.3		96.3	85.3
	tea garden	km^2	5.5	29.5	231.7		141.0					297.6						37.8		52.9		3.6		-	-
		%	36.2	34.5	47.6		28.5					55.2						7.6		24.6		5.0		-	-
	other	km^2	5.4	11.2	156.5		109.4					117.9						230.5		114.9		4.7		0.4	1.2
		%	35.5	13.1	32.2		22.1					21.9						46.4		53.5		6.6		0.5	2.8
	river	km^2	4.3	16.8	25.5		94.2					30.3						64.5		19.8		8.7		2.6	5.0
		%	28.3	19.7	5.2		19.1					5.6						13.0		9.2		12.1		3.2	11.8
	total	km^2	15.2	85.4	486.5		494.3					539.2						497.3		214.8		71.7		82.0	42.3
		%	100.0	100.0	100.0		100.0					100.0						100.0		100.0		100.0		100.0	100.0

Fig. 57. Shift in braided channel sections downstream indicating progressive aggradation between mid 20th century and beginning of 21st century (compiled by L. Starkel)
1 – rivers, 2 – upstream extent of meandering in mid-20th century, 3 – wide braided channels in 2001, 4 – meandering sections with point bars in 2001, 5 – margin of the Himalaya, 6 – extent of surveyed area, 7 – state or district boundaries

Przesunięcie odcinków roztokowych w dół biegu rzek, wskazujące na postępującą agradację między połową XX w., a początkiem XXI w. (oprac. L. Starkel)
1 – rzeki, 2 – zasięg meandrowania w połowie XX w., 3 – szerokie koryta roztokowe w 2001 r., 4 – odcinki meandrowe z odsypami na zakolach w 2001 r., 5 – brzeg Himalajów, 6 – zasięg obszarów badań, 7 – granice państw lub dystryktów



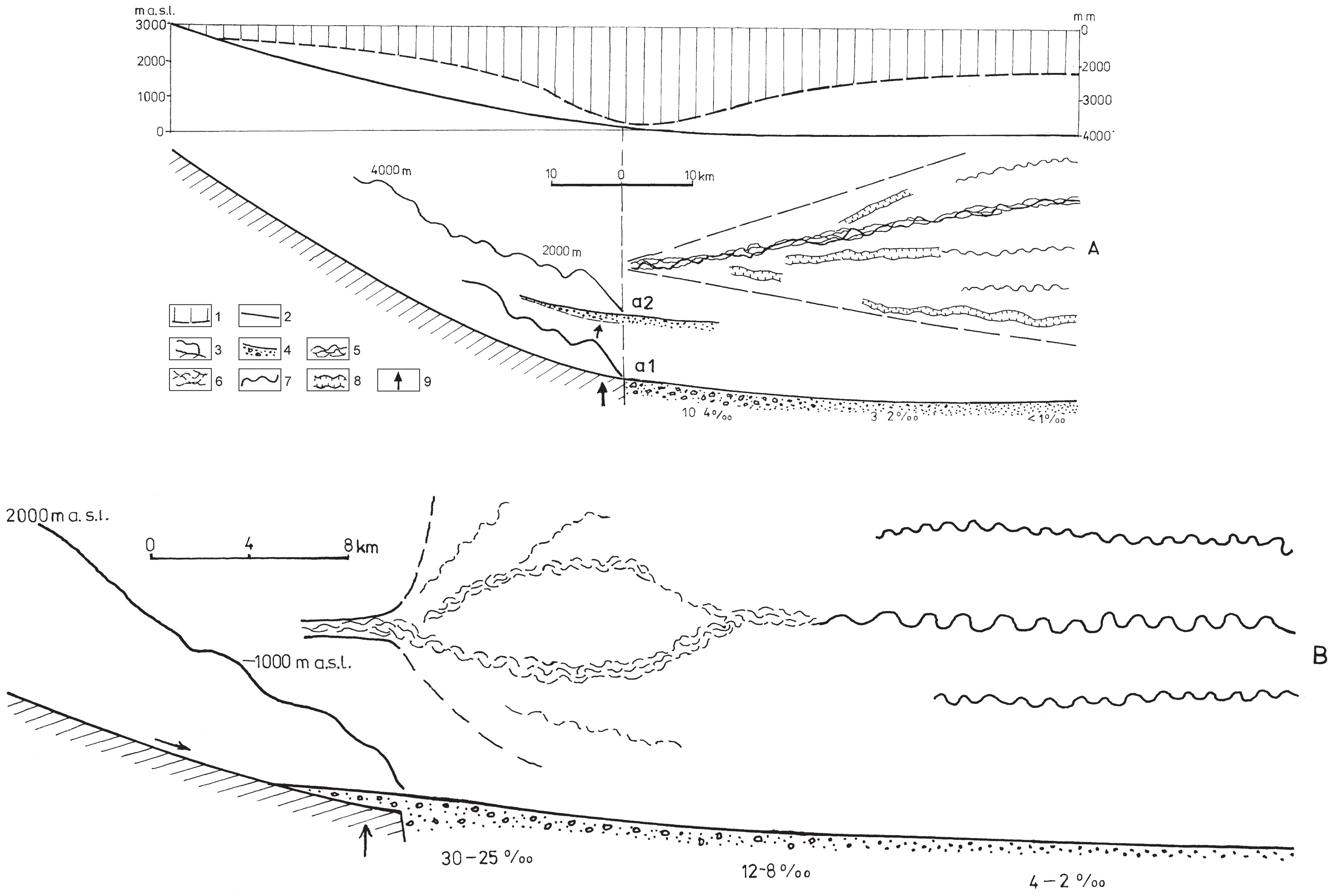


Fig. 59. Two general models of the piedmont zone (elab. by L. Starkel)
A – alluvial fans of large Himalayan rivers, B – alluvial fans of smaller periodic streams draining mountain margin (longitudinal and transversal section)
1 – rainfall transect, 2 – river channel longitudinal profile, 3 – bedrock and mountain front, 4 – coarser or finer alluvial sediments, 5 – braided channel, 6 – braided channel of episodic stream, 7 – meandering channel, 8 – incised paleochannel, 9 – uplift tendency

Dwa ogólne modele strefy piedmontowej (oprac. L. Starkel)
A – stożki piedmontowe dużych rzek himalajskich, B – stożki napływowe mniejszych rzek okresowych drenujących brzeg gór (profil podłużny i poprzeczny)
1 – przekrój wysokości opadów od gór do przedpola, 2 – profil podłużny koryta rzeki, 3 – cokół skalny i brzeg gór, 4 – aluwia grubo- i drobnoziarniste, 5 – koryto roztokowe, 6 – koryto roztokowe rzeki epizodycznej, 7 – koryto meandrowe, 8 – wcięte paleokoryto, 9 – tendencja podnosząca