II MOUNTAINS AND PLAINS

II.1 THE MAIN RIVER SYSTEMS

Although the two major rivers after which the basin is named have their origins within 250 km from each other on either side of the Himalaya, and their outlets adjacent to one another in the northernmost part of the Bay of Bengal, their courses show important contrasts (Figures 1 and 2).

The *Ganges* rises south of the main Himalayan divide near Gangotri in the Indian state of Uttar Pradesh. Initially it runs in southerly directions and at a steep gradient (Figure 2a), before breaking through the outer Himalayas near Dehradun and reaching the WNW-ESE oriented plain that is named after it at Hardwar, some 350 km from the source.

From here onwards, the Ganges continues to flow at ever smaller gradients, viz. from about 100 cm/km in the piedmont zone around Hardwar to less than 6 cm/km in Bihar (Figure 2a). Meandering as well as braiding occurs here (Singh & Verma, 1987).

Between Hardwar and the river's mouth (a stretch of 2600 km) the Ganges is joined by numerous tributaries, both from the young mountain range in the north as well as from the old plateau in the south (Figure 1). The most important tributary is the Yamuna, which drains more than one third of the entire Ganges basin, including a significant portion of the southwestern plateau. It joins the Ganges at Allahabad. The major Himalayan tributaries are the Karnali (draining 12% of the basin) and the Sapt Kosi (9%). The latter river is particularly notorious for its unreliable character and claims have been made that this river alone contributes 40% of the entire sediment load of the Ganges (Alford, 1988a). The most important tributary from the south is the Son, which covers almost 7% of the total area, has a fairly steep gradient (45 cm/km on average) and a rather flashy flow regime (Singh & Singh, 1987). Near Farakka the Ganges splits up into several branches, the most important of these being the Hooghly (which reaches the Bay of

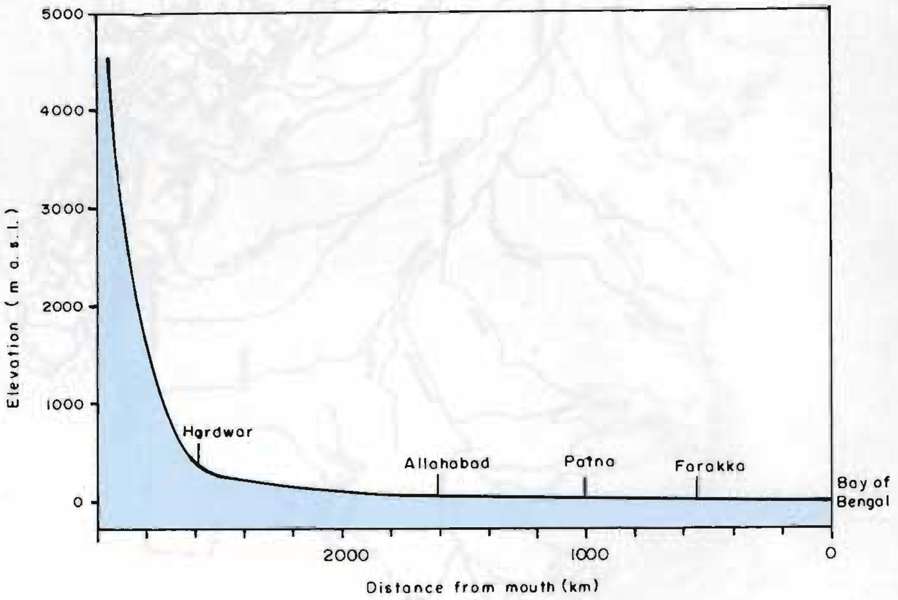


Figure 2a **Approximate longitudinal profile of the river Ganges as determined from small-scale maps.**

Bengal at Calcutta), the Madhumati, and the Ganges proper. The latter eventually joins the Brahmaputra and is then called Padma (see below).

The *Brahmaputra* (or Tsangpo as it is called in Tibet) on the other hand, originates in the Kailas range north of the high Himalaya. It does not break through the mountains immediately, but flows eastward for about 1200 km and at a fairly low gradient (Figure 2b) along the bottom of a flat tectonic valley parallel to and about 160 km north of the Himalaya (Figure 1). At the extreme eastern end of its course in Tibet, the Tsangpo suddenly takes a turn to the south and cuts a deep and narrow gorge upon crossing the high Himalayan range. The gradient of the river in the gorge section is extremely steep (Figure 2b). The river then traverses another 225 km of mountainous terrain before debouching onto the Assam plain near Pasighat at an elevation of only 155 m. After being joined by the Dibang and Lohit rivers, the combined flow, which is now called Brahmaputra, moves westward through the valley of Assam for about 720 km, becoming strongly braided in response to the greatly reduced slope of its bed (Figure 2b; Goswami, 1985). Before turning south again at Dhubri, the Brahmaputra receives major contributions from a number of Himalayan and other rivers (Figure 1).

Shortly after crossing the border with Bangladesh, the river is joined by the Tista, which, like the Kosi, for centuries has been notorious for its capacity to flood. The Brahmaputra then bifurcates: the smaller (eastern) channel retains the name Brahmaputra and the main channel is now called Jamuna. Some 200 km further south the Jamuna joins forces with the Ganges, the combined flow now being called Padma. The latter (and also the

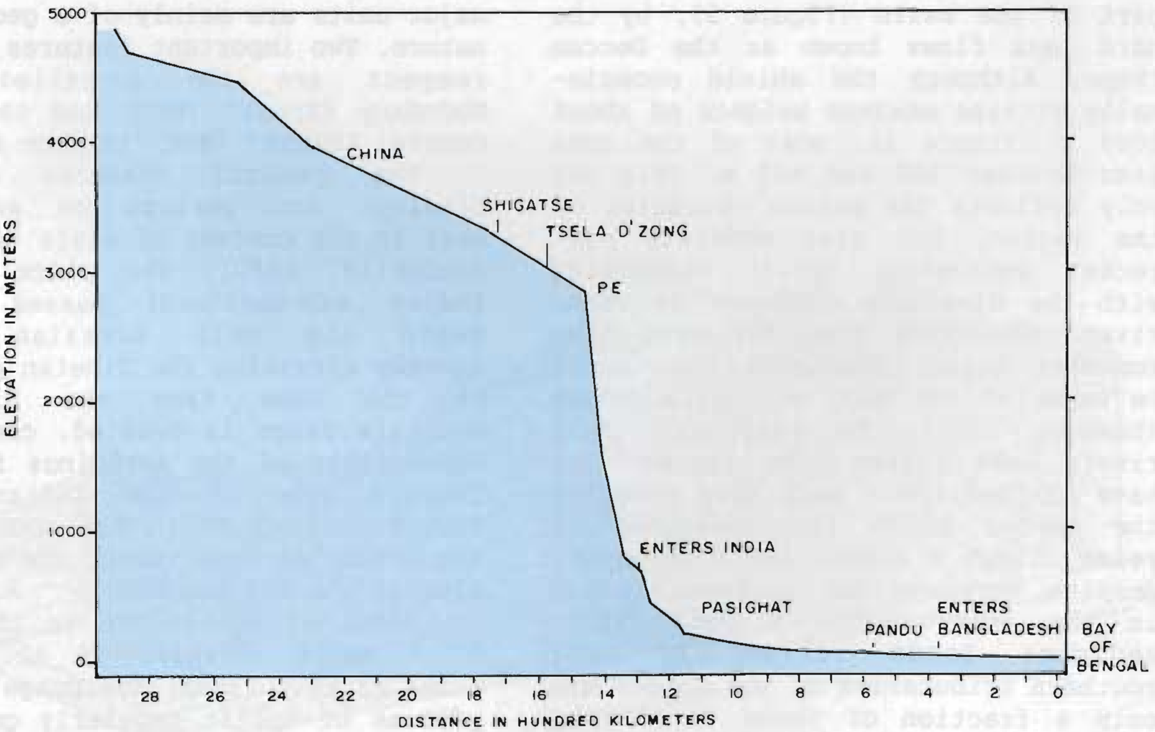


Figure 2b Longitudinal bank profile of the Brahmaputra River (after Goswami, 1985).

Brahmaputra) eventually becomes part of the Meghna river system, which drains most of eastern Bangladesh and the surrounding hills, before discharging their waters into the Bay of Bengal (Figure 1).

II.2 GEOLOGY AND GEOMORPHOLOGY

II.2.1 Ganges River Basin

A broad distinction can be made between the old and geologically stable shield area in the south, the Indo-Gangetic depression in the centre, and the young and geologically active Himalayan mountain range in the north (Figure 3).

Southern Plateau

The southern plateau consists largely of very old (Palaeozoic and older) crystalline and sedimentary rocks, in some parts overlain by younger (Mesozoic) sedimentary rocks, and, especially in the southwestern part of the basin (Figure 5), by the hard lava flows known as the Deccan traps. Although the shield occasionally attains maximum heights of about 1000 m (Figure 1), most of the area lies between 300 and 600 m. This not only reflects the mature character of the region, but also moderate sub-recent geological uplift associated with the Himalayan orogeny. As such, rivers emanating from the area have somewhat higher gradients than would be expected for such an old landscape (Saxena, 1987). In addition, these rivers have flashy flow regimes and have shifted their beds upon entering the Ganges plain for thousands of years (Singh & Singh, 1987). However, despite very serious surface erosion in the area (Samuel & Das, 1982), sediment loads carried by most southern tributaries of the Ganges are only a fraction of those carried by the northern tributaries (Gupta, 1975; see section III.6).

Himalaya

As for the Himalayan range, a frequently used sub-division, which is more or less applicable over the entire length of the chain as covered by the present study, follows that proposed for Nepal by Hagen (1969) (Figures 3 and 4).
The various units are roughly parallel to each other and from north to south consist of:

(1) the Tibetan Marginal Range and Plateau, sometimes called Tethys- or Trans-Himalaya (and known as Darma-Johar in the western parts of the mountains);
(2) the Great or High Himalaya (called Himadri in the west);
(3) the Middle or Lesser Himalaya, and (4) the Siwalik foothills.

The Middle Himalaya consists of the Fore-Himalaya (also known as the High Mountains), the central Midlands, and the Mahabharat Range (Figure 4). The latter two are sometimes referred to as "Middle Hills" (Nepal) or "Himachal" (India).

The boundaries between the four major units are mainly of a geological nature. Two important features in this respect are the so-called "main boundary thrust" (MBT) and the "main central thrust" (MCT) (Figure 4).

The general features of the Himalaya can perhaps be explained best in the context of plate tectonics (Stöcklin, 1980). The plate of the Indian sub-continent passes underneath the main Eurasian plate, thereby elevating the Tibetan plateau. At the same time the Himalayan mountain range is created, consisting essentially of the scrapings from the forward edge of the Indian plate forced back (i.e. to the south) over the advancing mass (hence the northern dips of the MBT and MCT).

Rates of uplift are in the order of 1 mm/yr (Zeitler et al., 1982; Iwata et al., 1984). "Slippage" in the process of uplift regularly generates tremors and earthquakes.

In the following pages the four major units will be described briefly (Gansser, 1964; Rupke, 1974; Stöcklin, 1980; Carson et al., 1986; Figures 3-5).

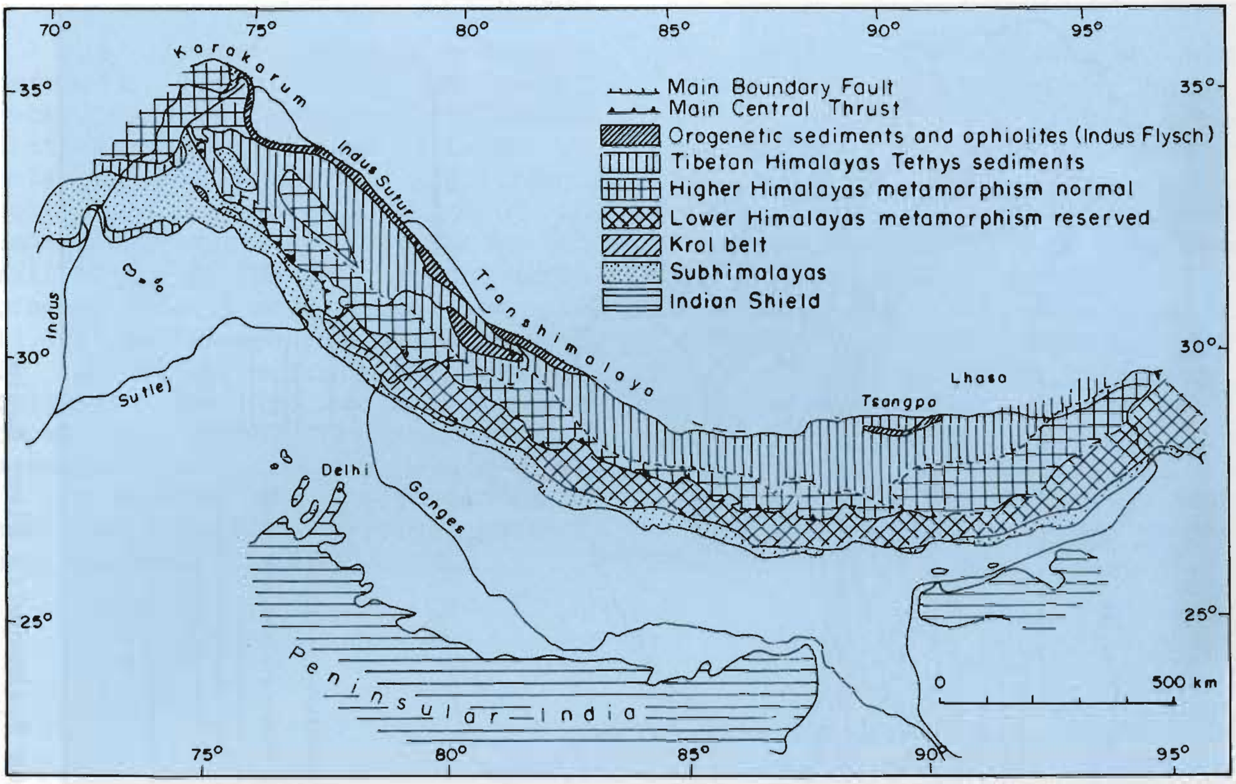


Figure 3 Main geo-structural features of the Ganges-Brahmaputra River Basin (after Gansser, 1964).

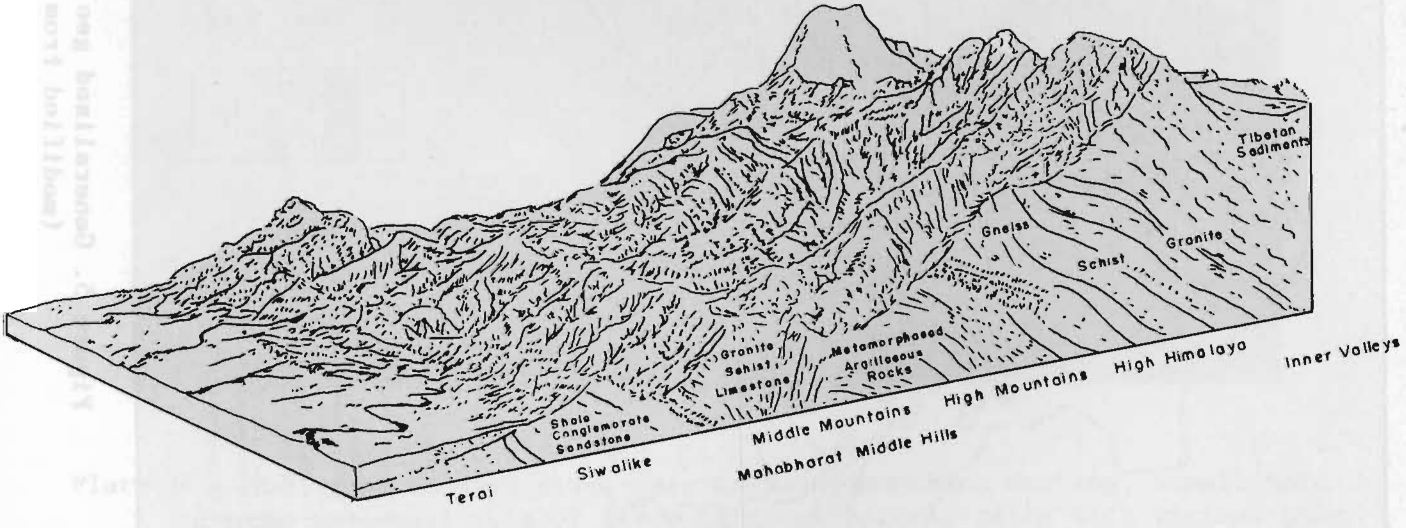


Figure 4 Physiographic zones of the Nepal Himalaya (Galay, 1987; modified from Nelson et al., 1980, and Rámsay, 1986)

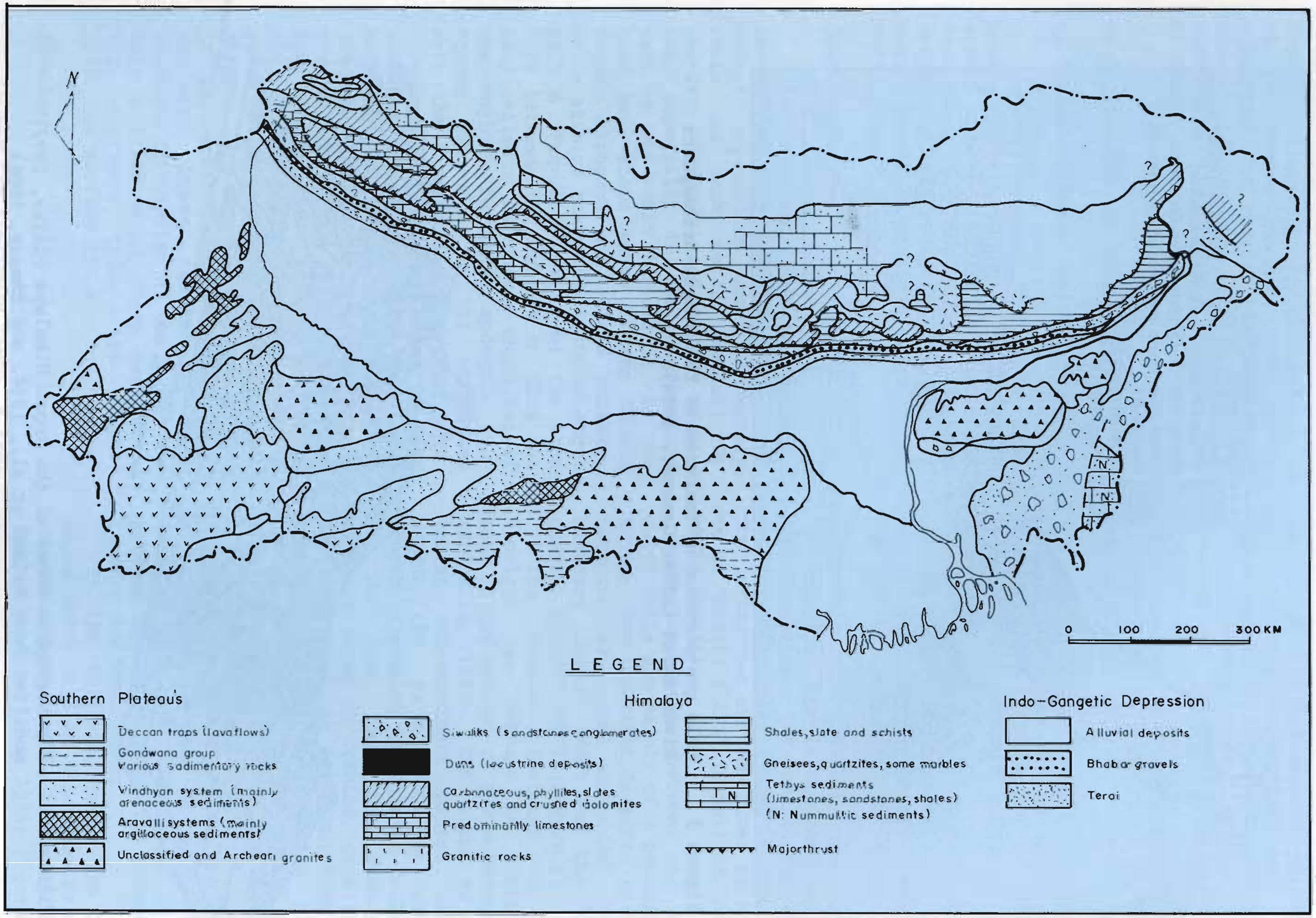


Figure 5. Generalized geological map of the Ganges-Brahmaputra River Basin (modified from Gansser, 1964; Fuchs, 1980).

The *Tibetan Marginal Range* consists largely of sedimentary rocks, such as limestones and shales, that have been little affected by metamorphism. Topography is strongly controlled by the lithology of the underlying rocks. Situated in the rain-shadow of the great peaks, annual precipitation totals are low (see II.3.1) and vegetation, where present, is sparse and xerophytic. As such, gullying, initiated and maintained by occasional showers, is widespread in areas with soft deposits (Plate 13).

In view of the low precipitation and high elevation, physical weathering processes (rock fall/frost shattering, solifluction or debris flows on slopes wetted by snowmelt, undercutting by rivers, etc.) predominate over chemical weathering, resulting in poorly developed and shallow soils. A number of the most important tributaries of the Ganges (e.g. Karnali, Gandaki, Arun) originate in this zone, breaking through the entire mountain chain. Such rivers are called antecedent as they were in existence before the Himalayan orogeny. As such, these river systems are millions of years old. They generally follow Palaeozoic fault systems that have been preserved throughout the orogeny (Plate 1).

Plate 1 **The upper Gandaki river near Kagbeni, southern Mustang, Nepal. Note the various levels of river terraces corresponding with various phases of uplift and river incision.**

The *Great Himalaya* physiographic region includes all the great peaks and consists predominantly of metamorphic rocks. The most resistant of these (gneisses, quartzites, siliceous marbles, occasionally granites and certain types of schists) often constitute the highest parts. The entire region is subject to intense physical weathering. In addition to most of the processes indicated for the Tibetan Marginal Range, the High Himalaya is characterized by active glaciation. Glaciers, cirque bases, U-shaped valleys, hanging tributary valleys, moraines and avalanche slopes are all common landforms. More than 80% of the region has bedrock at or near the surface on very steep terrain (Plate 2).

Plate 2 **Physical weathering processes are extremely active in the glaciated environment of the High Himalaya (North face of Annapurna, Manang district, Nepal).**

The next unit, the *Fore Himalaya* (or High Mountains) is essentially distinguished from the Great Himalaya by the presence of a smaller amount of snowpack, reflecting lower elevations because of slightly less resistant (but also metamorphic) rocks. All valleys in this region have been glaciated in the past. Active river down-cutting since the glaciation has produced impressive canyons and high relief is common. River gradients are high to very high (cf. Figure 2b). Mass movements are frequent, especially along waterways and on the steeper slopes (Plate 3). Moderate gully erosion sometimes results from snowmelt, whereas sheet erosion is induced occasionally by overgrazing of alpine grasslands on moderate to steep slopes.

Soils are coarse-textured and often shallow, reflecting the cool climate and resistant bedrock. Trees, when present, are generally coniferous and often scattered and give way to grassland at higher elevations (3500-4000 m).

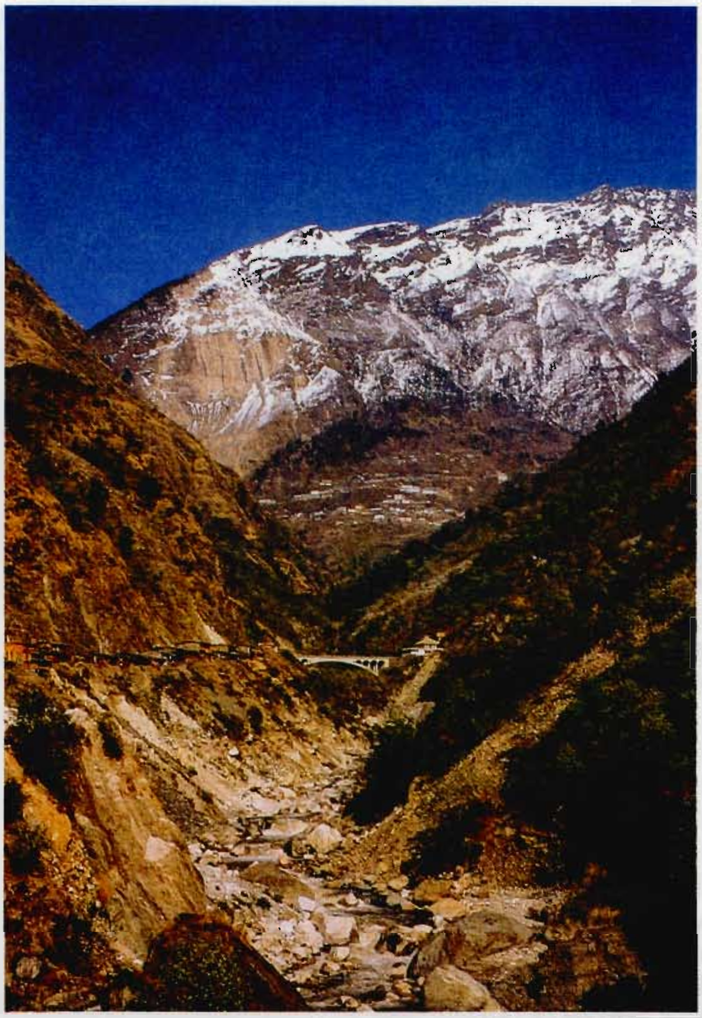


Plate 3 **Upon crossing the High Himalaya, rivers such as the Bhote Kosi in Central Nepal, have carved deep gorges. Note the active erosion and mass-movement processes in the riparian zone.**

The Main Central Thrust (Figure 4), although a fairly irregular zone rather than a sharp line (Figure 5), forms a well-defined boundary between the relatively high Fore Himalaya and the much lower (600-2000 m) *Central Midlands*. As the MCTZ is highly fractured, it is also the scene of intense mass movement processes (see Chapter IV). The Central Midlands generally consist of weakly to moderately metamorphosed rocks that are less resistant to erosion than the more highly metamorphosed rocks exposed further north (Plate 4). Consequently, slopes may be gentler, especially on the relatively soft phyllites. Since the region has not experienced significant glaciation and because of the warmer climatic conditions prevailing here, fairly deep (often reddish) soils have developed in the phyllites.

Steeper slopes (and shallower soils) are associated with harder rock types, such as quartzites and limestones, which are especially common in the western part of this zone (Figure 5). The lowest parts of the Central Midlands are found in structurally controlled valleys, which often contain extensive ancient lake or river terraces (Plate 5). The latter are remnants of past river damming due to huge landslides, or may represent the deposits of large glacial outburst floods before the last glaciation (Carson 1985).

Plate 4

Typical view of the Middle Hill region of Central Nepal near Dhulikhel. Note gully erosion and frequent landslide scars in grazing land.

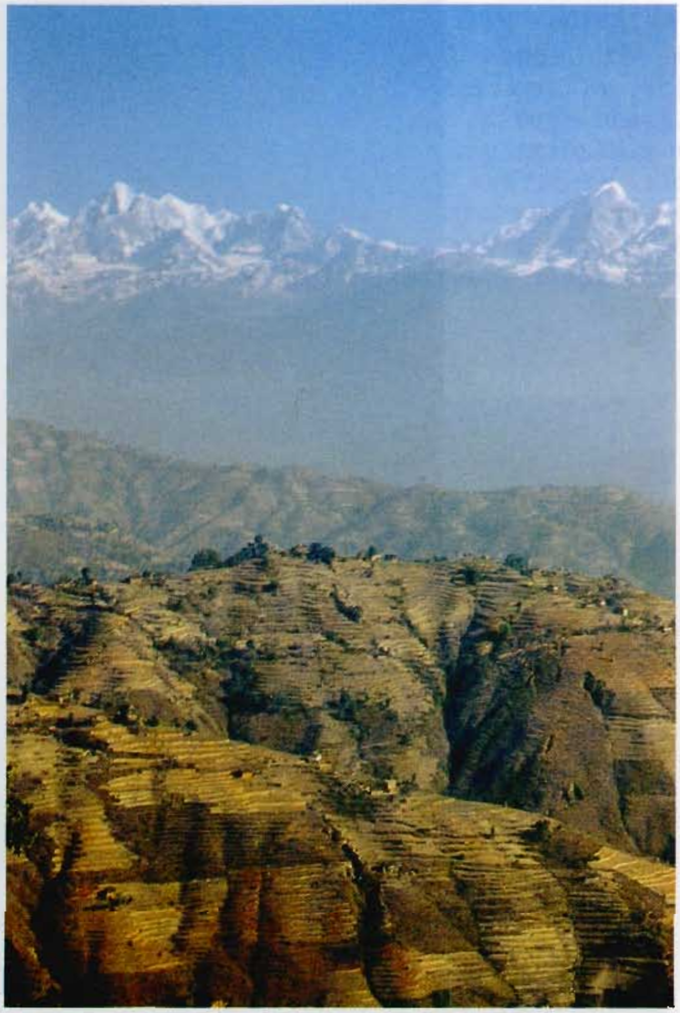


Plate 5

Land use and erosion processes in the Kathmandu valley, Middle Hill region, Central Nepal. Note frequent shallow landslips in scrubland and old major slide in river bend in background.

Gradients of the main rivers flowing through the region are much gentler than in the High Himalaya and many tributaries form extensive alluvial fans near confluences. River bank cutting is also a widespread phenomenon in these valleys. Surface erosion is minimal, even on the steepest slopes, as long as they are covered with the original sub-tropical and warm-temperate forests. However, considerable parts of this relatively densely populated region are now occupied by agricultural fields and more or less severely degraded scrub and grasslands (see Section II.4; Plate 4). The consequences for hillslope hydrological response to rainfall and intensity of erosion processes associated with such changes in land-use, will be discussed in Chapter IV.

In contrast to surface erosion, mass movements have always been common on steep (> 30 °) slopes in this region (Plate 4). There are indications, however, that the number of shallow (less than 3 m deep) slides is increasing following vegetation removal, even on less steep slopes (Carson, 1985; Euphrat, 1987; Manandhar & Khanal, 1988; see Chapter IV).

The third and southernmost unit of the Middle Himalaya is called *Mahabharat Lekh* in Nepal (Figure 4). It rises to heights of upto 2500 m and is made up of rock types that are more competent (i.e. resistant to erosion) than those of the Central Midlands (although they are much less metamorphosed than the hard rocks of the High Himalaya). This leads to steep topography and often relatively thin soils. Common lithologies are quartzites, schists, gneisses, and (especially in the western parts) limestones and dolomites (Figure 5). Deeper soils can be found on river terraces and on fractured granite (Carson et al., 1986).

The Mahabharat range is geologically the most complex of the various zones, consisting of a number of thrust sheets ("nappes") pushed towards the south. When these were created, they presented a barrier to the rivers flowing south from the High Himalaya and many rivers changed their courses in a westerly or easterly direction (Figure 1) before finding a weak zone and breaking through. River gradients in the Mahabharat Lekh are again higher than in the Central Midlands.

Due to the often very steep topography and the presence of only a shallow veneer of colluvium over resistant bedrock, natural erosion by mass movement processes is high (Carson et al., 1986; Plate 6).

The range also constitutes a barrier to moist air masses coming from the south and slopes with northern aspects receive much less rainfall than slopes with southern aspects (Figure 10). Therefore surface erosion hazards are variable. Forest cover (broad-leaved and coniferous) in this zone is generally much better than in the Central Hills.

South of the Main Boundary Fault the Middle Himalaya abruptly gives way to a series of relatively low (up to 1200 m) ridges called the Siwaliks (Figure 4). These consist of Tertiary unconsolidated and highly erodible fluviatile sediments ranging from relatively fine-grained graywackes in the south ("Lower Siwaliks"), through soft sandstones interbedded with thin layers of clay ("Middle Siwaliks"), to very coarse sands and conglomerates ("Upper Siwaliks") in the north (Figure 6a).

The maximum thickness of the Siwalik formation has been estimated at over 4000 m in Nepal (Weidner, 1981) to about 5500 m in the Kumaon Himalaya (Rupke, 1974). As such they bear testimony to the long standing erosion history of the Himalayan range. Although relative differences in elevation throughout the Siwaliks are generally much less than 1000 m, the landscape is quite rugged and its river system exceedingly flashy (Singh et al., 1982).

In the Nepalese Siwaliks, about ten times more area was mapped as dry river channels than in the Middle Himalaya (Carson et al., 1986; Plate 7), despite the fact that much of the area is still forested (mostly

Plate 6

Deep-seated slides on well-forested hillslopes in the Mahabharat range of Central Nepal. Slides of this size are capable of temporarily damming a river, which upon bursting may produce a devastating surge of water and sediment.

Plate 7

Although the Siwaliks in general still have good forest cover, pressures on this very vulnerable ecosystem are increasing. Note the remarkably wide valley bottoms with braided rivers (Central Nepal)

Shorea, but more scrubby in the drier parts of the region). Burning and grazing of the understorey is widely practised. In combination with the weakly structured nature of the soils and the prevailing high rainfall intensities, this has led to intense surface erosion, e.g. in the vicinity of Chandigarh (Pant, 1983). In addition, natural slope instability is such, that some of the area has been rated as the most unstable in all of Nepal (Carson et al., 1986).

An important feature of the Siwalik range is the occurrence of rather broad E-W oriented valleys (*"Duns"*), filled with lacustrine sediments deposited at a time when rivers were obstructed in their flow by the rise of the Siwaliks (Plate 8). Erosion from the hillsides has produced numerous alluvial deposits, which, like the lacustrine sediments, present more or less severe surface erosion and gullying hazards, depending on cover and slope steepness (Nelson et al., 1980). The Siwalik zone is separated from the Indo-Gangetic depression in the south by an active thrust fault (Figure 6a).

Indo-Gangetic depression

The Indian plate has been bent downward by the weight of the Himalaya, thus creating a major structural basin, filled with debris from the mountains in the north, and to a lesser extent from the southern plateau. The "northern" deposits are often grouped into a piedmont (footslope) zone and more lowlying alluvial deposits. The entire complex is commonly referred to as the ***Terai***, although the upper part of the piedmont is known as the ***Bhabar*** zone (100-300 m a.s.l., Figure 5).

The Bhabar formation essentially consists of very coarse-textured alluvial fan deposits topped by a thin layer of finer textured material. The thickness of the sediment is at a maximum close to the Siwaliks and may reach 5000 m (Carson et al., 1986). Soils are well to excessively drained and pose drought problems. Forest clearance has been limited up to now, mainly for this reason, but where it has occurred, serious sheet and gully erosion has been the result. Because of the dramatic reduction in river gradients upon leaving the Siwaliks, streams, which are heavily laden with sediment during the monsoon, assume a braided pattern (Plate 9). River beds can be up to several kilometres wide and erosion is lateral rather than vertical (cf. Section III.6). Indeed, the piedmont cone south of the Himalaya is one of the most impressive (and active!) of any such system on earth (Plate 9).

Much of the water infiltrating into the coarse Bhabar deposits emerges a few kilometres downstream, producing a sudden change in river morphology from braided to meandering (Figure 6a). This coincides with a knickpoint in river gradient, with the deposits becoming increasingly finer textured to the south (Weidner, 1981). Also, drainage density increases considerably below this "line of saturation". From here onwards (in the Terai proper), a system of sandy levees and more clayey depressions ("basins") is found, which bears no relationship to the present-day drainage pattern (Figures 6b & c), although the depressions get flooded occasionally. Rice is widely cultivated in these "basins", whereas the (higher) levees are used for settlements and roads.

In between the old basin/levee system and the active river channels, another sub-recent system exists, called the Meander Floodplain (Figure 6c). Its channels are only flooded during extreme events (Weidner, 1981).

In contrast to all other physiographic zones described above, the Terai is a zone of deposition rather than erosion. In addition, it suffers greatly from the rapid and unpredictable shifting of river beds (Carson, 1985; Section III.6). The sub-tropical forests of the Terai are being converted to agricultural fields at a rapid rate (Section II.4.2).

The alluvial deposits of the ***Ganges plain*** are mainly composed of unconsolidated beds of sand and gravel (former channel beds), silt and clay

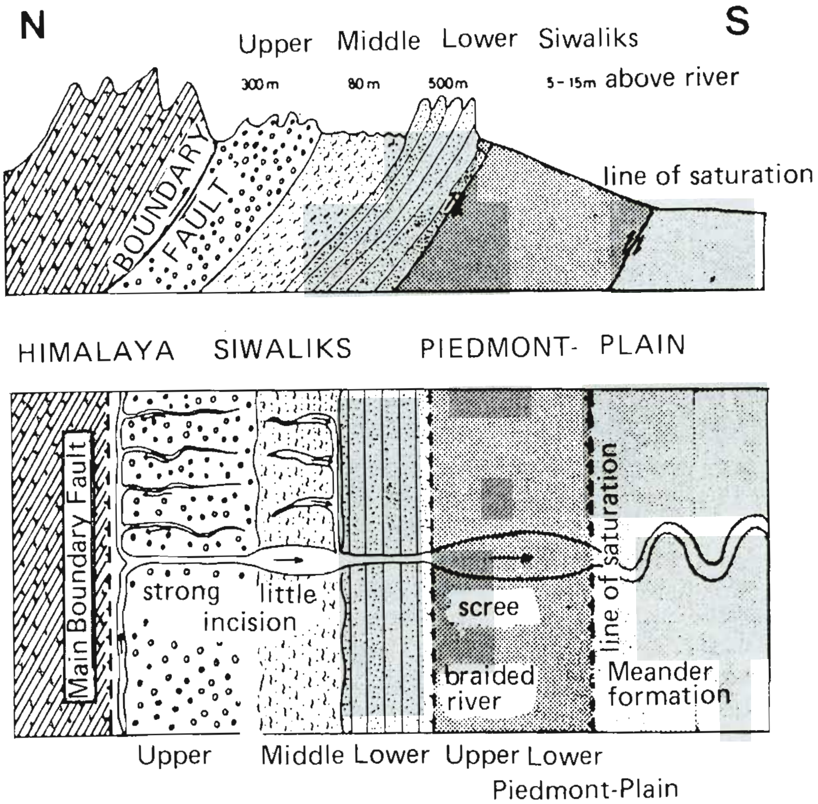
Plate 8

A Dun valley in Central Nepal. To the right the well-forested steeply sloping beds of the Upper Siwaliks, to the left the intensively cultivated southern margin of the Mahabharat. Note the huge landslide scars in the foreground.

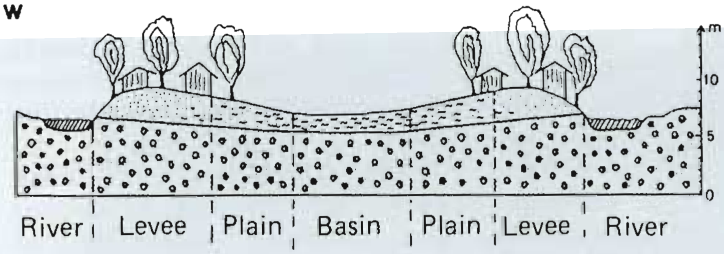
Plate 9

Upon entering the piedmont (Bhabar) zone, the Himalayan rivers deposit large amounts of coarse material and continue to flow through unstable channels.

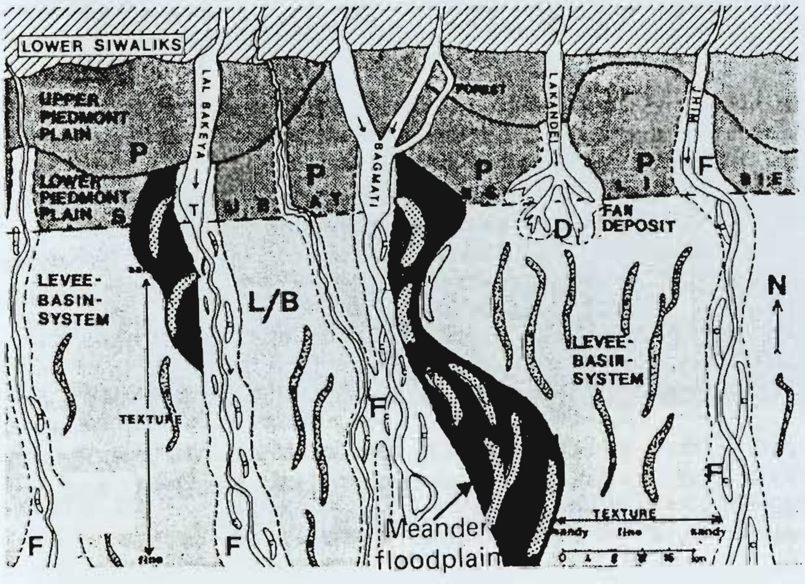
Figure 6. (after Weidner, 1981).



(a). Geology, geomorphology and river dynamics of the Siwalik-Piedmont zone.



(b). Cross section of the Levee-Basin system of the Terai .



(c). Spatial distribution of relief units distinguished in 6a and b.

(former depressions), and their mixture in varying proportions. Although the alluvial fitting on average is 1300-1400 m deep, decreasing gradually southward, a zone of over 8000 m (!) depth runs along the foot of the Himalayas (Singh & Verma, 1987).

A distinction is made between the *Bhangar*, or high (> 15 m above the plains) interfluvial zones above the general limit of flooding, and the *Khadar*, the more lowlying riverine tracts whose sandy to clayey deposits are annually renewed.

II.2.2 **Brahmaputra River Basin**

Excluding the deltaic parts for the moment, the Brahmaputra River Basin can be subdivided into four major physiographic units, viz. the old Meghalaya tableland and the younger Patkai-Naga (or Purvanchal) ranges in the south, the central Assam valley depression, and the eastern extension of the Himalaya in the north (Figure 3).

The ***Meghalaya plateau*** rises to elevations of 600 m in the west to about 2000 m in the centre and consists mainly of very old (Pre-Cambrian) hard crystalline rocks (granites and the like). Along the western and southern margins flat-lying sedimentary rocks (dominated by sand- and limestones of Mesozoic to Tertiary age) are exposed. Whereas the central and eastern parts form a true plateau, the western and northern fringes are highly dissected, forming a series of irregular low hills down to the Assam valley (Das et al., 1987).

To the east of the plateau, and separated from it and the Assam valley by a major fault, the ***Purvanchal*** is found. It consists of a strongly fractured series of N-S to NE-SW trending ridges. Rocks comprise a variety of Tertiary sediments, topography is steep and river valleys narrow. In addition, the area is extremely unstable in terms of seismicity due to its proximity to the main transform fault along which the Indian and South-East Asian tectonic plates rub shoulders (Haroun er Rashid, 1977). Elevations range from a low 150 m in the southwest to over 3000 m in the extreme northeast. Most of the area, however, is found between 900 and 2100 m (Singh & Mukherjee, 1987).

The ***Assam valley*** is an almost flat plain underlain by some 1500 m of alluvium. Its width ranges from about 90 km at the upstream end to about 60 km lower down. Within the plain a number of isolated granitic hillocks, that have become detached from the Meghalaya plateau, are found. As can be expected from the contrasts in geology between the mountains in the north and in the south, the physiography of the two river banks differs markedly, especially in the western part of the valley.

In the north, a situation similar to that described earlier for the Terai exists, with braided streams that start to meander upon passing the line of saturation. However, before joining the Brahmaputra, these rivers run almost parallel to the main stream as they encounter its levees. In the south on the other hand, the valley is much less wide and the small tributaries flowing from the Meghalaya plateau run in much less meandering courses (Figure 1).

The ***Eastern Himalaya*** is runs through Sikkim, Bhutan and Arunachal Pradesh. The general division of Siwaliks (locally called ***Duars***), Middle and Great Himalaya and Tibetan Marginal Range still applies here, although the topography of the Middle Himalayas now rises steadily and merges with the Great Himalaya. As such the latter do not stand out as much as they do in Nepal and further west (Jangpangi, 1978). Also the depression associated with the Central Midlands is hardly developed here.

Instead, there is a growing tendency for spurs from the Great Himalaya to radiate southward (e.g. the Black Mountains in Bhutan) as one moves towards the east. This is in line with the general change of direction in the axis of the mountains as they approach the eastern end of the Indian tectonic plate.

The *Bengal Basin* (elaborately described by Haroun er Rashid, 1977) has been filled with sediments washed down from the surrounding highlands, mostly since Pleistocene times. Morphologically speaking, the area consists of the floodplains of the rivers traversing it, with all the features common to such systems (Plate 10), ending up in a major delta (Figure 1).

Although the basin as a whole is a zone of deposition, it is nevertheless (like the Indo-Gangetic depression) subject to tectonic movements, with some parts actively sinking and others rising. Indeed, the change in the course of the Brahmaputra in 1787 during a single flood event has been described as having become possible because of such movements (Morgan & McIntire, 1959). Estimates of the rates of sinking vary from 2 to 6 cm/yr (Haroun er Rashid, 1977). Needless to say that such areas have become even more liable to flooding than before (Section III.5).

II.3 CLIMATE

II.3.1 Spatial and seasonal variations in precipitation

The climate of the Indian sub-continent and the Himalaya is dominated by the monsoon, the seasonal reversal of winds and associated rain. During the sun's annual march, the differential heating of the various latitudinal zones generates air movements, whose general annual patterns are quite predictable (Figure 7). However, as we shall see later, there are significant and unpredictable deviations from the overall pattern (Mooley & Parthasarathy, 1983).

In the Indian Ocean region the dominant pattern is one of high-level winds that blow NE to SW between October and June. During this time relatively little precipitation is generated.

Plate 10 **View of the Jamuna floodplain between Dacca and Bahadurabad, Bangladesh (photograph by G.J. Klaassen).**

Figure 7a.

Normal dates of the onset of the southwest monsoon (after Rao, 1981).

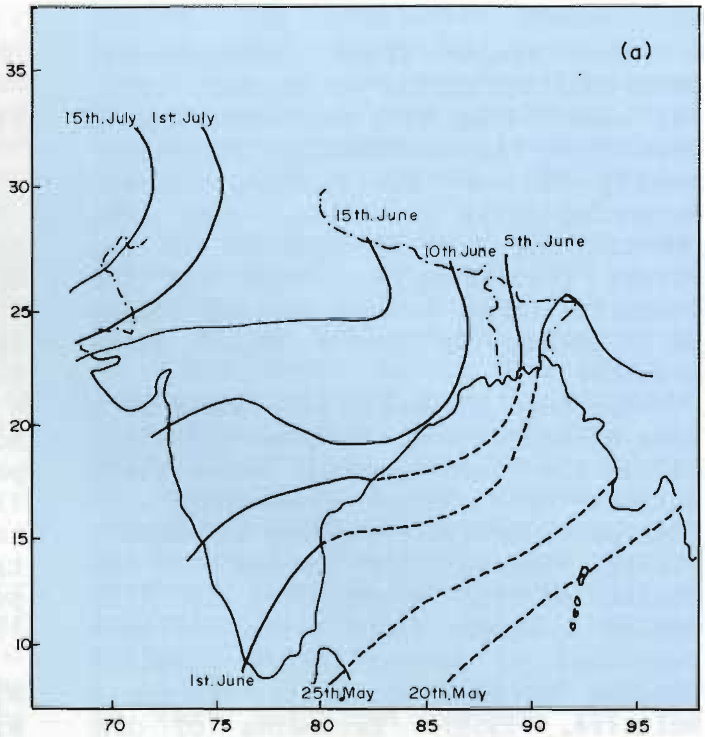
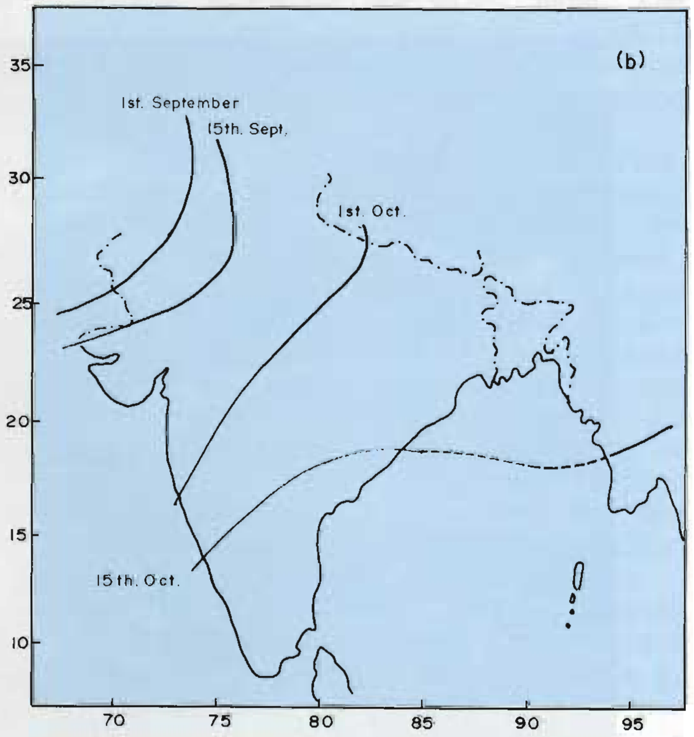


Figure 7b.

Normal dates of the withdrawal of the southwest monsoon (after Rao, 1981).



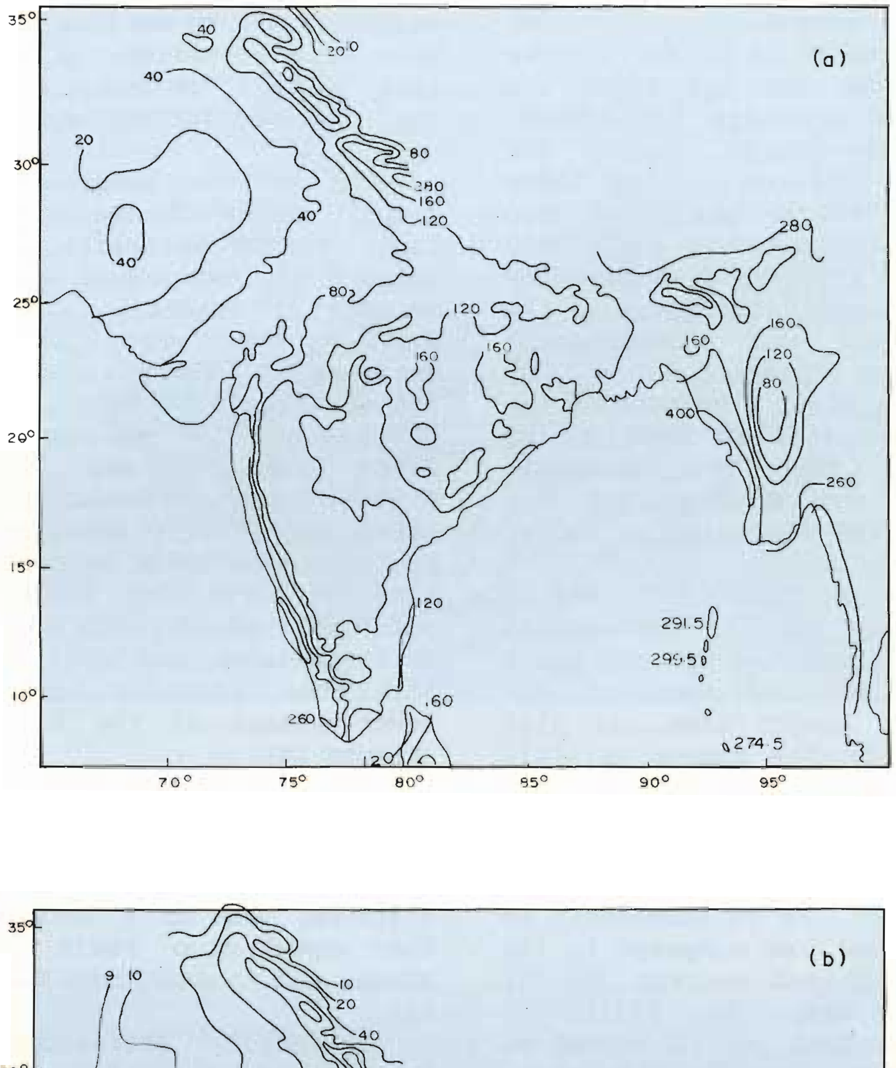


Figure 8. Mean annual (a) and summer monsoon (b) rainfall totals (cm) over the Indian sub-continent (after Rao, 1981).

This changes to a predominant movement of upper air from SW to NE about three months after the sun has begun its march into the northern hemisphere. Coming from the Indian Ocean, the southwesterly winds are warm and laden with moisture. As the air rises upon reaching the land mass, it cools off, whereby its moisture-holding capacity is reduced. Heavy rainfall is the result all over the sub-continent between June and September.

In fact, rainfall over much of the area is concentrated so much during these months, that the isohyetal patterns for the monsoon and the annual totals are very similar indeed (Figure 8).

A glance at Figures 7 and 8 reveals that not only is the eastern part of the combined river basin subjected to the influence of the monsoon for a longer time, it also receives considerably higher rainfall totals than most of the western parts. Also, the number of raindays (with rain > 2.5 mm) per year is significantly higher in the east (ranging from ca. 75 in Bangladesh to 100-150 in Assam), as compared to the central (ca. 50) and western (50-75) portions of the basin (Rao, 1981).

Apart from this overall trend of lesser rainfall towards the west, there are marked topographical effects producing strong local variations throughout the entire river basin.

For example, some of the world's highest rainfall totals have been recorded at Cherrapunji on the southern slopes of the Meghalaya plateau, where the moist air from the Bay of Bengal suddenly rises by 1200 m (Rao, 1981). At Shillong, situated only 50 km to the north on the same plateau, rainfall has already decreased to about 2400 mm/yr, declining steadily to 1600-1800 mm/yr as one descends into the Assam valley. It rises again to 4000 mm/yr on the lower Himalayan slopes of Arunachal Pradesh (Figure 9a).

Little is known about the behaviour of rainfall in the higher parts of this region (Rao, 1981; Goswami, 1985), but recent data from Bhutan (Figure 9b; Sharma, 1985) suggest a strong decline in precipitation with elevation. As shown below, this pattern deviates somewhat from that observed further west.

The various longitudinal physiographic zones of the Himalaya, with their strong contrasts in elevation (Figure 4), experience widely varying amounts of rainfall (Figures 10 and 11). To start with (taking Nepal as an example), there is an increase in annual rainfall from the southern Terai (ca. 1500 mm) to the Siwalik range (over 2000 mm). North of the Siwalik and Mahabharat mountains, there are several areas where annual precipitation falls below 1500 or even 1000 mm due to their sheltered positions which deprives them of moisture-laden southerly winds. Rainfall then increases again along the lower slopes of the Great Himalaya (Figure 10).

Maximum totals are experienced around Pokhara, at the foot of the Annapurna Himal, where topography rises dramatically over a very short distance, and to a lesser extent in the upper Arun basin between the Khumbu and Kanchenjunga Himals (Figure 11).

Regionally therefore, elevation may strongly influence rainfall totals, sometimes even to the extent that the general east-west trend is superseded (Figure 11). These spatially varying amounts of rainfall represent an even stronger variation in rainfall erosive power, or erosivity (Chapter IV.2).

Statistically significant relationships between annual rainfall and elevation have been derived for some parts of the Lesser Himalayas (Meyerink, 1974; Kathyar & Striffler, 1984; Ramsay, 1985), although some investigators have been unable to detect any such pattern (e.g. Dittmann, 1970).

It should be realised that such relationships have only local predictive value. In addition, they only hold for a certain range in altitude. Above a critical elevation (2500-3500 m: Upadhyay & Bahadur, 1982; Dobremez, 1976), a reduction in

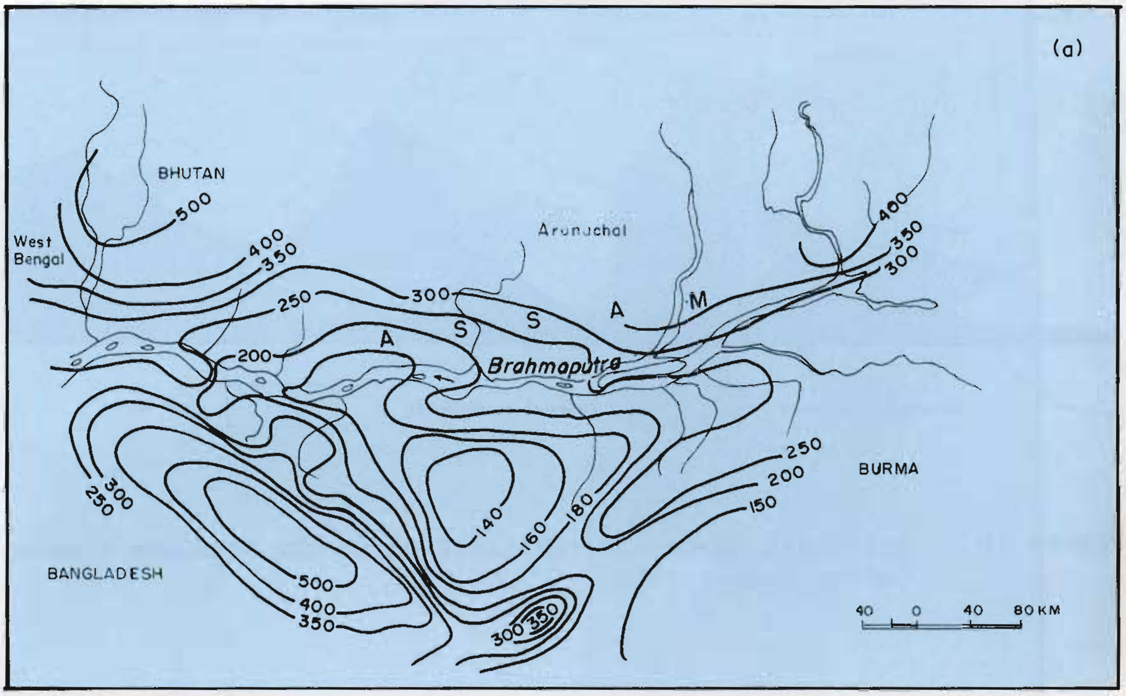


Figure 9a Isohyetal map of the Assam valley and adjoining highlands (after Goswami, 1985).

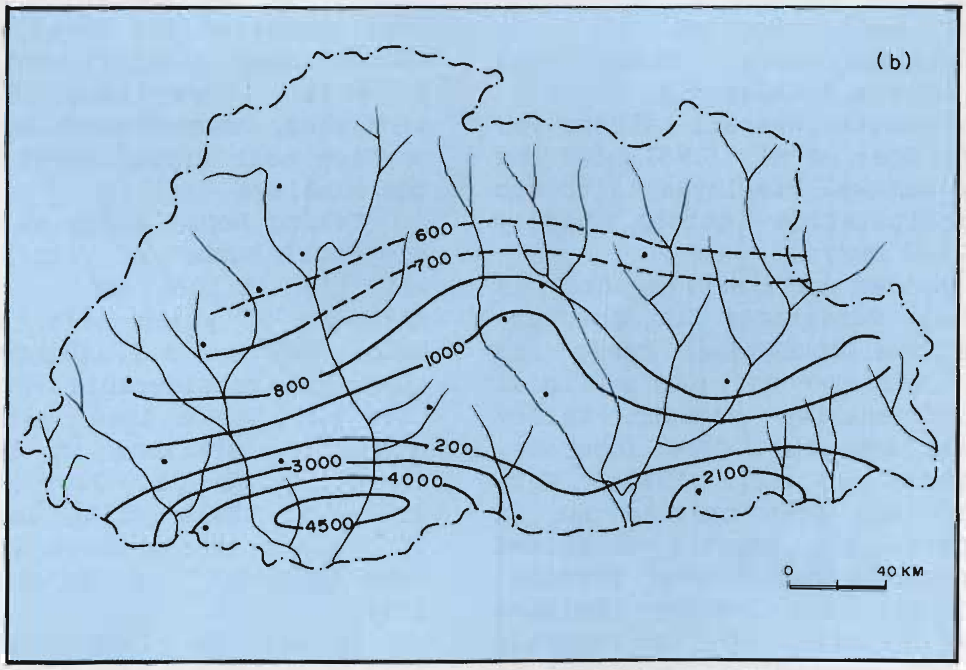


Figure 9b Isohyetal map of Bhutan (modified from Sharma, 1985).

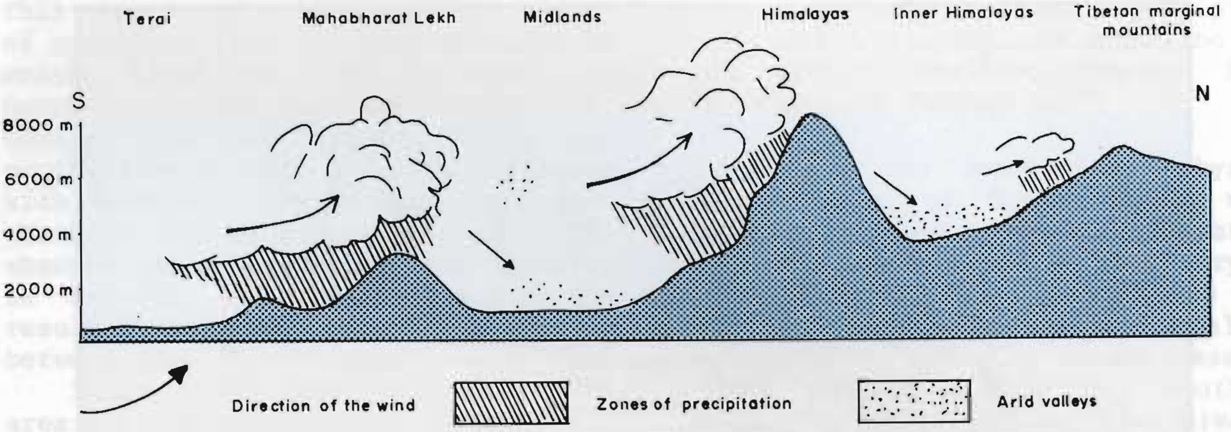


Figure 10 Principal zones of precipitation in the Nepalese Himalaya (after Hagen, 1969).

precipitation is often observed (cf. Figure 11).

North of the Great Himalaya, precipitation totals also decrease rapidly to less than 500 mm/yr in the Dolpa and Mustang districts.

Equally low amounts of precipitation have been reported for the Tibetan plateau (e.g. Lhasa: 360 mm/yr; Majupuria & Majupuria, 1988).

A very similar overall pattern was observed by Dhar et al. (1987) for the Kumaon and Garhwal Himalayas, although there precipitation totals rarely exceeded 2000 mm/yr.

Superimposed on these regional to sub-regional variations in precipitation in the mountains, there are important differences on a local scale, for example between valley bottoms and exposed ridges (Domroes, 1979; Higuchi et al., 1982). Very little work has been carried out in this respect, but results collected to date suggest (much) lower precipitation totals for valley bottoms (where the majority of the rainfall stations are located) as compared to slopes and ridges (Higuchi et al., 1982). The dry-valley bottom effect has been ascribed to the occurrence of persistently ascending mountain breezes (Flohn, 1970).

This observation not only has important agricultural and hydrological implications, but also suggests that regional precipitation totals as presented on isohyetal maps, etc. often will be underestimates.

A minimum rain-gauge network density of one gauge per 100 km^2 has been suggested for areas experiencing convectional rainfall and orographic effects (Chyurlia, 1984). Such densities, however much desirable, are nowhere near approximated anywhere in the Himalaya.

Taking Nepal again as an example, the total number of rainfall stations was 138 (1/1070 km^2) in 1975, the majority of which (83%) was located below 2000 m a.s.l. (Dobremez, 1976). However, considerable progress has been made since then, with the total number of stations in 1984 already amounting to ca. 300 (1/490 km^2), fifty of these (17%) located above 2000 m and thirty above 2500 m a.s.l. (HMG Ministry of Water Resources, 1986).

It will be clear from the above, that information on the amounts of precipitation falling as *snow* is particularly limited. Chyurlia (1984) reported a weak increase in snowfall with elevation for three stations in Nepal. In addition, he estimated seasonal variations in snowline

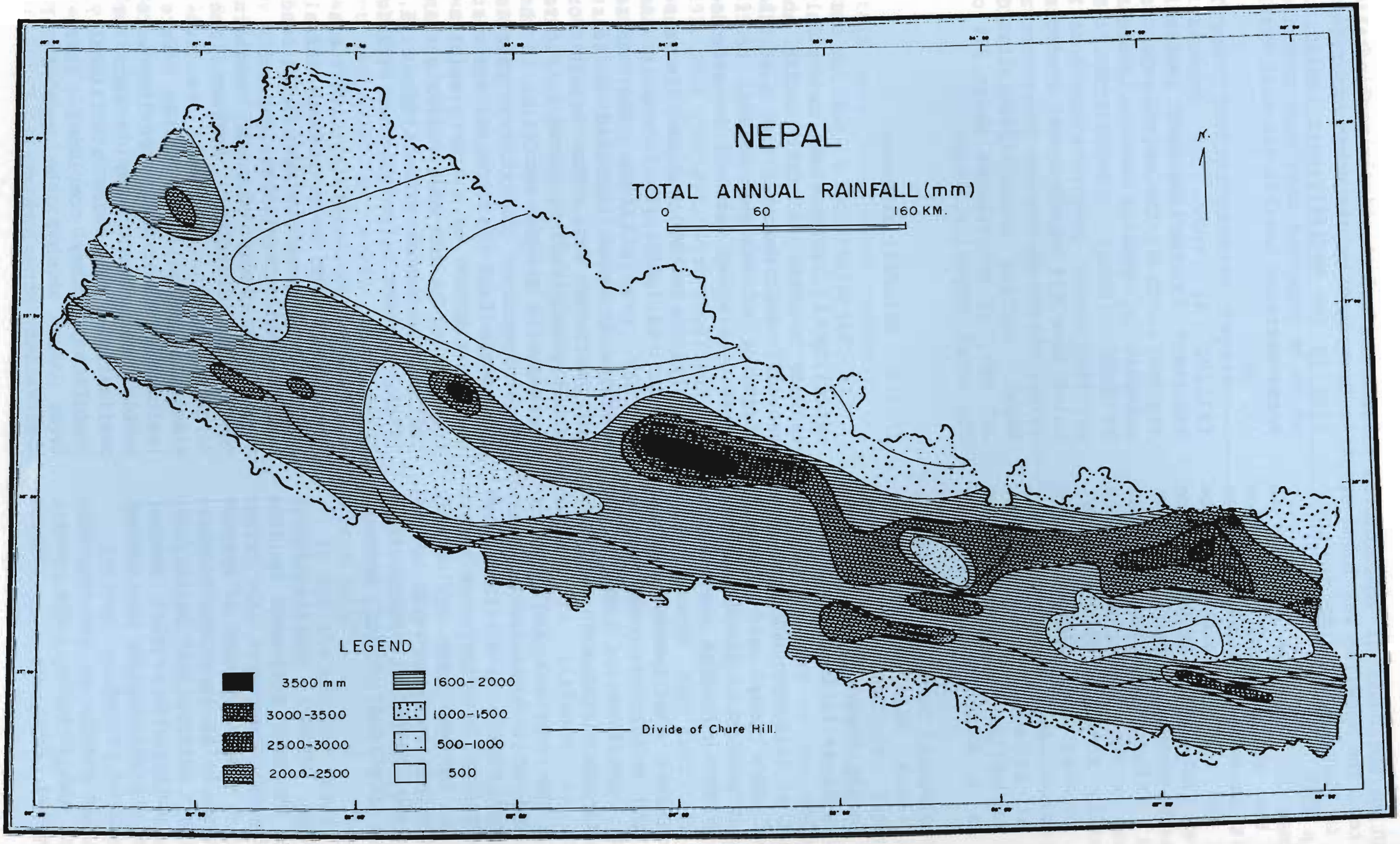


Figure 11 Mean annual precipitation (mm) in Nepal (after Chyurlia, 1984).

elevation on the basis of temperature lapse rates. The snowline was found at 2400 m in January, rising to about 5200 m in July.

Whereas it is quite feasible to monitor the areal extent of snow cover, it is much more difficult to estimate the actual amounts of snow falling on such areas. In the absence of snowpack surveys, Chyurlia (1984) combined information on seasonal variations in snow cover extent with mean monthly snowfall for a (very) limited number of high-elevation precipitation stations in Nepal, arriving at an annual total of ca. 1200 mm. Naturally, this must be considered as a crude first (under)-estimate.

The Geological Survey of India has conducted mass balance and other glaciological studies for several glaciers in the headwater area of the Ganges as well as in Sikkim since the mid-seventies.

As part of this research program a network of snow poles and ablation stakes was installed in the Beas basin in upper Himachal Pradesh (Anonymous, 1981a).

Bagchi (1982) used Landsat imagery to study the extent of snowcover in the same catchment. Given the difficulties associated with reliable estimation of snowfall at remote locations, the approach followed by Bagchi (1982) of linking fluctuations in snowcover extent with streamflow rates, seems to be more promising. After all, one of the principal applications of snow surveys is to determine the possible contribution of snowmelt to streamflow (cf. Section III.3).

Although annual precipitation totals are strongly dominated by the summer monsoon throughout the area (Figure 8), a certain amount of precipitation also falls in other months. In the western parts of the basin, 10-30% falls during the winter months and another 10-20% during the spring (or pre-monsoon) period.

Negligible quantities are recorded in October and November, the post-monsoon period (Dhar et al. 1987). Since most of the winter precipitation is generated by disturbances originating in the Mediterranean region, it is to be expected that such contributions decrease towards the east (Table 1).

Winter precipitation, mostly falling as snow, is especially important in the elevated semi-arid regions north of the main range. For example, at Kyelang in the Himachal Pradesh (total precipitation 555 mm/yr), winter precipitation constitutes some 45% of the total (Domroes, 1979), whilst at Jomosom (West-Central Nepal, average annual precipitation 255 mm), it contributes about 23% of the total (Chyurlia, 1984).

II.3.2 Rainfall extremes

In characterizing a location climatically, it is important to not only examine average rainfall totals and seasonal distribution, but also the frequency of extreme events, be it flood-generating rainfall or extended dry spells.

Chyurlia (1984) analyzed the year-to-year variability of annual and monthly precipitation for those stations in Nepal that had at least ten years of data. The result for annual precipitation, shown in Figure 12, suggests greater variation in the western parts of the country. This is due to the fact that towards the west the contribution of winter precipitation, which is far more variable than that of the summer monsoon (Chyurlia, 1984), becomes more important (Table 1).

Mooley & Parthasarathy (1983) examined above- and below-average annual rainfall extremes between 1871 and 1980 for 306 rainfall stations all over India, except for the northern mountainous districts. However, the Gangetic plain, as well as sub-Himalayan Bengal and Assam, were included in their analysis. They were unable to detect any trends or oscillations that were statistically significant. They concluded, therefore, that during the period of observation, annual rainfall

TABLE 1. Precipitation totals at selected stations in the Himalaya between December and March (after Dhar et al., 1987)

Station	Elevation (m)	Precipitation (cm)
Dalhousie, Himachal Pradesh	1960	58
Mussoorie, Garhwal Himalaya	2040	27
Mukteshwar, Kumaon Himalaya	2310	19
Jumla*, West Nepal	2300	13
Jiri*, East Nepal	2000	9
Darjeeling, North Bengal	2130	10

*Chyurlia (1984)

totals were distributed randomly in time.

In four years (1877, 1899, 1918 and 1972), more than 40% of India suffered a severe drought (over 70% in 1899!). Similarly, excessive rainfall was widespread over India in 1878, 1892, 1938 and 1961, with about 40% of the country being affected during the extreme event of 1892 (Mooley & Parthasarathy, 1983).

Interestingly, the occurrence of excessive droughts or rains in the northern districts that the present report is concerned with, showed comparatively little overlap between districts. In other words, droughts or excessive rains in western Uttar Pradesh would often show up in eastern U.P. as well, but not necessarily in Sub-Himalayan Bengal, and generally not at all in Assam (Mooley & Parthasarathy, 1983).

This would suggest that widespread flooding in the region is influenced by the areal extent of extreme rainfall more than by any other factor (Raghavendra, 1982; cf. section III.5).

The occurrence of a (very) wet or dry year seems to be related to the degree to which depressions are able to penetrate towards the west. Wetter years showed a distinctly higher proportion of depressions moving west of 80° E.L. (Mooley & Parthasarathy, 1983).

In addition, the regional distribution of rainfall appears to be strongly related to the location of the "monsoon trough", a zone of relatively low pres sure, normally running between southern Bengal and northwestern Rajasthan. The trough may shift towards the foothills of the Himalaya, producing a marked decrease in rainfall over India to the south of the trough, but a distinct increase over the Himalaya (Dhar et al., 1982a).

The synoptics of this situation, which is commonly referred to as a "break" in the monsoon, have been described by Ramaswamy (1962). To illustrate the magnitude of the phenomenon: Dhar et al. (1982a) reported about twice as much rainfall over eastern Nepal and Sikkim during "break days".

As for the extreme years, Mooley & Parthasarathy (1983) showed that during droughts (over Peninsular India) the average frequency of a "break" situation was about three times that observed during "flood" years. Also, the average length of the longest spell of "break" was two to three times higher during dry years.

Extreme amounts of rain falling over periods of one to several days are obviously of great practical significance because of their role in

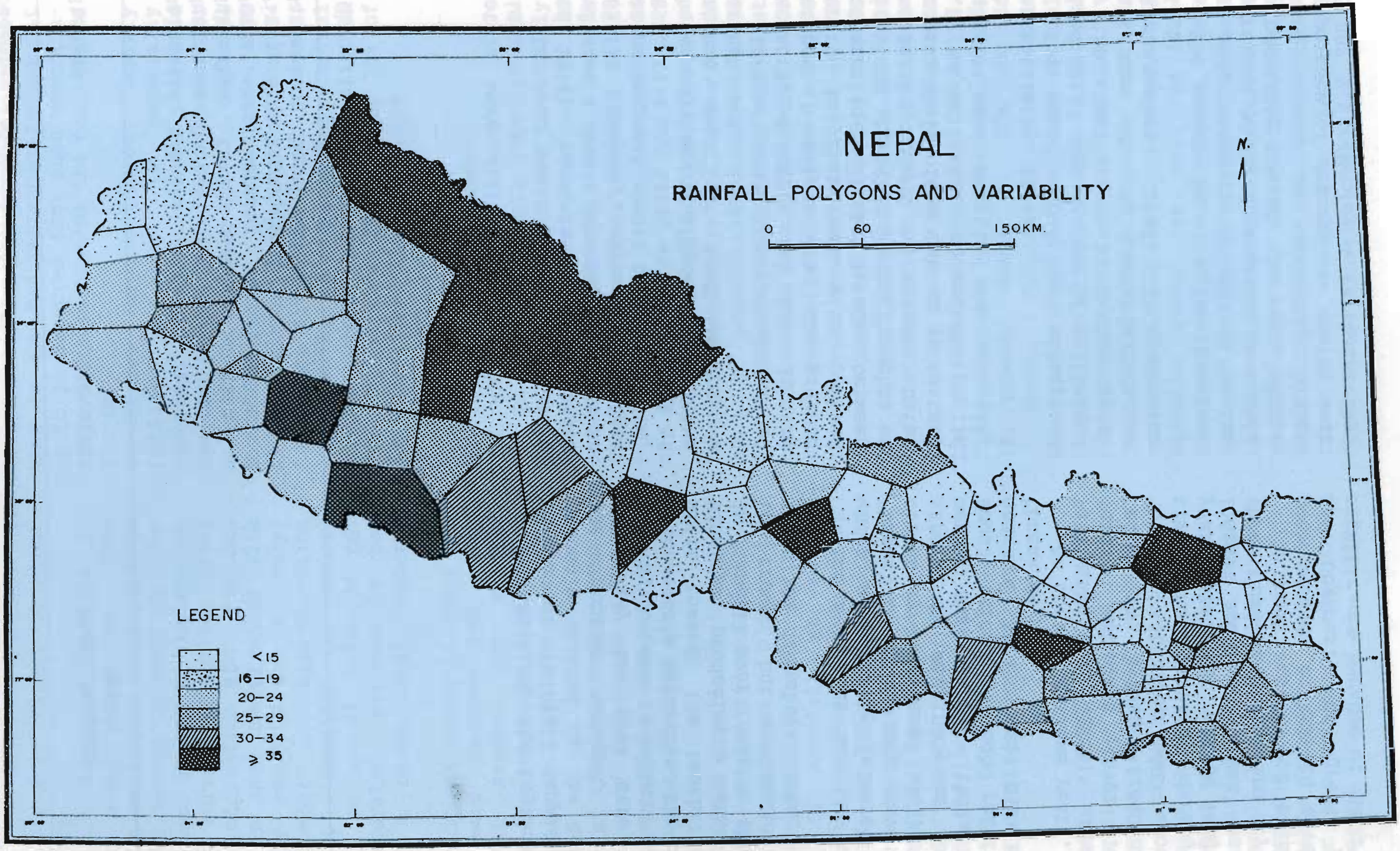


Figure 12 Variability index of rainfall polygons in Nepal (after Chyurlia, 1984).

generating major floods. This is especially so during the height of the summer monsoon, when soils all over the river basin are quite wet and have relatively little opportunity to accommodate such extreme additions of rain.

Although the issue of flooding will be worked out more fully in Sections III.4 and 5, the regional variation in extreme amounts of daily rainfall will be discussed briefly in the following.

The highest amounts of rainfall recorded on a single day at a number of selected stations throughout the basin are presented in Figure 13. Since the information was compiled from widely different sources, the periods of record differ between (groups of) stations, ranging from 30 to 60 years. Although this will doubtlessly introduce some bias, the regional trends should be reasonably representative.

By and large, maximum observed 24-hour rainfall figures exhibit a spatial pattern mirroring that of the annual or monsoonal rainfall (Figure 8). In other words, there is a trend of increasing values towards the east, and a decrease as one goes from the plains to the mountains (Figure 13).

As such, there again seems to be a natural tendency towards the greatest flooding potential in the eastern and lower parts of the basin.

The highest daily rainfall ever observed in the Ganges basin amounted to 823 mm, recorded at Nagina (Uttar Pradesh) in September 1880. The associated two-day total exceeded one metre of water, viz. 1042 mm (Sharma & Mathur, 1982).

The corresponding maximum daily rainfall in the Brahmaputra basin amounted to 1036 mm at Cherrapunji, (August, 1841; Holeman, 1968). It should be realized, however, that such extreme values often represent the core of a much larger "field" of rain with (much) lower amounts falling as one moves away from the centre (Figure 32).

Within the delta and adjoining coastal areas to the east, extreme rainfall may also be associated with typhoons. These occur, on average, about six times a year, arriving either in early summer (April, May), or in September-October, during which time much of Bangladesh is already inundated anyway.

Cyclones often generate waves that may be three to eight metres high, causing enormous damage, especially when they coincide with high tide (Haroun er Rashid, 1977).

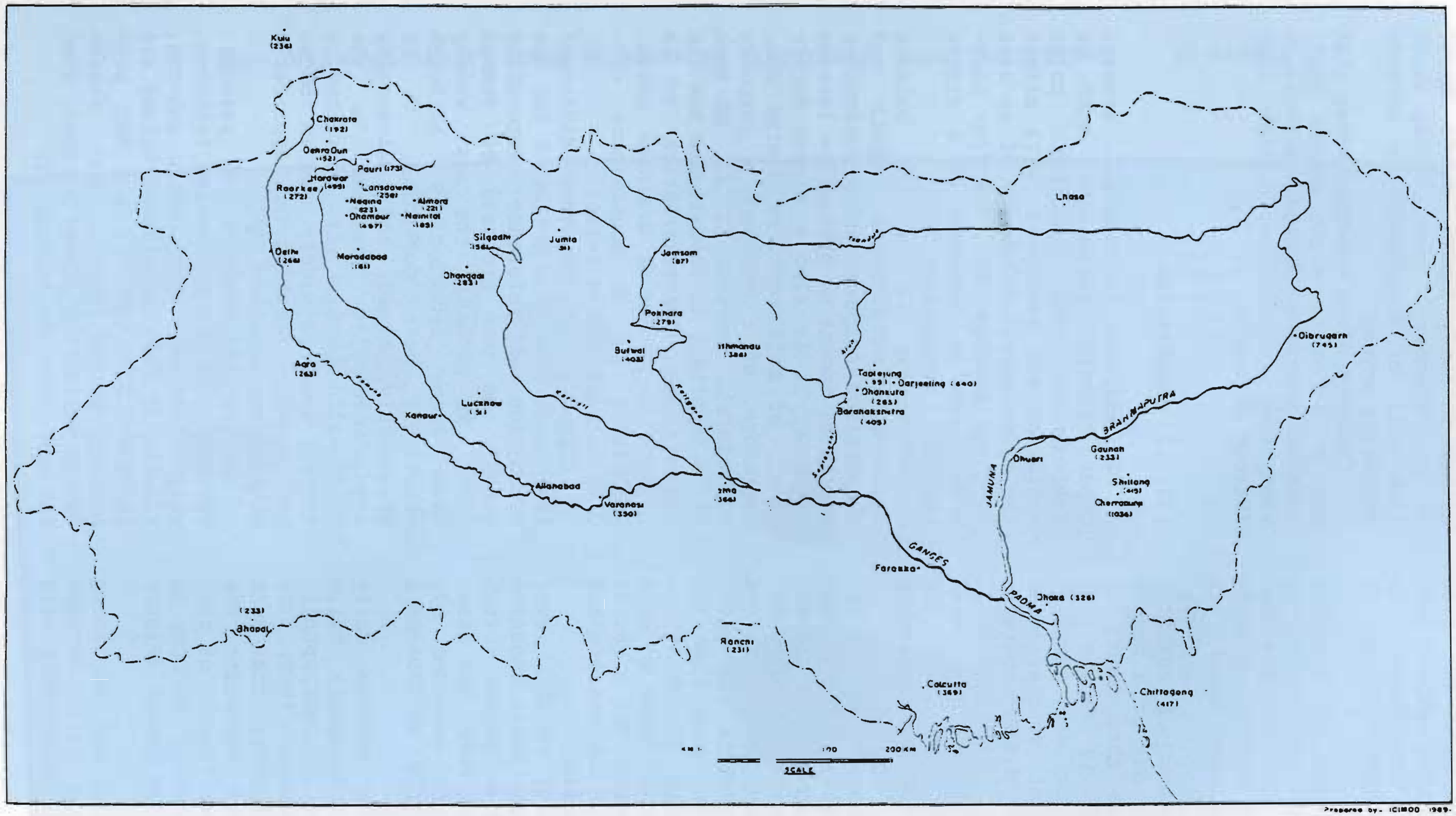
III.3.3 **Evaporation**

In addition to rainfall, several other climatic parameters, such as temperature and humidity, solar radiation and windspeed, will affect the hydrological behaviour of an area of given geology, etc. The four parameters can be combined in a single variable, evaporation.

Eventually it is the balance between precipitation inputs and evaporation outputs, which determines the total amount of streamflow leaving an area. It is also a strong determinant of soil moisture status and, therefore, of a catchment's response to rainfall (Section III.4). As such it is important to investigate how the evaporative characteristics of a climate vary over a drainage basin, especially so in mountainous conditions with strong relief.

Arguably, of the many different techniques that are available for the estimation of reference evaporation rates, the one proposed by Penman (1956) is probably the most widely used among hydrologists. Although relatively data demanding, it is physically based and universally applicable (in contrast to the "rational" formula of Thornthwaite (1948), which is widely used in India, but strictly speaking not applicable outside northeastern USA).

Figure 14 presents the seasonal variation in monthly Penman reference evaporation over the Indian sub-continent. By far the highest values are recorded for the hot and dry pre-monsoon period (April, May). Evaporation during the summer monsoon, when the sun is at its highest, is



Prepared by:- ICIMOD 1989.

Figure 13. Approximate maximum observed 2[illegible]-hr rainfall totals at selected stations in the Ganges-Brahmaputra River Basin (compiled from: Climatological Records of Nepal 1971-1986; Nayava, 1974; Raghavendra, 1982; Rao, 1981; Sharma & Mathur, 1982; Sharma et al., 1982; Starkel, 1972).

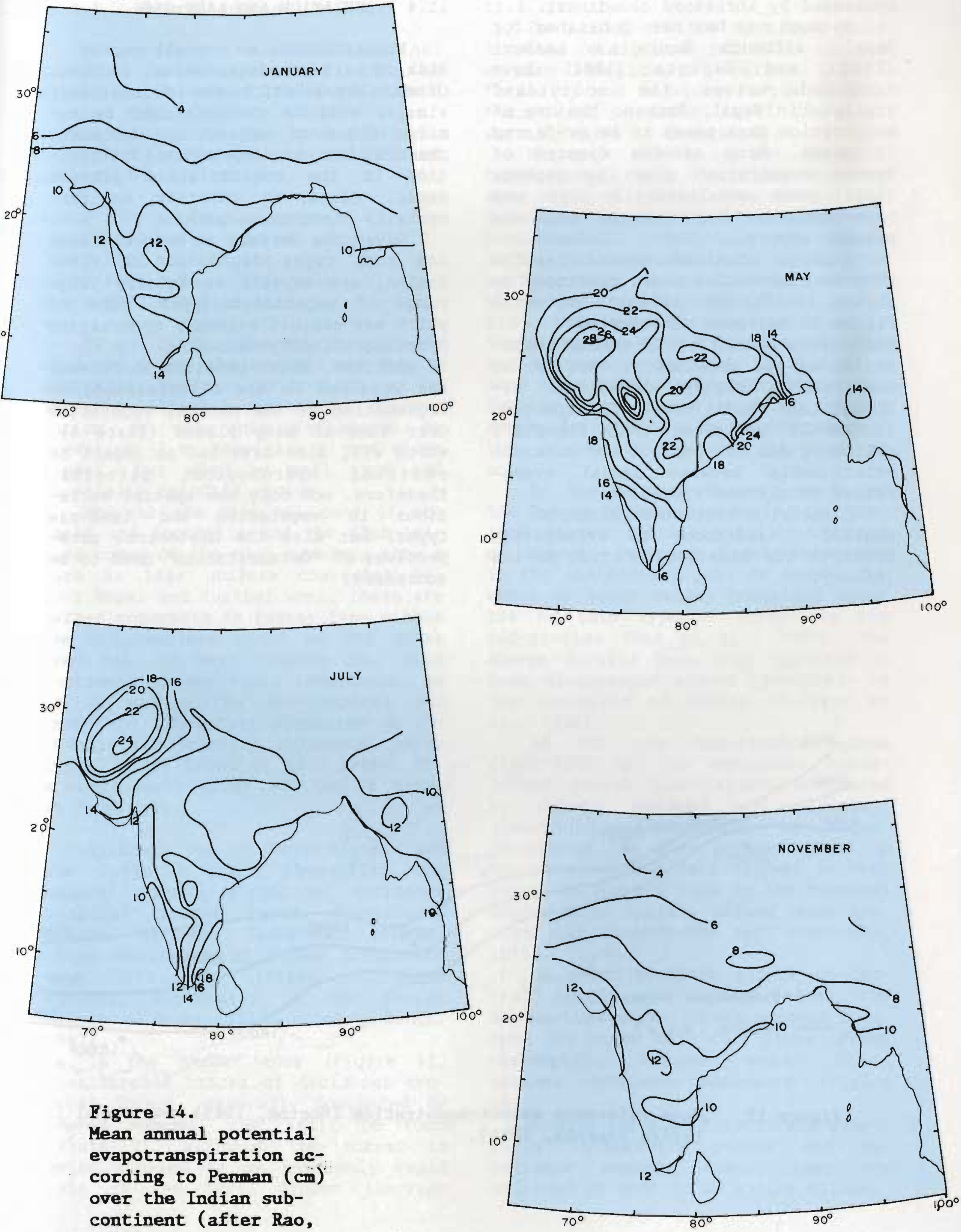


Figure 14.
Mean annual potential evapotranspiration according to Penman (cm) over the Indian subcontinent (after Rao, 1981).

moderated by increased cloudiness.

No such map has been published for Nepal, although Gurung & Lambert (1977) and Sapkota (1984) have reported values for individual stations in Nepal. Rather, the use of evaporation pans seems to be preferred in Nepal. Many of the figures of Penman evaporation given by Sapkota (1984) seem unrealistically high, and have therefore been omitted from the present report.

Sapkota obtained better results with an alternative model developed by Morton (1983), on the basis of which Figure 15 has been constructed.

There is a reduction in annual evaporation as one goes north, that is, as one reaches higher elevations. Although this result was to be expected, it should be noted that Sapkota's estimates did not exhibit any clearcut relationship between annual evaporation totals and elevation.

Clearly, a characterization of spatial variations in evaporation rates in the Himalaya is still in its infancy.

II.4 VEGETATION AND LAND-USE

Vegetation is an overall expression of various environmental factors. Often, areas which are climatically similar will be characterized by similar forms of vegetation. As such, observations of vegetation distribution in the region could provide useful clues to identify environmentally homogeneous areas.

Given the variety in meso-climates and rock types found in the river basins, one expects an equally large range of vegetation types, some of which may exhibit strongly contrasting hydrological behaviour.

In addition, heavy pressure on forests has resulted in the disappearance or degradation of the natural vegetation over time in many places (Plate 4), which will also have had an impact on existing hydrological patterns. Therefore, not only the spatial variations in vegetation and land-use types, but also the historical perspectives of "deforestation" need to be addressed.

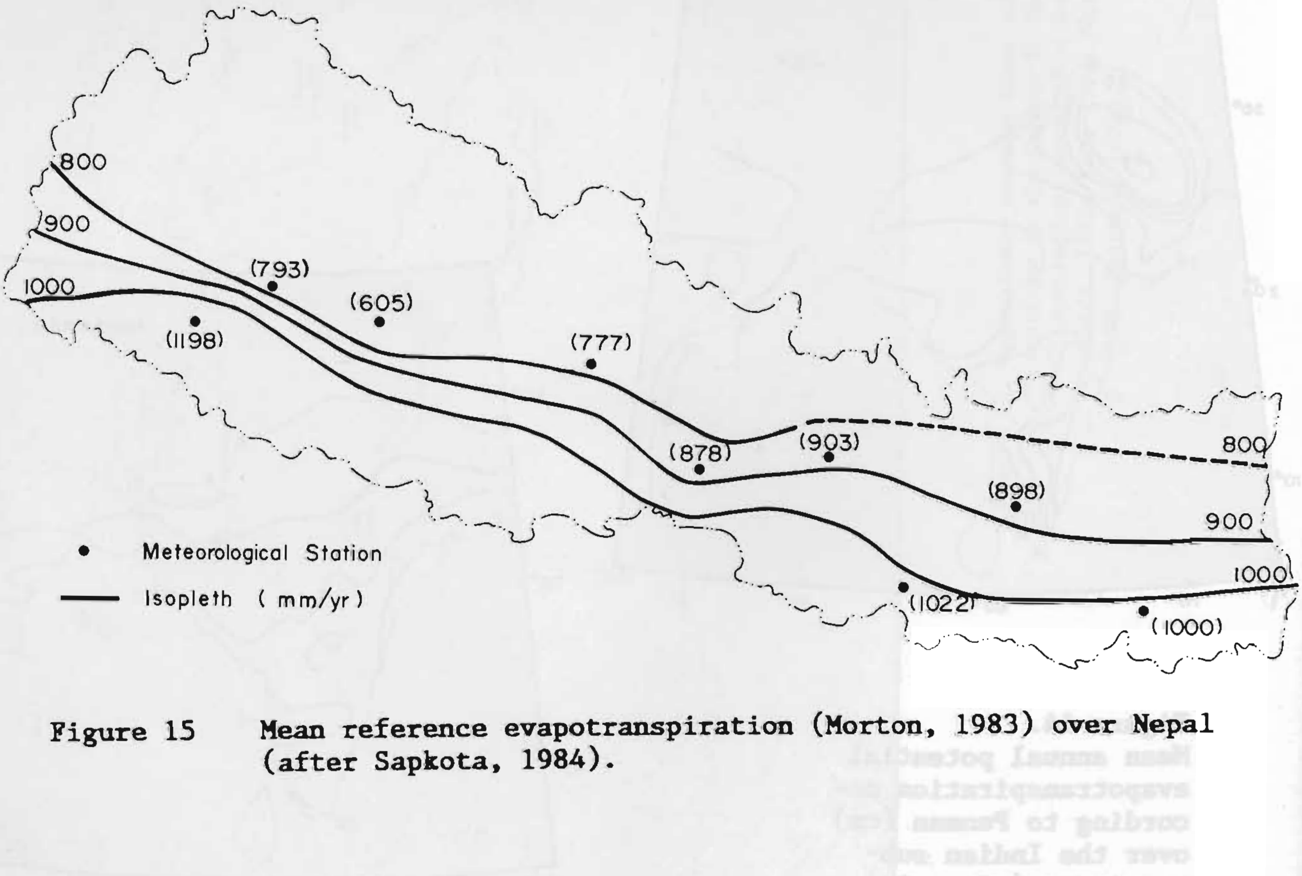


Figure 15 Mean reference evapotranspiration (Morton, 1983) over Nepal (after Sapkota, 1984).

II.4.1 Natural vegetation

With respect to the altitudinal zonation of vegetation in the Himalaya, Shrestha (1988) discussed several classification schemes proposed for the Nepalese Himalaya, and opted for the following simplified general sub-division:

Below 1000 m: Tropical zone
1000-2000 m: Sub-tropical zone
2000-3000 m: Temperate zone
3000-4000 m: Sub-alpine zone
Above 4000 m: Alpine zone

By and large, this sub-division is also valid for the Eastern and Kumaon Himalayas. However, as pointed out by Shrestha (1988), vegetation distribution is not only influenced by elevation (i.e. temperature) and slope aspect, but also by soil type and especially rainfall regime.

Whereas the Tropical zone of the Terai and foothills and the (Sub-)alpine zones of the High Himalaya show a more or less uniform character all over Nepal and further west, there are marked contrasts in forest type within the intermediate zones as one moves from east to west (Figure 16). Such contrasts assume extra importance, as it is within the Sub-tropical and Temperate zones that pressures on the forests are heaviest (Dobremez, 1976; Gupta, 1983; Mahat et al., 1986a, b). A north-south cross section is given in Figure 17.

Although the Southern Plateau and the Gangetic plain constitute the natural domain of various deciduous **tropical forest** types (containing *Shorea*, *Tectona*, *Dalbergia*, etc.), three millennia of human occupation have left very little of these forests, especially in the plains (Singh & Verma, 1987; Singh & Singh, 1987).

In the Bhabar zone (Figure 5), considerable tracks of deciduous tropical forest, generally dominated by *Shorea robusta*, can still be found (Plate 9), although the forest is being cleared at an extremely rapid rate in the Terai proper (Section II.4.2).

In general it can be stated that in the Terai (and probably in the entire region), wherever soil fertility and moisture status permit, there will be agricultural cropping, part of which is irrigated.

Although *Shorea* is the dominant tree species all over the Tropical zone, it is joined by a few co-dominants, which vary with changes in environmental conditions (Dobremez, 1976). The important thing in the present context is a tendency towards more open forest towards the west. Also, that part of the Siwalik hills bordering the Bhabar is extremely dry and vegetation response is that of a more open canopy and reduced stature. Smaller trees are also found in the *Shorea* forests of the Mahabharat near the transition to the Sub-tropical zone.

In the rainier eastern parts of the Ganges-Brahmaputra basin, the lowland forest initially still consists of *Shorea*, becoming (semi-)evergreen in the easternmost part of Assam. The whole of Assam valley contained about 13% of this type of forest in the mid-sixties (Das et al., 1987). The *Shorea* forests have been reported to have disappeared almost completely in the foothills of Bhutan (Sargent et al., 1985).

As for the **Sub-tropical zone** (1000-2000 m), an evergreen broad-leaved forest association, dominated by *Schima wallichii* and various chestnuts (*Castanopsis*) is found throughout the area between Assam in the east and the Kali Gandaki in West Nepal. As was the case in the Tropical zone, these forests become more species rich towards the east (Dobremez, 1976).

On drier southern slopes in Central Nepal and further east, the *Schima-Castanopsis* forest becomes more open and mixed with chir pines (*Pinus roxburghii*). Further west, chir assumes complete dominance (Figure 16).

Because the pine forests are generally intensively grazed and experience regular fires, they are believed by some to be a fire climax.

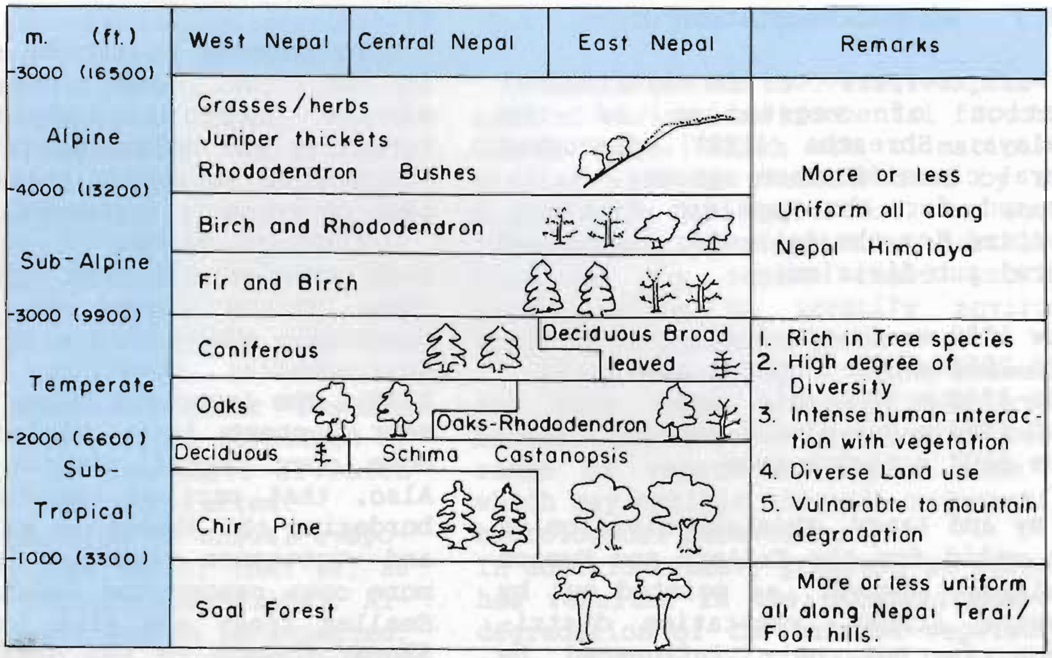


Figure 16 Vegetation zonation in the Nepalese Himalaya (after Shrestha, 1988).

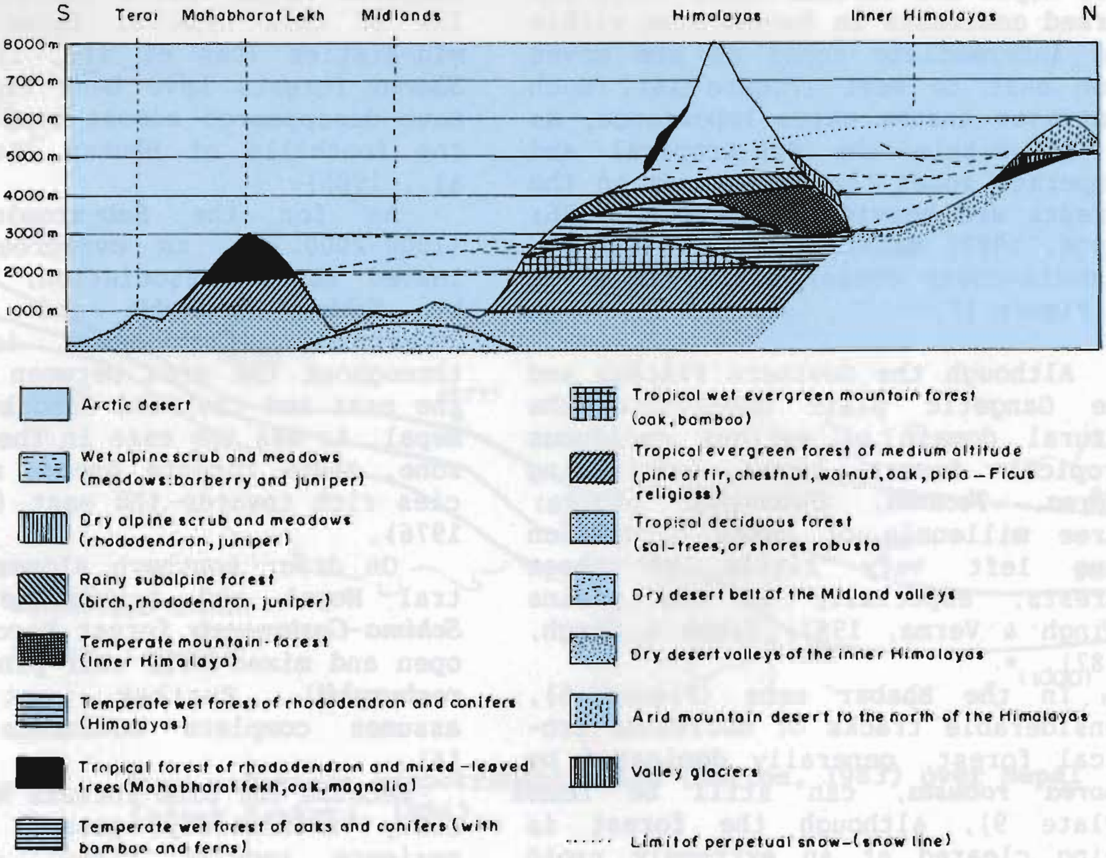


Figure 17 Cross-sectional representation of vegetation zones in the Himalaya (after Hagen, 1969).

Although this is true in Central and East Nepal (Shrestha, 1988), Dobremez (1976) reported the occurrence of pure stands of chir pine in West Nepal, which had not been subjected to fire or grazing as long as anyone could remember.

The sub-tropical broad-leaved forests have suffered heavy losses over the years along the entire area both quantitatively and qualitatively (see the next section).

Both in the Nepalese and Indian Himalayas, one may find stands with numerous *Rhododendron arboreum* trees, often in association with evergreen oaks, in the upper reaches of the Sub-tropical zone. Shrestha (1988) remarks that water courses are quite scarce in this forest type, which seems to prefer south-facing slopes.

In the Garhwal Himalaya, *R. arboreum* is mentioned as a typical associate of chir by Gupta (1983), whilst a similar situation has been described for Bhutan by Sargent et al. (1985).

The **Temperate** zone (2000-3000 m) is situated above the upper limit of widespread agriculture, the major limiting factors for cropping being high cloud incidence during the summer monsoon and low temperatures in winter (Shrestha, 1988).

The lower half of this zone is dominated by various evergreen species of oak, which constitute the main canopy, often attaining heights of 35-40 m. The lower strata are generally composed of laurels and magnolias. Especially in East Nepal and south of Annapurna Himal, the trees are heavily loaded with mosses (Plate 11).

Interestingly, the high humidity levels in these forests seem to reflect a large number of rainfall events rather than high rainfall totals in the case of East Nepal, and vice versa in the Annapurna region (Dobremez, 1976).

According to the same author, such differences in rainfall intensities also result in different mass movement hazards after clearing. As such, forest removal is supposedly less hazardous and therefore much more widely practised in East Nepal as compared to the mossy forest area in Central Nepal.

Since mossy, or "cloud forests" often receive additional inputs of moisture through the process of "cloud stripping" (Zadroga, 1981), their removal may have hydrological implications that differ from those associated with the clearing of "normal" forests (Chapter IV.1).

Lopping for fodder and grazing is a common practice in oak forests throughout Nepal and North India. In the East (Arunachal Pradesh, Assam), shifting cultivation (locally called *Jhum*) is widespread (Prasad, 1987).

In East Nepal, this practice is relatively common between 1500 and 2300 m, with a cycle of only four to ten years. Bamboo is commonly found upon disturbance, as is a pioneer species called *Eupatorium adenophorum*. Both species tend to hamper the regeneration of the oaks (Shrestha, 1988).

Towards the west, where drier conditions prevail, the protective undergrowth has often disappeared, largely as a result of intensive harvesting for fodder and fuelwood and regular burning to stimulate the fresh growth of grasses (Dobremez, 1976).

Here, the oaks are more drought resistant than their counterparts in the east. They represent the temperate equivalent to the sub-tropical chir belt below. From Nepal's Far West onwards, fairly open stands of deodar (*Cedrus deodara*) appear, becoming more common in the Kumaon and Garhwal Himalayas.

Above 2400-2700 m, where a snow cover is present for at least two months (Dobremez, 1976), the character of the oak forests changes. Whereas the main canopy is still dominated by oaks (mainly *Quercus semecarpifolia*), several deciduous species (especially maple) come to the fore as well. Again, both the number of species and canopy density increases towards the east.

On the wettest sites (East Nepal, Sikkim), almost pure stands of rhododendrons replace the oaks. In the western parts of the upper Temperate

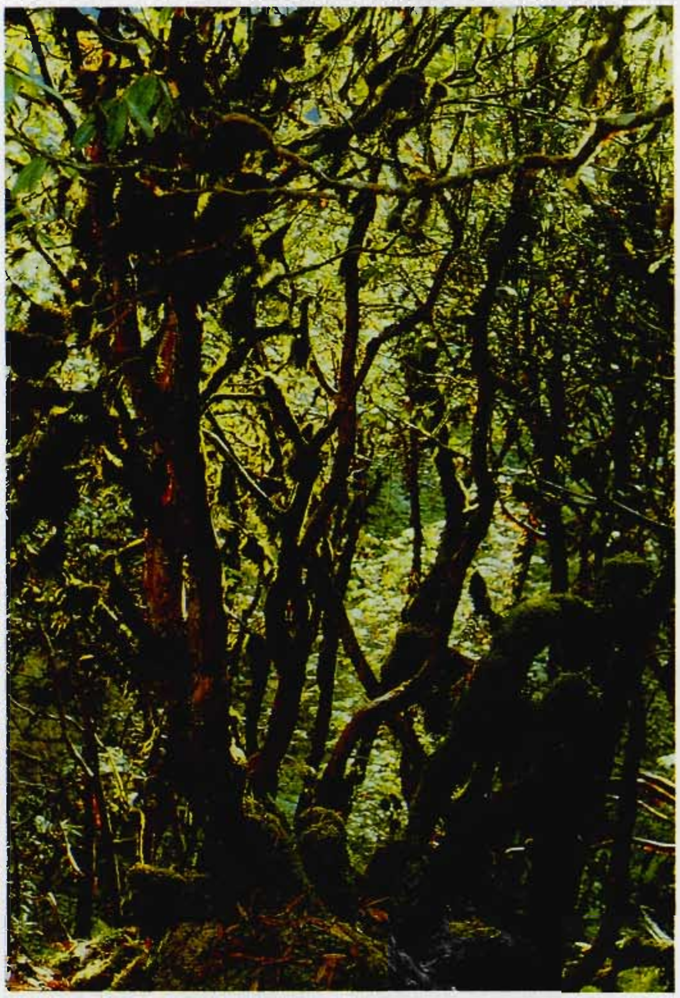


Plate 11

Mossy forest at 2600 m a.s.l. in Helambu, Central Nepal (photograph by R. Gerritsen).

zone, stands become more open and conifers increasingly important. Among the most common conifers are various pines, with junipers on the drier and fir on the colder sites. According to Dobremez (1976), abandoned fields in West Nepal at this elevation are often quickly invaded by *Pinus excelsa*.

Grazing pressure is high throughout the upper Temperate zone as high-altitude livestock moves down in search of warmth and low-altitude cattle migrate upwards in search of more fodder (Shrestha, 1988).

In the **Sub-alpine zone** (3000-4000 m) winters become much more severe and rooting opportunities are often restricted. This zone is dominated by relatively open stands of silver fir (*Abies spectabilis* and *Abies pindrow*), with oak and especially junipers on drier (western) and rhododendrons on wetter (eastern) sites.

At higher elevations, birch (*Betula utilis*) is quite common as well. One may also encounter groups of *Larix* (inner Himalayan valleys) or poplars and willows (valley bottoms) in this zone. The upper reaches of the Sub-alpine forests may be subject to disturbance by herders, who seek to enlarge the area for yak grazing (Dobremez, 1976; Sargent et al., 1985).

The vegetation becomes increasingly stunted with elevation, and above 4000 m (roughly coinciding with the timber line), in the **Alpine zone**, it is reduced to shrub size (junipers, rhododendrons), and finally consists

Plate 12 **In the dry valleys north of the main range, the drier southerly slopes bear a steppe-like scrub vegetation, whilst the moister northern slopes are covered with a mixture of conifers (Manang district, Nepal).**

of herbs and grasses only.

These grasslands are subject to grazing and collection of herbs for medicinal purposes (Shrestha, 1988). The shrubs may act as snowtraps. Diurnal variations in temperature and relative humidity are very large in the Alpine zone. Permanent snow is often found above about 5000 m (Dobremez, 1976).

Finally, a **Steppe zone** can be distinguished, characterized by open low vegetation dominated by *Caragana* sp. (Plate 12). It coincides with the arid Trans-Himalayan zone and its flora is strongly related to that of Tibet as expected (Dobremez, 1976). Interestingly, the permanent snow line is found at a higher elevation here than south of the Great Himalaya (Figure 17).

Diurnal fluctuations in temperature and especially relative humidity in the Steppe zone are considerably larger than for stations at similar elevations in the monsoonal part of the mountains (Dobremez, 1976).

II.4.2 **Agriculture**

The agricultural resource base in the Himalaya is severely limited by the steepness of the terrain, virtually all level land being restricted to alluvial landforms (Section II.2). As such, terracing of slopes is a dominant feature all over the region and has permitted farmers to grow crops on slopes that would have long since been washed away without such measures (Plates 5 and 19).

Cropping is done within the context of a mixed farming system, of which cattle and forests are also an integral part. Estimates of the number of hectares of forest land needed to support one hectare of cropland vary between three and six (Shrestha, 1988).

The link between the two forms of land use is constituted by livestock, which produces manure, draughting power, milk, etc. The animals are either allowed to graze in the forest (or its remnants), or are stallfed with fodder obtained from the forest. In addition, leaf litter is often collected for composting.

In general, there are two basic cropping systems in the mountains: one based on rice production on irrigated land, and another (more widespread) based on growing maize and millets on non-irrigated land. Potatoes often constitute the main winter crop.

There is an important difference in the types of terraces associated with the two systems: the ones used for irrigated agriculture must be flat (Plate 19), whereas the ones for rainfed cropping are often laterally or forward sloping (Plate 5).

As such considerable differences in surface erosion rates between the two types are to be expected (Section IV.2).

According to Shrestha (1988), yields per hectare of paddy, maize and millet have decreased by about 25% between 1970 and 1985 in the Arun area, a major river basin in East Nepal. This suggests that the present agricultural system is not fully sustainable (anymore). It also suggests that environmental degradation takes place both on the croplands and on the forest lands supporting them.

Coupled with an increase in population of about 1%/yr in the Arun area for the period 1971-1981 (Dunsmore, 1988), a rather grim picture emerges (Hrabovsky & Miyan, 1987).

An even less sustainable agricultural system (shifting cultivation) is practiced in the (sub) tropical zones of the eastern half of the mountains. Locally known as *Khorea* in East Nepal, as *Tsheri* in Bhutan, and as *Jhum* in North-east India, this type of farming is often found at (very) steep slopes, whereas the cycle of rotation has decreased to less than five years in many occasions (Shrestha, 1988; Toky & Ramakrishnan, 1981). Such short cycles have been shown to be not only economically non-viable, but also highly detrimental to the environment in the case of North-east India (Mishra & Ramakrishnan, 1983a,b).

In Nepal, abandoned fields are often quickly colonized by ***Eupatorium adenophorum***, initiating the natural succession to the original forest. However, due to the increasingly shorter cycles, a mixture of young secondary forest types occur, which do not get the chance to mature. ***Eupatorium*** also invades marginal grazing land (Shrestha, 1988). In the Sub-alpine zone sheep, goat and yak graze the pasture lands, but herds are maintained only in the vicinity of forest (Shrestha, 1988). Grazing has always been important above 3000 m and the high pressure on the oak forests of the Temperate zone, both from above and from below, has already been indicated. Table 2 illustrates this rather well for Nepal.

By contrast, in the plains, the bulk of the land is devoted to agricultural cropping, much of which is irrigated. Whereas wheat is the main crop in the upper parts of the Gangetic plain, rice is becoming more important as one goes east (Singh & Singh, 1987; Singh & Verma, 1987).

An interesting observation on cropping patterns in the lowlands of Bangladesh has been reported by Currey (1984). The traditional system (*aus* crop) was adapted to the annual inundation in that the crops were harvested before mid July, just before flooding would normally set in. Modern agriculture, on the other hand, involves year-round cropping and is consequently much more vulnerable to flooding (Figure 18; see also Paul, 1984).

II.4.3 Forest conversion and degradation: a historical perspective

Much has been made of accelerated deforestation in the Himalayas since the last three decades or so, and of the ensuing environmental consequences, both locally and downstream (Eckholm, 1975; Bowonder, 1982; Myers, 1986).

This rapid rate of deforestation

Table 2. Relative proportions of land-use types in the physiographic regions of Nepal (%) (after Carson et al., 1986)

	Irrigated Rice	Rainfed Cultivated	Grazing and Scrub	Degraded Forest	Closed Forest	Other*	Total Percent	Total 000ha
Terai	50	6	4	2	26	12	100	2110
Siwaliks	7	5	7	9	68	4	100	1886
Middle Mountains	7	15	36	18	22	2	100	4443
High Mountains	1	5	30	15	40	8	100	2959
High Himal	0	0.0**	29	2	2	67	100	3349
TOTAL								14748

*boulder, rock, ice etc.
**0.0 less than .5%

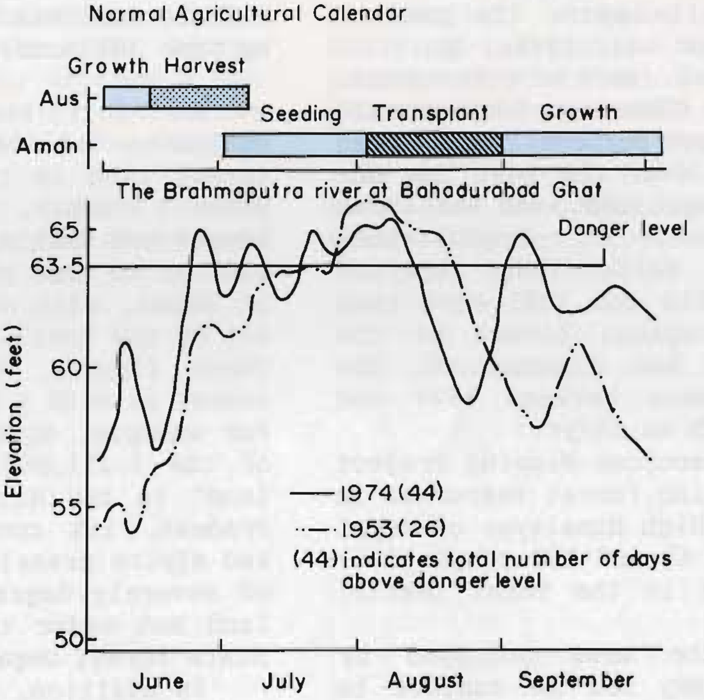


Figure 18 **Agricultural calendar in relation to timing of flooding in Bangladesh (after Currey, 1984).**

is often seen as a recent, yet terminal phenomenon, unless truly drastic measures are taken. It has been suggested, for example, that there would be no more accessible forest left anymore in most of Nepal around the year 2000 if the presently assumed rates were to continue (World Bank (1980) in Gilmour, 1988).

However, there is a growing body of literature, mostly based on the interpretation of time sequences of aerial photographs or satellite imagery, which indicates that there has been very little change in the area occupied by forest and agricultural land in Nepal's Middle Hills since 1964 (Bajracharya, 1983; Strebal, 1985; Malla, 1985).

In addition, evidence based on oral history research in two hill districts in central Nepal suggested that the forest boundaries have remained more or less stable for at least a century (Mahat et al., 1987).

In other words, the bulk of deforestation in the hills must have taken place well before the present century (Mahat et al., 1986a, b).

In the Terai, on the other hand, rates of forest clearance for agricultural and other purposes have been extremely high over the past few decades, even though the area has known a long history of exploitation (Tucker, 1987). Malla (1985) reported that between 1954 and 1981 more than 60% of the tropical forest of the Nepalese Terai had disappeared. The rate of clearance between 1977 and 1981 was as high as 3%/yr.

The Land Resources Mapping Project estimated existing forest resources in the Middle and High Himalayas of Nepal as per 1984 at 42 and 35% respectively, and at 23% in the Terai (Malla, 1985).

Whereas the *area* occupied by "forest" land may not be subject to great changes, there is reason enough for grave concern. Although estimates of demand for fodder and fuelwood vary widely (Thompson & Warburton, 1985), there can be little doubt that in many areas demands exceed supplies (Kayasthra, 1988).

The decline in crop yields in East Nepal referred to in the last section may be seen as a sign on the wall in this respect (Shrestha, 1988). All over the hill region, there has been a marked reduction in forest density, especially on the edges bordering agricultural lands.

As such, deforestation is not so much a loss of forest area, but rather a loss of forest quality (Panday, 1986). Moench & Bandyopadhyay (1986) have described some of the mechanisms involved, showing how a loss of forest cover can occur even though overall biomass productivity far exceeds village demand (see also Gilmour, 1987).

Despite increasingly successful attempts at reforestation and a growing interest of farmers to plant trees on their own lands, the balance is still heavily on the negative side (Gilmour, 1988).

Nevertheless, there is a growing awareness of the situation at all levels and there is reason to believe that the predicted mega-crisis may well be far less terminal than thought by some (Gilmour, 1988; Panday, 1986).

As for the Indian Himalaya, estimates of the areal extent of forest land in the Hill Districts of Uttar Pradesh, sub-Himalayan West Bengal and Sikkim, suggest a situation similar to that of the Middle Himalaya of Nepal, with values between 30 and 40% of the total area (Tejwani, 1985). These figures, however, need to be looked at with a fair deal of caution. For example, Gupta (1983) showed that of the 3,253,000 hectares of "forest land" in the Hill Districts of Uttar Pradesh, 15% consisted of ice, rock and alpine grasslands, and another 27% of severely degraded scrub and wasteland not under the management of the State Forest Department.

In addition, there is no guarantee that the area actually managed by the Forest Department does consist of well-stocked forest. Tejwani (1985) estimated that about 60% of the land managed by the Department was considered "exploitable".

According to Tucker (1987), the first wave of massive deforestation in the Indian Himalaya occurred in the 1850's and 1860's in the wake of the establishment of British control in the upper Ganges plains and the associated building of a railway network. Completely unregulated exploitation took place, especially in the Tropical (*Shorea robusta*) and Sub-tropical (Deodar) zones (cf. Section II.4.1).

With the establishment of the Indian Forest Service soon after, the damage to *Shorea* forests (not deodar) was repaired to a fair degree and for more than a century a sustained yield production system was effected.

However, a considerable portion of the forests were placed under the control of the Revenue Department, which did not do much to preserve them. In addition, private contractors caring little for environmental values, were generally involved in harvesting the timber for distant markets until fairly recently. Meanwhile, access to these forests by the local population was limited (Tucker, 1987), which led to tensions long before the Chipko movement came into existence. Under pressure of the latter, the Indian Government has recently imposed a ban on all commercial forestry operations in the Himalaya, initially for fifteen years.

Degradation of the forest continues, nevertheless, as a result of ongoing exploitation by the local population (Moench & Bandyopadhyay, 1986).

As for the rate of "deforestation" in the Indian Himalayas, Tejwani (1985) suggested a similar trend as for the entire nation, which experienced an overall loss of forest over the period 1951 to 1980 that exceeded planting rate by some 16%. This may well be a conservative estimate in the light of the findings of Gilmour (1988) for the Nepalese Middle Hills.

In Bhutan, Arunachal Pradesh and Purvanchal, forest cover is much better than in the West (over 60%; Tejwani, 1985), although shifting cultivation is widespread. According to Sargent et al. (1985), Bhutan enjoyed a forest cover of about 55 % in 1978, 22 % of which was close-canopied and almost certainly primary. The destruction of the *Shorea* forests of Bhutan has already been indicated, but Sargent et al. (1985) also signalled heavy pressures in the Sub-tropical vegetation zone, mainly in the form of (commercial) logging and grazing. Shifting cultivation is especially a problem in the south-eastern parts of Bhutan (Upadhyay, 1987).

In Meghalaya and Nagaland, forests make up only 10 to 20% of the land area and the *Jhum* cycle has become critically short (Section II.4.2).