IV. Macro-scale Hydrology of the Hindu Kush-Himalayan Region

Macro-scale characteristics of the major rivers of South Asia have been described by Sharma (1983), Rao (1984), and Bruijnzeel and Bremmer (1989). This section is basically a summary of the information contained in these publications and is included here to demonstrate some of the difficulties involved in inferring meso-scale characteristics of the mountain headwaters of these rivers from observations of macro-scale hydrological regimes, as measured at lowland stations.

The Indus Basin

The Indus River originates north of the Great Himalayas on the Tibetan Plateau, near Lake Mansarowar and Mt. Kailash. The river flows westwards, south of the Karakoram Range and north of the Great Himalayas, to Mt. Nanga Parbat, where it turns sharply to the south, flowing through Pakistan into the Arabian Sea near Karachi. Below the Tarbela dam, the river is joined from the east by the Beas, Jhelum (Chenab), Ravi, and Sutlej rivers, originating in the western Himalayas, and, from the west, the Kabul and Swat rivers (Figure 6).

The flow of the upper Indus has been gauged since the early 1960s by the Pakistan Water and Power Development Authority, WAPDA, at several sites upstream from Tarbela reservoir (WAPDA 1979). The furthest upstream of these stations is at Partab Bridge just below the confluence of the Gilgit River. WAPDA also operates gauging stations on the upper Indus at Kachura near Skardu, south of the central Karakorams; on the Shyok River, that drains the eastern Karakoram; on the Hunza River at Dainyor Bridge near Gilgit in the western Karakoram; and on the Gilgit River just downstream from its confluence with the Hunza River.

The average annual flow of the upper Indus River, with a surface area of approximately 250,000 sq. km., is estimated to have a volume of 115,000 million cubic metres. This represents an average depth of between 350-400 millimetres of water over the upper watersheds (Goudie et al. 1982).

Climate

The climate of the upper Indus basin is transitional between that of Central Asia and the monsoon climate of South Asia (Rao 1981). The climate varies considerably with latitude, altitude, aspect, and local relief, e.g., rain shadows caused by high mountain masses such as Nanga Parbat. The availability of climatic data varies widely in the region. There are few climatic data for the upper Indus basin, but long-term temperature and precipitation records are available for Gilgit (1,490 m). The most significant features of the regional climate of the upper Indus are the low overall precipitation, the great range of mean monthly temperature values, the low winter temperatures, and severe frosts during portions of the winter season (Goudie et al. 1982).

Rainfall data for the region indicate that while annual totals may be low at the altitudes of the valley floors, individual storm totals may be quite high. In Gilgit in 1979/1980, the yearly precipitation total was 155 mm, accumulated during 62 days of precipitation. Of this total, however, 67 mm of precipitation (43% of the total) fell on just five days, 40 mm fell on three consecutive days in May, and the largest daily precipitation was 18 mm (Ferguson 1984). This tendency for precipitation to be low overall, but for there to be a small number of storms each year, sometimes with intense rainfall events, has considerable hydrological and geomorphological significance, especially in terms of erosion, mass movements, and the production of debris flows.

Most of the precipitation is not derived from the Indian monsoon, but from depressions moving in from the west during the spring and summer. Monsoon disturbances do occasionally succeed in extending sufficiently far north to enter the area, however, and, when they do, precipitation levels can be substantially increased. Great fluctuations in regional rainfall totals due to the annual variation in the scale, extent, and frequency of disturbances are further complicated by the localised nature of most storms, marked rain shadow effects, and topographical influences on local and regional wind systems. Variability is as important as the more obvious aridity (Rao 1981). Although the valley floors are quite arid, precipitation amounts almost surely increase substantially with increasing altitude (Dreyer et al. 1982). As examples, measurements of the thickness of the annual layers of ice in the firn basin of the Batura glacier and the monitoring of the annual discharge of meltwater from the glacier have led Chinese investigators to suggest that precipitation above the regional snow line (at 4,700-5,300 m on this glacier) may exceed 2,000 mm annually (Batura Glacier Investigation Group 1979). Canadians, working further to the east near the Biafo glacier found, totals in excess of 1,400 mm annually at comparable altitudes.

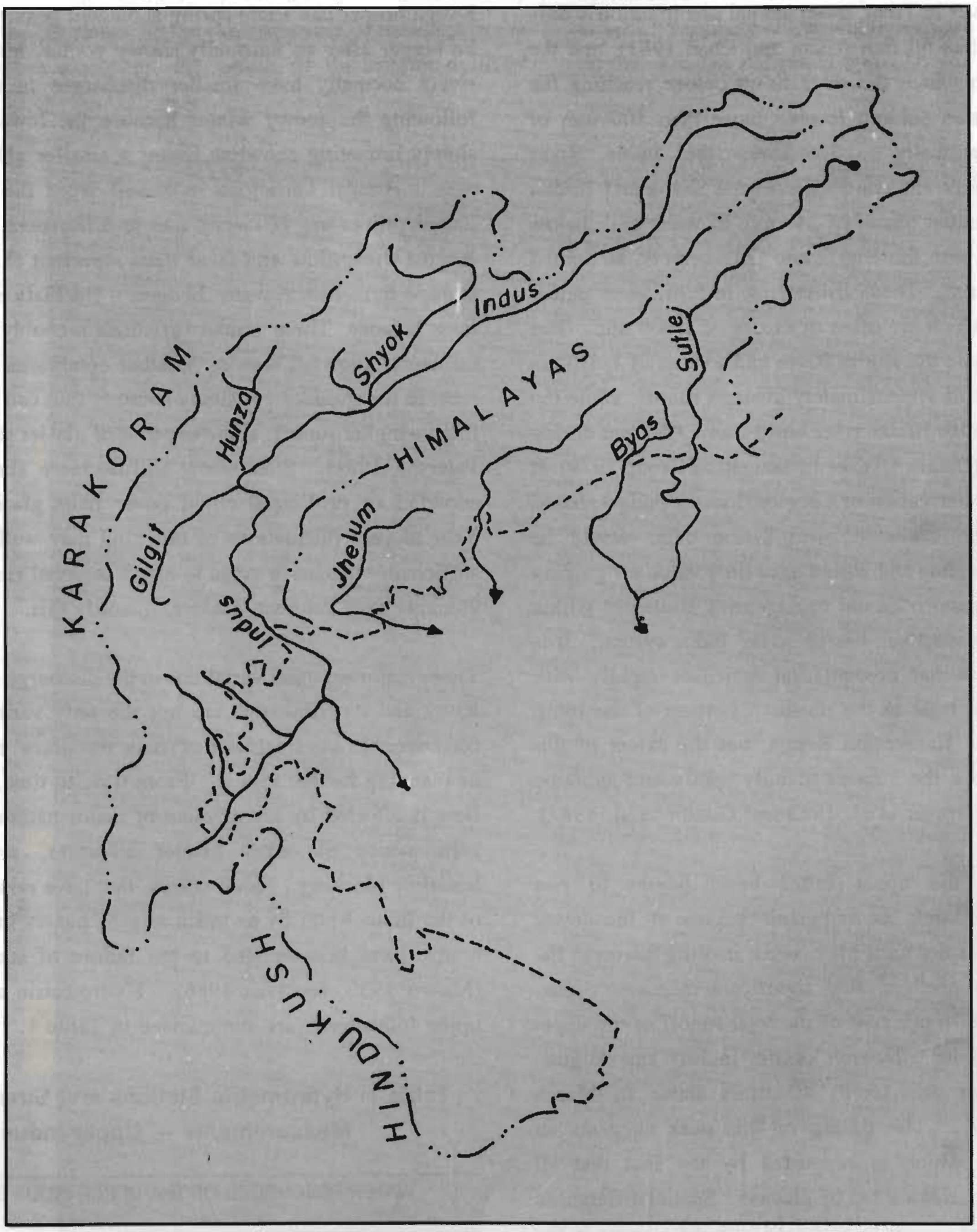

Figure 6: A Sketch Map Showing the Mountain Catchments of the Upper Indus Basin

Note: The broken line represents the piedmont - the lower limit of the mountain portion of the basin.

Temperature regimes are similarly variable. During the winter months, freezing conditions extend down to the valley floors, with snowfalls, while summer temperatures may exceed 40 degrees Celsius. Frost action probably operates through an enormous altitudinal range, with three to six months of freeze-thaw conditions between 1,500 m and 3,000 m, two separate three-month periods between 3,000m and 4,500 m (spring and autumn), above which level a summer phase dwindles from six months at 4,500 m to zero at approximately 7,000 m (Hewitt 1968).

Streamflow

This river system illustrates one of the central problems associated with determining the hydrologic regime of many of the watersheds of the region. At the headwaters of the upper Indus River in Tibet, mean annual precipitation is only slightly more than 50 mm (Guan and Chen 1981), and the valleys through which the river flows before reaching the plains of Pakistan seldom receive more than 100 mm of precipitation annually. However, the Indus River immediately below the confluence of the Shyok and Braldu rivers has an annual runoff of 240 mm of water and, below the confluence with the Hunza and Gilgit rivers, an annual runoff of 370 mm. These tributaries, in turn, have annual runoff depths which are often in excess of 1,000 mm. The Batura tributary to the Hunza River had a value of 1,570mm in 1970, a year of approximately average runoff, while the value for the entire Hunza river basin was 1,050 mm during that same year (Batura Glacier Investigation Group 1979). It is apparent that derivation of a regional water budget, based solely upon the available precipitation data, would be extremely misleading and would have little value for guiding most types of environmental management strategies within any of the individual sub-basins of the Indus system. It is equally apparent that precipitation increases rapidly with altitude here, at least in the northern portion of the Indus basin within the Karakoram Range,. but the extent of this increase has been the subject of only spotty and sporadic measurements (Dreyer et al. 1982 and Goudie et al. 1982).

Streamflow in the upper Indus basin begins to rise marginally in March as snowmelt begins at the lower altitudes, but it is not until May, when melting begins at the altitudes of the glaciers, that significant increases occur. Between 40 and 70 per cent of the total runoff of the upper Indus basin and its tributaries occurs in July and August, when discharges are 15 to 40 times those in March (WAPDA 1979). The timing of this peak suggests an icemelt origin, which is supported by the fact that all significant tributaries are fed by glaciers. Spatial differences in average runoff appear to correlate with differences in the percentage of each basin covered by permanent snow and ice, while differences in the timing of the peak correlate with differences in the altitudinal distribution of this snow and ice cover.

Streamflow varies considerably from year to year. For example, runoff from the entire Karakoram Region (upper Indus plus Gilgit and Hunza rivers) was 370 mm in 1970 but 540 mm in 1973 (WAPDA 1979). Differences in the annual flow of the Indus, further downstream, have been related to winter snowcover as measured on satellite images, and by attempts made to forecast streamflow using this snowcover index, but there are complications with this approach. Runoff from the sub-alpine zone south of the Karakoram Range proper has a late spring snowmelt peak that ought to be bigger after an unusually snowy winter, but glacier-fed rivers normally have smaller discharges in the summer following the snowy winter because the lower and more slowly retreating snowline means a smaller ablation (melt) area. Annual variations in runoff from the Karakoram Range proper are primarily due to differences in July and August streamflow and these must represent changes in the storage term of the water budgets - fluctuations of glacier mass balance. These annual variations probably depend less on winter snowfall than on weather conditions and melting rates in the summer. A sunny summer thus can be expected to give higher runoff, at the expense of glacier storage (e.g., Paterson 1981). Streamflow will decrease abruptly when snowfall or prolonged cloud cover halts glacier melting. Year to year fluctuations of this kind may well apply over sufficiently extensive areas to affect regional runoff, but no attempts have yet been made to quantify this.

These major seasonal variations in the discharge of the Indus River and its tributaries are not the only variations to be considered in any treatment of water resources' management or planning for the region. From time to time, the river's flow is affected by the creation of major natural dams as a consequence of either glacier advances, mudflow, or landslide blocking. Flood waves, that have raised the level of the Indus River by as much as nine metres in only a few hours, have been related to the failure of such blocking (Mason 1930, see Ives 1986). Hydrometric data for the upper Indus basin are summarised in Table 1.

Table 1: Hydrometric Stations and Streamflow Measurements -- Upper Indus Basin

WATER RESOURCES OF THE UPPER INDUS BASIN

River	Station	Area sq.km.	Avg Q m^3/s	Q mm	Q mcm
Hunza	Dainyor	13157	379	910	11965
Gilgit	Gilgit	12095	287	750	9041
Indus	Kachural	112664	990	270	30220
Shyok	Yugo	33670	310	290	9769
Indus	Partab	142700	1760	390	55500

Source: WAPDA 1979.
Note: mcm = Million Cubic Metres.

The Ganges Basin

The Ganges basin parallels the long axis of the Himalayan Range, from the headwaters in the western Indian State of Himachal Pradesh. The course of the river has not been determined by downcutting and erosion, throughout much of its length, but rather by the downwarping of the crust in the "subduction zone" to the south of the tectonic uplift of the Himalayas. The total surface area of the basin is approximately 1,000,000 sq. km., of which more than 80 per cent is located south of the main river channel in the lowlands of India. As the river flows eastwards, past the southern front of the Himalayas, it is joined from the north by the Sarda, Karnali, Narayani, and Sapta Kosi rivers, all of which originate either wholly or partially within Nepal or on the Tibetan Plateau (Figure 7).

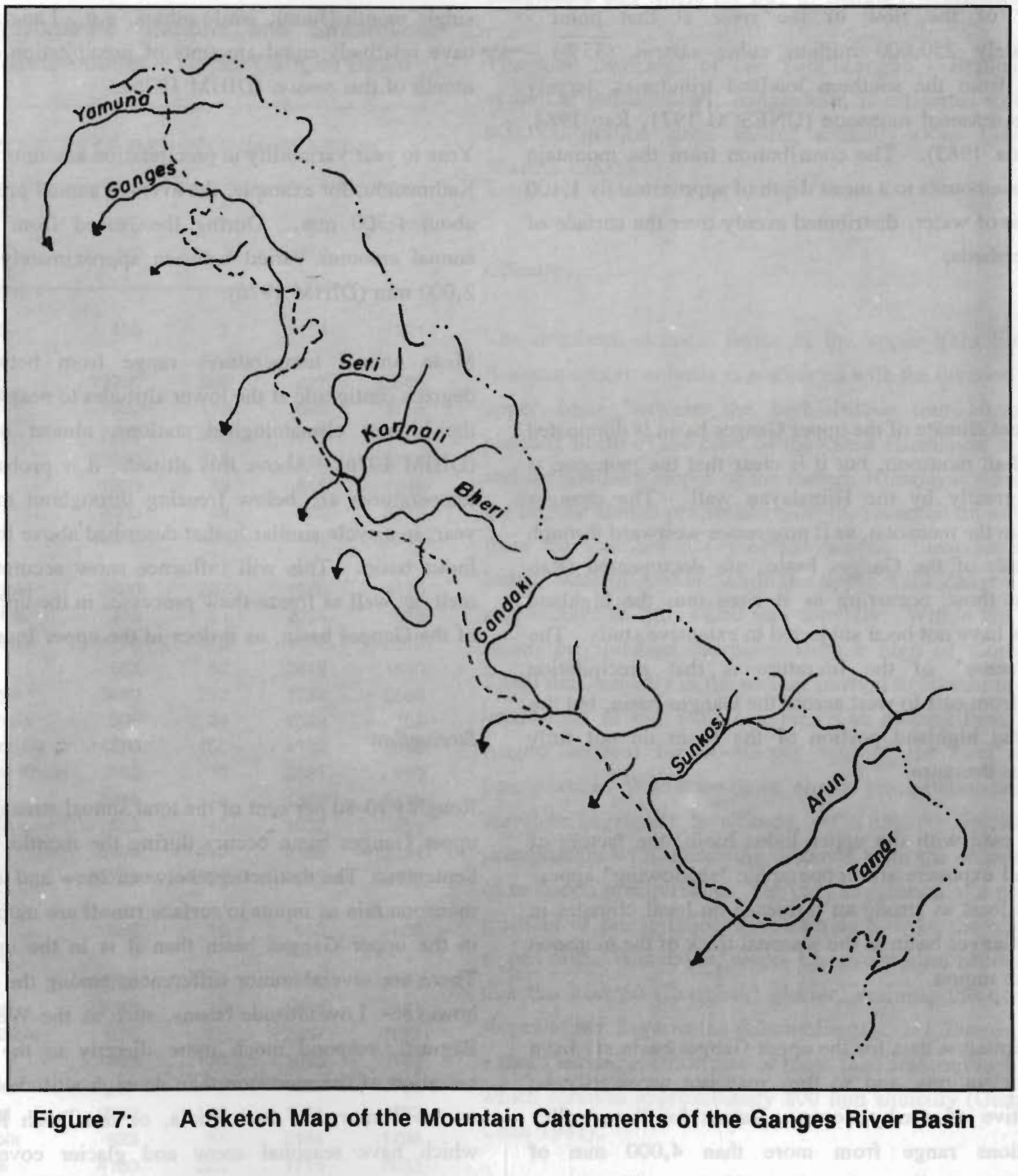

Figure 7: A Sketch Map of the Mountain Catchments of the Ganges River Basin

Note: The broken line represents the lower limit of the mountain portion of the basin.

The only extensive data concerning streamflow from the mountain portion of the Ganges basin are on the Nepalese portion of the basin.

Hydrometric data are available from 48 stations in Nepal for different portions of the time period 1961-1989. Most stations are covered for the entire period, but a few were either discontinued or only established during this time (HMG Department of Irrigation, Hydrology, and Meteorolgy [DIHM] 1977, unpublished, and USGS 1962).

Of the total flow of the Ganges River, above its confluence with the Brahmaputra - approximately 460,000 million cubic metres annually - approximately 50,000 million cubic metres (10% of the total) originate in the Indian Himalayas, while approximately 145,000 million cubic metres (32%) flow from the mountain watersheds of Nepal and Tibet. The remainder of the flow of the river at that point - approximately 250,000 million cubic metres (55%) - originates from the southern lowland tributaries, largely during the seasonal monsoon (UNESCO 1971, Rao 1984, and Sharma 1983). The contribution from the mountain watersheds amounts to a mean depth of approximately 1,100 millimetres of water, distributed evenly over the surface of these watersheds.

Climate

The regional climate of the upper Ganges basin is dominated by the Indian monsoon, but it is clear that the monsoon is modified greatly by the Himalayan wall. The changes occurring in the monsoon, as it progresses westward through the lowlands of the Ganges basin, are documented (Rao 1981), but those occurring as it rises into the highland watersheds have not been subjected to extensive study. The general "sense" of the literature is that precipitation decreases from east to west across the Ganges basin, but the data for the highland portion of the basin do not fully support this decrease.

As is the case with the upper Indus basin, the factors of altitude and exposure and topographic "shadowing" appear to exert at least as strong an influence on local climates in the upper Ganges basin as the seasonal track of the monsoon through the region.

Most precipitation data for the upper Ganges basin are from valley-floor stations, and so they may not necessarily be representative of nearby slopes. Values for these valley floor stations range from more than 4,000 mm of precipitation annually to less than 400 mm. The lowest values are from stations north of the main crest of the Greater Himalayas, such as those stations located in the upper Karnali or Kali Gandaki basins. Japanese studies in the upper Khumbu basin of eastern Nepal have suggested that precipitation on ridges and in high glacierised basins can exceed that of adjacent valley floors by a factor of four to five during the monsoon months (DIHM 1976 and Yasunari and Inoue 1976).

It is not uncommon for 10 per cent of the total annual precipitation to occur in a single day and for 50 per cent of this total to occur during ten days distributed over the rainy season. Seventy to eighty per cent of the annual total occurs during the months from June-September, and some stations, e.g., Kathmandu, Nepal, show peak precipitation during a single month (June), while others, e.g., Langtang, Nepal, have relatively equal amounts of precipitation during each month of this season (DIHM 1976).

Year to year variability in precipitation amounts is great. In Kathmandu, for example, the average annual precipitation is about 1,300 mm. During the period from 1921-1975, annual amounts varied between approximately 1,000 and 2,000 mm (DIHM 1976).

Mean annual temperatures range from between 20-25 degrees centigrade at the lower altitudes to near 0 degrees at the highest climatological stations, almost 4,500 masl. (DIHM 1976). Above this altitude, it is probable that air temperatures are below freezing throughout much of the year, in a cycle similar to that described above for the upper Indus basin. This will influence snow accumulation and melt, as well as freeze-thaw processes in the upper altitudes of the Ganges basin, as it does in the upper Indus basin.

Streamflow

Roughly 70-80 per cent of the total annual streamflow of the upper Ganges basin occurs during the months from June-September. The distinctions between snow and ice-melt and monsoon rain as inputs to surface runoff are much less clear in the upper Ganges basin than it is in the upper Indus. There are several minor differences among the sub-basins, however. Low-altitude basins, such as the West Rapti or Bagmati, respond much more directly to the onset and cessation of the monsoon than do high altitude basins such as the Tamur, the Seti Khola, or the Dudh Kosi, all of which have seasonal snow and glacier cover. While streamflow volumes from the high-altitude sub-basins begin to rise as early as April or May, it is not until the onset of the monsoon, normally in June, that a similar rise is seen in the low altitude basins. Also, the high altitude basins show a much slower diminution of streamflow at the end of the monsoon than do the low altitude basins.

It is in the total volume of water produced per unit area of watershed where the most marked differences between high and low altitude basins appear to occur, however. Runoff depths range from less than 1,000 mm annually in tributaries to each of the three major rivers, to more than 2,500 mm for high altitude sub-basins, in the central and eastern portions of Nepal, at the headwaters of the Narayani and Kosi river systems. Hydrometric data for the Nepal headwaters of this river are summarised in Table 2.

Table 2: Hydrometric Stations and Streamflow Measurements -- Upper Ganges Basin

WATER RESOURCES OF THE UPPER GANGES BASIN

STN. NO.	RIVER	AREA sq. km.	Qv m^3/s	Qs mm	mcm
170	Surnagad	188	7	1174	221
240	Karnali	19260	505	827	15926
250	Karnali	1980	119	1895	3753
260	Seti	7460	302	1277	9524
270	Bheri	12290	435	1116	13718
280	Karnali	1900	49	813	1545
290	Babai	3000	88	925	2775
	Total	42890	1498	1101	47241
410	Kali Gandaki	6630	267	1270	8420
415	Andhi Khola	476	31	2054	978
420	Kali Gandaki	4770	175	1157	5519
430	Seti	582	52	2818	1640
439	Marsyangdi	3850	212	1737	6686
440	Chepe Khola	308	24	2523	757
445	Burhi Gandaki	4270	160	1182	5046
446	Phalankhu Khola	162	13	2531	410
447	Trisuli	3948	173	1382	5456
448	Tadi Khola	653	40	1932	1261
450	Narayani	6104	419	2165	13214
	Total	31753	1566	1555	49385
550	Bagmati	585	16	863	505
604	Arun	28200	423	473	13340
610	Bhote Kosi	2410	79	1034	2491
620	Balephi Khola	629	53	2657	1671
630	Sun Kosi	1881	119	1995	3753
640	Rosi Khola	87	3	1087	95
647	Tama Kosi	2753	145	1661	4573
660	Likhu Khola	823	57	2184	1798
670	Dudh Kosi	4100	223	1715	7033
680	Sun Kosi	4917	89	552	2807
690	Tamur	5640	336	1879	10596
	Total	51440	1527	936	48155
	Grand Total	126083	4591	1148	144782

Source: HMG, Dept. of Hydrology and Meteorology 1977; unpublished

The Yalu Zangbu-Brahmaputra Basin

The headwaters of the Yalu Zangbu river system are immediately adjacent to those of the Indus River, north of the Greater Himalayas. The river flows eastward from this source, paralleling the north slopes of the Himalayas until it finally turns abruptly southward, traversing the eastern Himalayas and flowing out on to the plains of Arunachal Pradesh and Assam. The river joins the Ganges in southern Bangladesh and enters the Bay of Bengal (Figure 8).

The total discharge of the Yalu Zangbu - Brahmaputra system at Bahadurabad, Bangladesh, is estimated to be ca. 600,000 million cubic metres annually (Rao 1984 and Sharma 1983).

Climate

The dominant climatic factor in the upper Yalu Zangbu-Brahmaputra river basin is associated with the division of the upper basin between the high-altitude trans-Himalayan plateaux north of the crest of the Great Himalayas in Tibet and the southern slopes of the eastern Himalayas. Some of the highest annual precipitation depths recorded on earth are from the southern slopes of the eastern Himalayas in the Indian State of Assam, while the upper Yalu Zangbu basin may receive as little as 50 mm annually. Within the upper basin, precipitation decreases from a high of more than 3,000 mm annually in the eastern portion to 50 mm near the headwaters of the Yalu Zangbu. The months from June-August account for 60-80 per cent of the total annual precipitation. Within the basin, annual precipitation amounts correlate negatively to altitude, reflecting the decrease in precipitation with increasing distance from the source area of monsoon precipitation. The only suggestion of a positive gradient of precipitation with altitude is from the northern slopes of the Himalayas, where Chinese studies have shown that the Rongpu (Rongbuk) glacier, draining the northern slopes of Mt. Sagarmatha (Chomolungma, Mt. Everest), has a mean annual ablation rate of more than 550 mm in an area which receives approximately 200 mm annually (Guan and Chen 1981).

Streamflow

The spatial pattern of surface runoff depth over the upper basin correlates well with seasonal precipitation, decreasing from east to west (Guan and Chen 1981).

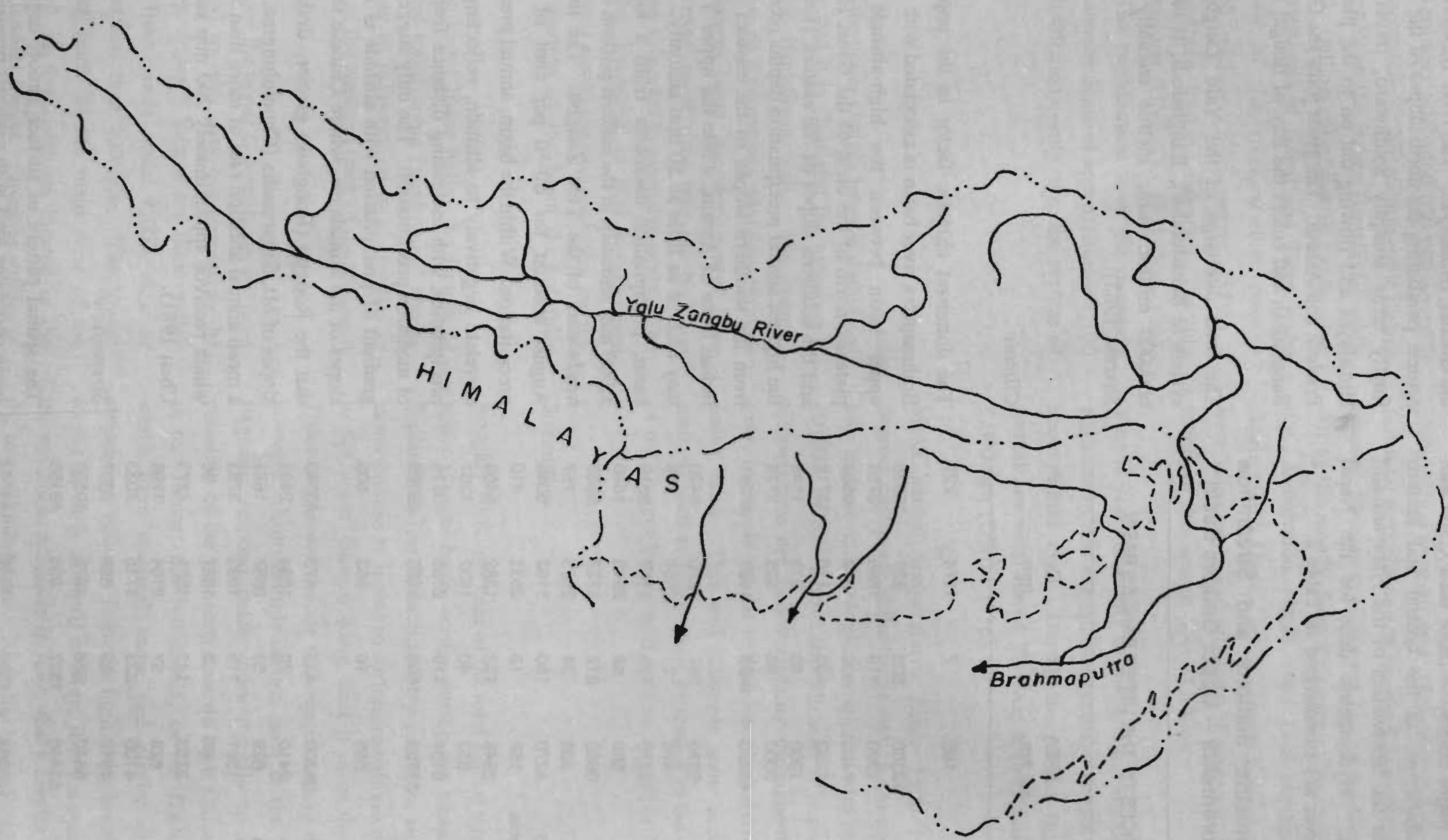

Figure 8: The Yalu Zangbu-Brahmaputra Basin Showing the Lower Limit of the Mountain Portion of the Basin

The timing of this runoff throughout the year, however, is not coincident with precipitation; it reaches a peak in August, by which time precipitation has already begun to decline. This may be a reflection of temporary storage of early precipitation as snow and the subsequent melting of those deposits. At the point where the river debouches on to the southern piedmont, it has a mean annual flow volume estimated to be approximately 200,000 million cubic metres (Rao 1984), or 33 per cent of the total flow of the river, yielding a mean depth of approximately 630 millimetres over the watershed above this point. Of this volume, 140,000 million cubic metres (70%) are derived from the Tibetan Plateau, with a mean runoff depth of 580 millimetres. Tributaries entering from the southern slopes of the Himalayas into the Indian State of Arunchal Pradesh, as well as from Sikkim and Bhutan, contribute an additional 180,000 million cubic metres annually (30%) to the total flow of the river. Hydrometric data for the headwater portion of this river system are summarised in Table 3 (Guan and Chen 1981).

Table 3: Hydrometric Stations and Streamflow Measurements - Yalu Zangbu Basin

WATER RESOURCES OF THE YALU ZANGBU BASIN

River	Station	Area sq. km.	Avg Q m^3/s	Q mm	Q mcm
Yalu Zangbu	Nugesha	106378	547	162	17300
Yalu Zangbu	Nugesha-Yangcun	46813	403	271	12700
Yalu Zangbu	Yangcun-Nuxia	36652	932	802	29400
Nyang He	Gyangze	6216	24	119	757
Lhasa He	Lhasa	26225	287	345	9050
Yi'ong Zangbu	Gongde	10917	378	1092	11900
Maguolong Zangbu	Gabutong	1653	136	2587	4290

Source: Guan and Chen 1981

Regional Values of Erosion and Sediment Transport

The Upper Indus Basin

In an average year, the entire Karakoram and Trans-Karakoram region above the Partab gauging station yields 160 million tons of sediment. This is equivalent to approximately 640 tons/km²/year or 0.15 km³ of unconsolidated sediment (Ferguson 1982).

There is a marked spatial variation in annual runoff and sediment yield. The Trans-Karakoram headwaters of the Indus River in Tibet and Ladakh, upstream of the Shyok confluence, appear to provide relatively little runoff and sediment, whereas the main Karakoram Range, extending across the Shyok, Braldu, and Hunza basins into the edge of the Gilgit basin, contributes disproportionately much more. The Hunza, in particular, yields 39 per cent of the total sediment load at Partab from only nine per cent of the area above that station. Erosion rates, as indicated by sediment transport data, vary by a factor of approximately six among the stations for which data are available. Some of this difference may be explained by differences in surface area, in that a larger basin provides more sites for intermediate storage of sediment in transport than does a smaller basin. The data generally, however, appear to correlate well with valley-to-summit relief differences among the basins and the glacier cover percentage. The relief provides the energy required for sediment transport while the glacial and periglacial moraines and alluvium are the source of much of the sediment (Ferguson 1982 and Goudie et al. 1982).

The average of 63 million tons of suspended sediment carried each year by the Hunza River is a very high load for a river draining only 13,200 sq. km. The mean yield on a per unit area basis is 4,800 T/km²/yr, about twenty-five times the global average. Comparison with other areas is complicated by the scale dependence of sediment load per unit area, as a result of increased depositional opportunities in larger basins. However, if load is plotted against basin area to allow comparison of relative erosion rates in terms of vertical departures from the general trend, the relationship shown in Figure 2 is obtained. Only two other mountain regions plot as high as the western Karakoram: the Nepal Himalayas and the southern Alps of New Zealand, both similar to the Karakoram in tectonic activity and glacier cover but each experiencing much greater annual precipitation as rain and snowfall. The only river system with an even higher erosion rate for its size is the middle Yellow River and its tributaries in the semi-arid plateau northeast of the Himalayas where thick loess (wind-blown dust) deposits are being dissected by gullying.

Together, the Hunza and Gilgit rivers contribute almost as much sediment to the upper Indus basin as the entire eastern Karakoram, that is four times more extensive. The denudation (erosion) rate for the entire Karakoram Region is over 1,000 tons/km^2/yr (0.4 mm/yr) and the region contributes 40 per cent of the load of the Indus River from only 15 per cent of the total area. This denudation rate is very high by world standards, despite there being no recognised significant contribution from accelerated soil erosion resulting from human uses (Goudie et al. 1982).

The Ganges Basin

Published data of sediment transport through the Ganges river system are relatively rare. Those which were found indicate that portions of this system may have even higher rates of unit area denudation than does the Indus basin (Carson 1985 and Bruijnzeel and Bremmer 1989).

The total Ganges' system is estimated to carry approximately 430 million tons of sediment per year, for a unit area denudation rate of slightly more than 400 tons/km^2/year (Holeman 1968). This is comparable to the unit area estimate for the upper Indus basin. Of the total volume of sediment passing through the Ganges' system annually, it has been estimated that 170 million tons, i.e., 40 per cent of the total, is produced by the Kosi River in eastern Nepal. This means a unit area denudation rate of 2,270 tons/km^2/year, 3.5 times that of the upper Indus basin. It has further been estimated that the Tamur River, a tributary to the Kosi River system, produces nearly 30 million tons of sediment annually from a surface area slightly more than 5,500 sq.km. - a denudation rate of more than 5,000 tons/km^2/year. This was the highest value found for the Hindu Kush-Himalayan Region during the preparation of this paper.

Nearly 50 per cent of the total surface area of the Kosi River is located north of the Great Himalayas on the Tibetan Plateau. If low values of sediment concentration, similar to those from the Yalu Zangbu, also characterise the headwaters of the Arun River (the tributary to the Kosi River located primarily in Tibet, the data suggest that values for much of the remainder of the Kosi River system may exceed 4,000 tons/km^2/year.

The Yalu Zangbu Basin

Data from the uppermost portion of this system in Tibet indicate very low values of sediment transport (Guan and Chen 1981).

Sediment transport measurements have been made at three sites along the Yalu Zangbu River, at Nugesha, Yangcun, and Nuxia in descending order downstream and on two tributaries: the Lhasa He at Lhasa and the Nyang He at Gyangze. Subsequent streamflow measurements are made at Passighat (at this point the river is known as the Dihang) and at Gauhati (Pandu) in India and Bahadurabad in Bangladesh. Due to some difficulties experienced in obtaining hydrological data for portions of the Hindu Kush-Himalayan Region, it is not known whether the Indian and Bangladesh stations also measure suspended sediment or whether the total volume for the basin - ca. 735 million tons - is an estimate.

The most striking feature of the limited amount of sediment data available for this river system is the great contrast between the upper portion, the Yalu Zangbu in Tibet, and the lower portion, the Brahmaputra, in the Indian State of Assam. With the exception of the Nyang He, which drains the northern slopes of the Great Himalayas, values of suspended sediment loads indicate erosion rates of at or below 100 tons/km^2/yr. The Nyang He has a mean value of 150 tons/km^2/yr. The lowest value, 34 tons/km^2/yr, has been measured in Lhasa for the Lhasa He that drains the southern slopes of the Tanggula Range which form the northern margin of the Yalu Zangbu watershed in Tibet (Guan and Chen 1981). If it is assumed that a value of 100 tons/km^2/year is representative of the Yalu Zangbu, this portion of the river may contribute as little as 30 million tons annually, or approximately four per cent of the total sediment load of the lower Brahmaputra.

Published data for the lower Brahmaputra portion of the river provide an estimate of the erosion rate of approximately 1,100-1,300 tons/km^2/yr for the entire basin. The most reasonable explanation for this is felt to involve the great differences that characterise the river gradients within Tibet and Arunchal Pradesh, plus the great increase in discharge as the river crosses on to the wetter southern slopes of the Himalayas. On the Tibetan Plateau, the river loses only approximately 500 m in altitude while flowing a distance of more than 2,000 km between its headwaters and Namche Bazaar. South of Namche Bazaar, it drops over 3,000 m in approximately 200 km, before flowing out on to the plains of Assam. This increase in stream gradient by a factor of ca. 60 times should greatly increase the erosive power of the river and increase the sediment load abruptly along the reach between Namche Bazaar and the foot of the Himalayan mountains. If the erosion estimates are corrected to reflect this fact, a value of approximately 2,250 tons/km^2/year is obtained for the portion of the river below the point at which the river crosses from Tibet into India.

This value is still not excessive by Himalayan standards, but it is higher than existing estimates based upon aggregate values for the entire Yalu Zangbu-Brahmaputra basin.

Sediment transport data for sites within the three river basins are given in Table 4.

Table 4: Measured Values of Sediment Transport -- Mountain Rivers of South Asia

SEDIMENT TRANSPORT--HINDU KUSH-HIMALAYAN REGION

River	Mean Annual Suspended Sediments (tons x 10^6)	Mean Annual Discharge (10^6 m^3)	Area (sq.km.)	Sediment Removal (tons/km^2/yr)
UPPER INDUS BASIN				
1. Hunza (Dainyor)	62.2	11965	13157	4805
2. Gilgit (Gilgit)	13.6	4458	12095	1122
3. Indus (Kachural)	87.1	30220	112664	773
4. Shyok (Yugo)	33.6	9769	33670	997
GANGES BASIN				
1. Tamur	55.6	10800	5680	5147
2. Kosi	62.4	22500	62000	2774
YALU ZANGBU BASIN				
1. Yalu Zangbu (Nugesha)	12.8	17300	106378	120
2. Yalu Zangbu (Yangcun)	14.0	30000	153191	91
3. Yalu Zangbu (Nuxia)	16.9	59400	189848	89
4. Nyang He	0.95	757	6212	153
5. Lhasa He (Lhasa)	0.89	26225	9050	34

Source: Ferguson 1984, Holeman 1968, and Mahmoud 1987

Glaciers of the Hindu Kush-Himalayan Region

With increasing altitude, the amount of annual precipitation that falls as snow increases, and the amount which does not melt during the year in which it falls also increases. This phenomenon gives rise to a perennial ice cover on the surface - a glacier (Patterson 1981). Where they exist in significant amounts, glaciers are an important natural reservoir of water and play an important role in the annual cycle of high and low river flow. In countries, such as Norway and Switzerland, that are extensively "glacierised", the hydroelectric generation industries place a high priority on understanding annual fluctuations in the amount of water stored as ice in these glaciers (Meier and Roots 1982).

It is estimated that between ten to twenty per cent of the total surface area of the Hindu Kush-Himalayas is covered by glaciers (Watanabe 1976). This is a percentage comparable to that of the Swiss Alps. An additional amount, which is as high as thirty to forty per cent, has a seasonal snowcover. This represents a significant form of natural storage, which lasts from a single season, in the case of the transient snowcover, to decades or centuries in the case of the larger glaciers. The importance of this natural reservoir appears to diminish from west to east across the region, being greatest in the Indus basin and least in the Yalu Zangbu-Brahmaputra basin (Evans 1977).

The major mountains of the upper Indus basin, the Karakoram, contain some of the longest glaciers outside the polar regions, and it is probable that they are a primary factor in determining both water availability and sediment in the upper Indus basin. There are more than 100 glaciers that are 10 km or more in length, with several exceeding 50 km. The Karakoram glaciers have maxima of both snowfall and ablation (snow and ice-melt) during the summer half year - and are among the steepest in the world. Their termini are the lowest in the region, often reaching subtropical desert conditions (Mason 1930).

The mean annual precipitation near the termini of Karakoram glaciers is generally less than 100 mm, with a summer daily maximum of 15 mm. Equilibrium lines (the altitudinal zone on the glacier surface where accumulation as snowfall is just balanced by melt) lie in the range of from 4,800 to 5,400 m. Studies have shown that the annual water exchange at the equilibrium line can exceed 1,000 mm and the mean annual runoff for at least one glacierised basin - the Batura - exceeded 1,500 mm during a summer melt season (Batura Glacier Investigation Group 1979). This means that the glaciers of the Karakoram have very high "activity indices", an indicator of the total amount of water passing through the glacier system annually. Consequently they have high flow rates, ranging between 100 and 1,000 metres/year, while there is historical evidence of flow rates of 30 metres/day for a glacier in the late 1800s. It is apparent that the glaciers of the Karakoram have advanced periodically well beyond their present termini positions, often at very high rates. The early scientific literature for the region records instances of glacier advances that have dammed rivers, creating large transient lakes which have subsequently led to massive flooding in downstream areas as ice dams were breached (Mason 1930).

As a result of the high rates of flow, the Karakoram glaciers both actively erode their beds and transport the erosion products to the headwaters of glacial rivers, which then move the sediment into the larger rivers of the region. The percentage of sediment contributed as a direct consequence of glacier erosion is unknown, but, taken together with the stream erosion of older glacial moraines and alluvial valley fills, it could account for the bulk of the sediment moving through the upper Indus system (Ferguson 1982).

The glaciers of the Himalayan mountains in the upper Ganges and Yalu Zangbu-Brahmaputra basins are much smaller and have lower activity indices, in general, than those of the Karakoram. The largest glaciers, located primarily in the Tamur and Dudh Kosi basins in eastern Nepal, do not exceed 20 km in length. There are glacierised (ice-covered) mountains and basins throughout the length of the Himalayas, but few of the glaciers have been the subject of any serious scientific investigation. Japanese studies have shown that the glaciers on the southern (or the Ganges) slope of the southern Himalayas are "warmer" and more active than those on the northern slopes. Chinese studies of the Rongpu glacier, draining the northern slopes of Sagarmatha (Chomolungma, Mt. Everest) indicate that it has an annual water budget of ca. 500 mm, while Japanese studies on the southern flank of the mountains near this point found activity indices exceeding this by a factor of two or three (Watanabe 1976).

Glaciers are both elements of the high mountain hydrologic cycle and indicators of both spatial and temporal variations in it. The low altitude, climatological stations which exist in the Hindu Kush-Himalayan Region could be providing a very incomplete picture of the hydrometeorological environment of the mountains or the changes that are occurring. Studies of the high snowfields and glaciers could provide much useful information concerning the "upper half" of the Hindu Kush-Himalayan mountains, concerning which relatively little of consequence is known at present, at least from a hydrological perspective.