V. Meso-scale Hydrology of Nepal: A Reconnaissance Study

Three of the major northern tributaries to the Ganges River system originate either in the Himalayan mountains of Nepal or on the Tibetan Plateau to the north - the Sapta Kosi River in Eastern Nepal, the Narayani (Gandaki) River in Central Nepal and the Karnali (Ghaghara) River in Western Nepal (Figure 9). While the potential for development of the water resources of these basins has been the topic of speculation for many years (Hagen 1980), and in spite of their considerable importance to the regime of the Ganges River (Rao 1984 and Sharma 1983), few scientific studies of the hydrology of these rivers have been undertaken.

The three major river basins of Nepal contain a total of over 40 hydrometric stations where streamflow measurements have been made for periods of up to 30 years. These basins represent approximately three-quarters of the total surface area of the northern headwaters' region of the Ganges River. As such, the hydrometric data from them are a valuable source of information concerning the role headwater tributaries play in the cycles of that river. Much emphasis is currently being placed on the development of the water resources of the country to meet the growing demands for domestic and agricultural water supplies and hydroelectric generation. Many of these projects have not been successful (Gyawali 1991).

The hydrometric data collected by the HMG's Department of Hydrology and Meteorology (DHM) are essentially unanalysed. While analysis of the existing databases cannot eliminate all uncertainties concerning the regimes of the rivers of Nepal, these data are a valuable source of information, and their use could help resolve many of the issues now associated with the hydrology of the Ganges basin and its tributaries.

The water resources of Nepal, and attempts to develop these resources in a sustainable manner, can be considered an analogue of problems and potentials characterising the entire Hindu Kush-Himalayan Region.

- The seasonal fluctuation in the volume of water and sediment flowing through the rivers of the Kingdom, in response to climatic and geomorphological controls, is great. The so-called "high-magnitude, low-frequency" events, such as flooding and drought, play a role in determining the development potential of these rivers which is perhaps greater than that of better-understood river systems.

- The problems of meeting the domestic water needs of growing urban populations often conflict with traditional and potential agricultural uses.

- The hydroelectric potential of the rivers is great, but the harnessing of this potential will require innovative engineering and environmental approaches.

It is a basic premise of this discussion that solutions to such problems may not be possible at the present time, given the lack of engineering and environmental principles for the extremes that characterise the Hindu Kush-Himalayan Region.

In the context of understanding the spatial and temporal distribution of the water resources of Nepal, the most salient characteristics of the country are the extreme local topographic relief, together with the marked changes this relief produces in the air masses traversing the country each year. This interaction between the mountain topography and the atmosphere produces a complex mosaic of hydrometeorological environments over the surface of the Kingdom, ranging from the hot, seasonally-wet middle mountains (Mahabarat Lekh and Siwaliks) and piedmont (*Terai*) to the snow and glaciers of the Great Himalayas and the Tibetan Plateau. It is from a better understanding of this diversity, resulting from the interaction between terrain and meteorology, that principles to guide water resources' development planning must be drawn.

Within this mosaic, water resources' development projects and problems exist along a wide range of spatial scales. These range from the needs of domestic water supply or irrigation of dry season crops, on the scale of individual villages and fields, to the flooding that periodically affects portions of the major rivers of the region.

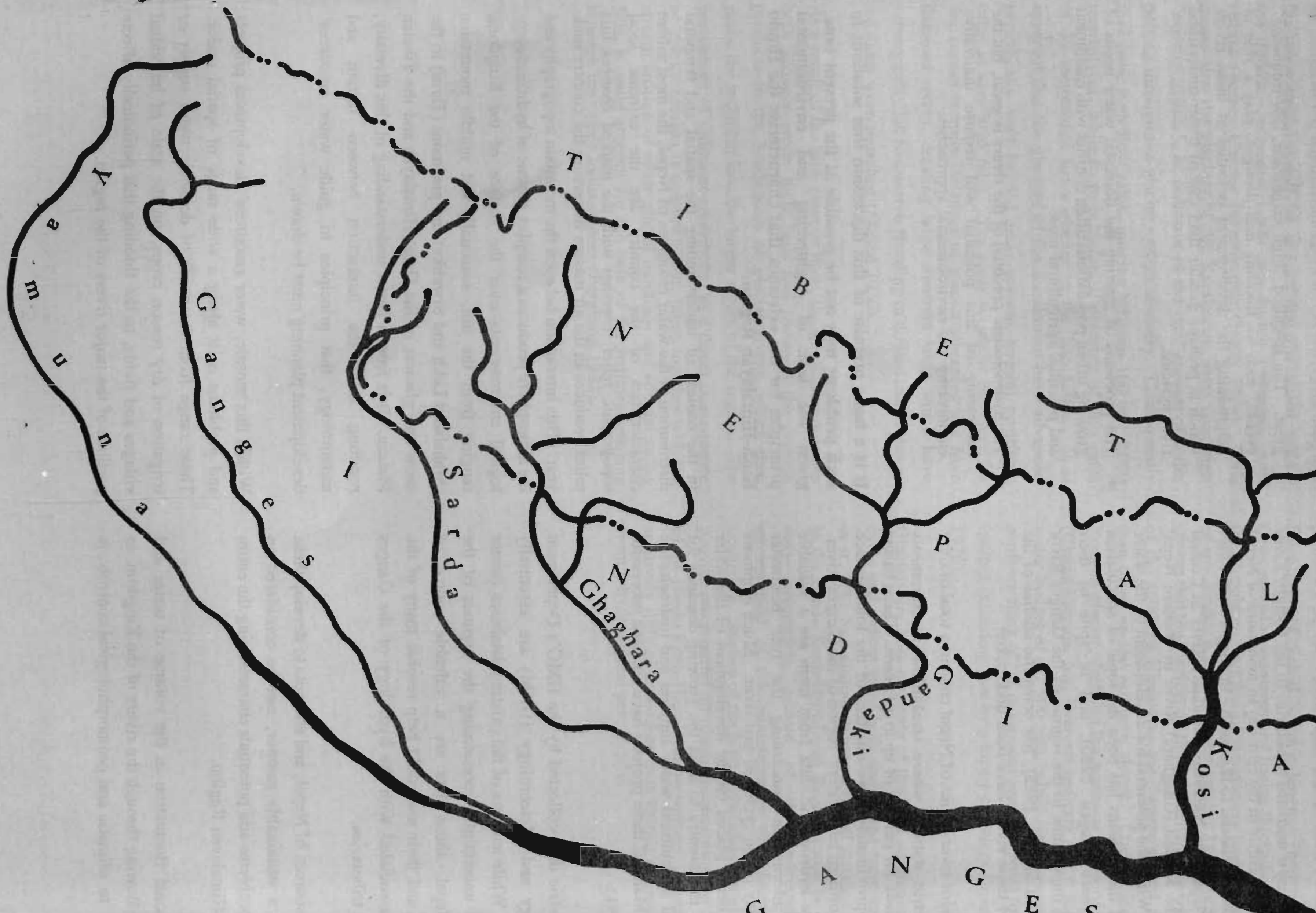


Figure 9: Three of the Major Tributaries to the Ganges River Originate in the Nepalese Himalayas: the Ghaghara (Karnali), the Gandaki (Narayani), and the Kosi

Problems associated with the water supplies of major population centres, such as the Kathmandu Valley, or the development of the hydroelectric potential of the rivers of the country fall within intermediate scales. Water is involved in virtually every facet of everyday life and resource development in the region. Wise use of the resource has the potential to improve the quality of life at all spatial scales, both in Nepal and in the broader region of which it is a part. At the same time, these rivers represent a great potential for destruction if they are improperly understood or managed.

There are at least three major types of river system (and thus, complex hydrometeorological environments) in Nepal.

- Those rivers with headwaters in the Mahabharat Lekh or Siwaliks, **south** of the main crest of the Great Himalayas. These include rivers such as the Bagmati River, which flows through the Kathmandu Valley, and the West Rapti River in the central portion of the Kingdom;

- Those rivers with headwaters **primarily** on the southern slopes of the Great Himalayas. These include rivers such as the Tamur and Dudh Kosi rivers in the Kosi system, the Trisuli and Marsyangdi rivers in the Narayani system, and the Bheri and Seti rivers in the Karnali system.

- Those rivers with headwaters **primarily** on the northern slopes of the Great Himalayas and on the Tibetan Plateau. These include rivers such as the Arun and Bhote Kosi in the Kosi system, the Kali Gandaki in the Narayani system, and the Karnali in the Karnali system.

Each of these three river types will present particular problems for management or development planning. Each should have a characteristic annual streamflow regime. Each should have a distinct relationship between streamflow and sediment transport.

Most of the large river systems in Nepal will present a differing combination of these three water resource environments. Based upon this hierarchy, development of methodologies for project design or management, and modelling or monitoring of water resources within the Hindu Kush-Himalayan Region, will be possible only if the relative contribution of each major source at the project site is known and the significance of that source determined. Each of the major water resource environments may be further sub-divided into changes in project scale, but the dominant elements - the varying importance of monsoon precipitation and snow- or ice-melt with geographic location, together with the strong control of topography on water resources' availability - will remain essentially constant.

This study is considered to be a reconnaissance analysis of the hydrological environment of the rivers of Nepal, in that it only begins to deal with the range of analyses possible for the existing databases. For the most part, values used are those for monthly or annual means. Only a portion of the total available data is considered. There has been no effort to analyse the hydrological data from catchment basins within the Siwalik or Middle Hills.

The Database

The data used in this study are standard streamflow and climatological measurements made by the Department of Irrigation, Hydrology, and Meteorology (DIHM) of HMG/Nepal (1976 and 1977 published and unpublished). They consist of mean monthly precipitation amounts and mean air temperature and evaporation measurements from climatological stations in Nepal, ranging in altitude from 90 masl to 3,857 masl. Streamflow measurements from 26 hydrometric stations in the region were analysed for this study. These basins ranged in size from 87 sq. km. to more than 25,000 sq. km.

Sketch maps showing the location of the gauged sub-basins for the three major river systems used in this study are shown in Figures 10, 11, and 12. The numbers in each sub-basin correspond to the numbering system of the Nepal Department of Hydrology and Meteorology, although only whole number values have been used. The names, numbers, topographic characteristics, and date of installation of stations are given in Table 5.

The availability of climatological data varies widely in the region. There is a total of approximately 350 climatological stations in Nepal, of which published data for 165 were obtained for this study. Of the 165, 30 stations (18%) are located between 2,000 and 3,000 metres and 17 stations (10%) between 3,000 and 4,000 metres. The remainder (72%) are all below 2,000 m, generally concentrated within the Siwalik, the Mahabharat Lekh, the Middle Hills, and along the valley floors of the major rivers.

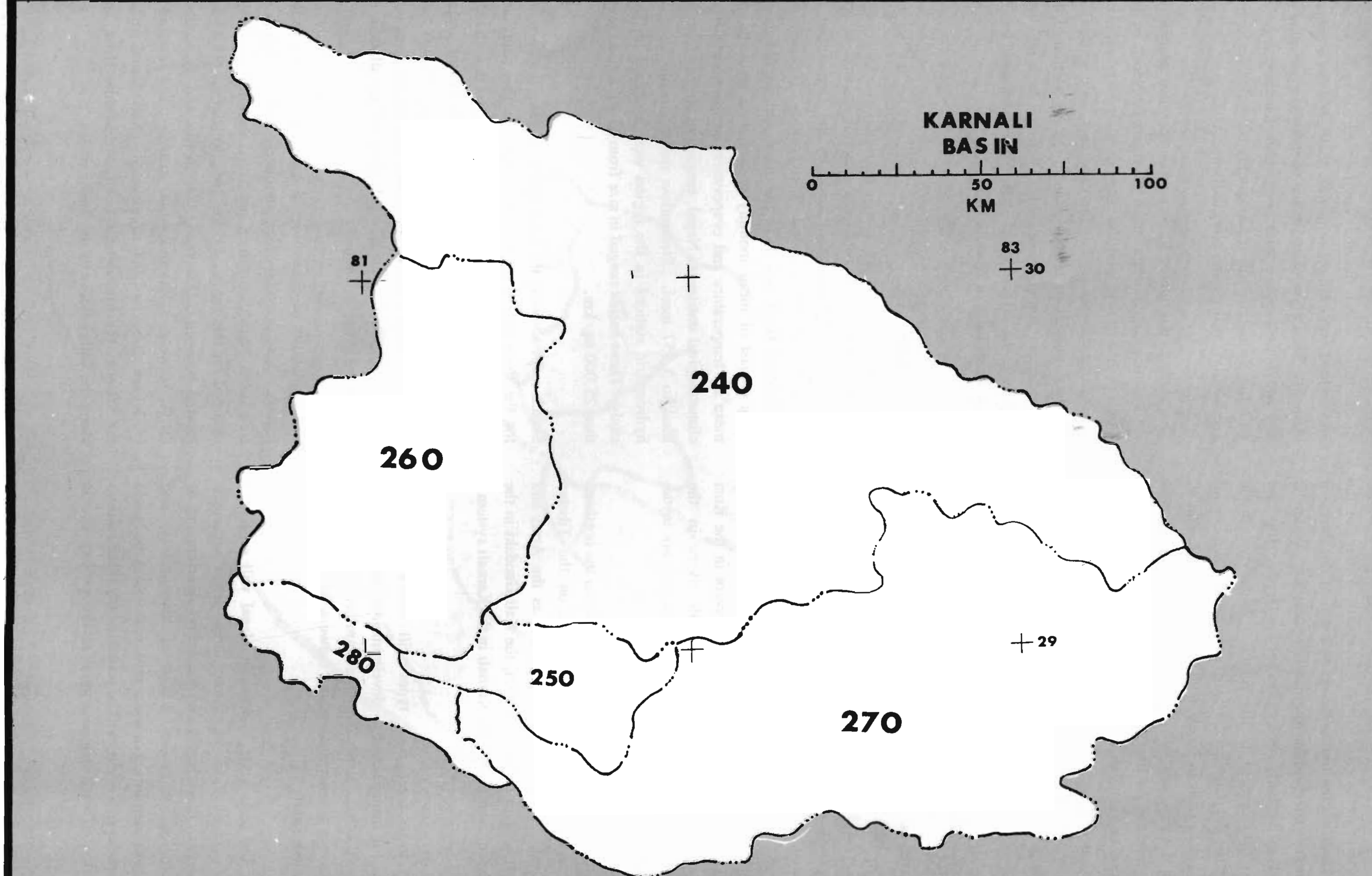


Figure 10: Gauged Sub-basins of the Karnali River for which Data Were Used in This Study

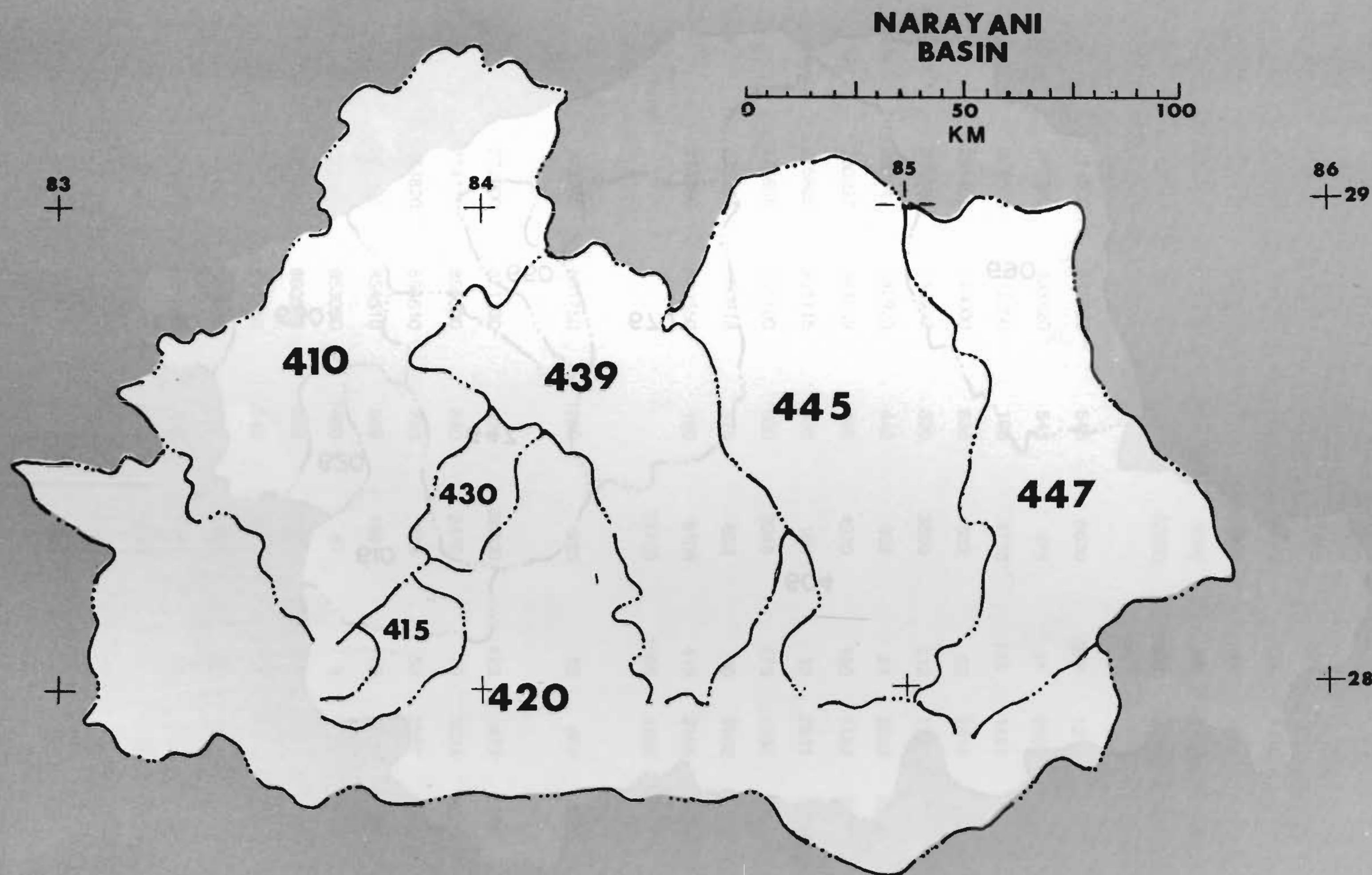


Figure 11: Gauged Sub-basins of the Narayani River for which Data Were Used in This Study

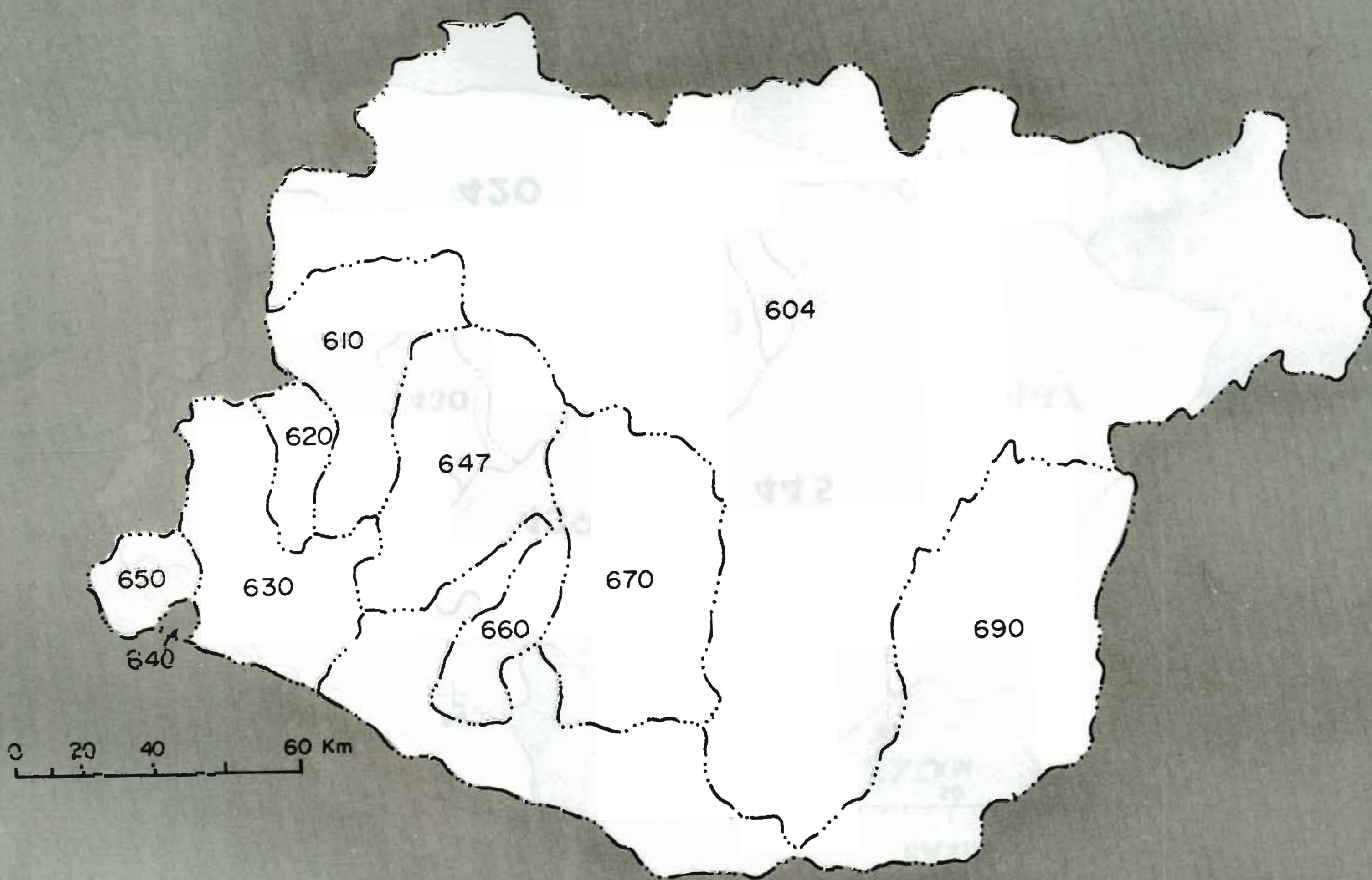


Figure 12: Gauged Sub-basins of the Sapta Kosi River for which Data Were Used in This Study

Table 5: Selected Hydrometric Stations of Nepal

STN. NO.	RIVER	LAT °N*	LONG °E*	GAGE ELEV.	AREA sq.km.	Qv m³/s	Qs mm	AVG	RECORDING DATE
170	Surnagad	292730	803310	1110	188	7	1174	1900	Jan 66
240	Karnali	285710	812630	629	19260	505	827	5200	Jan 61
250	Karnali	285740	810710	320	1980	119	1895	2200	Jan 63
260	Seti	285840	810840	328	7460	302	1277	3200	Feb 63
270	Bheri	284520	812100	246	12290	435	1116	4400	Jan 63
280	Karnali	283840	811730	191	1900	49	813	1500	Jan 62
290	Babai	282520	812210	192	3000	88	925	600	Jul 66
	Total				42890	1498	1101		
410	Kali Gandaki	274500	842050	546	6630	267	1270	4200	Apr 64
415	Andhi Khola	275820	833520	543	476	31	2054	1000	Feb 64
420	Kali Gandaki	274500	842050	198	4770	175	1157	3200	Apr 64
430	Seti	281400	840000	830	582	52	2818	1000	Jan 64
439	Marsyangdi	275535	842942	320	3850	212	1737	4200	Jun 73
440	Chepe Khola	280341	842923	442	308	24	2523	2800	Nov 63
445	Burhi Gandaki	280237	844859	485	4270	160	1182	5400	Nov 63
446	Phalankhu Khola	275825	851115	630	162	13	2531	2000	Apr 69
447	Trisuli	275808	851100	600	3948	173	1382	5200	Apr 67
448	Tadi Khola	275135	850818	475	653	40	1932	2100	Jun 68
450	Narayani	274230	842550	180	6104	419	2165	1000	Feb 62
	Total				31753	1566	1555		
550	Bagmati	273940	851750	1280	585	16	863	1600	Jul 62
604	Arun	272000	871130	414	28200	423	473	6000	May 75
610	Bhote Kosi	274710	855320	840	2410	79	1034	5200	Feb 65
620	Balephi Khola	274820	854610	793	629	53	2657	3000	Dec 63
630	Sun Kosi	273330	854510	589	1881	119	1995	NC	Mar 64
640	Rosi Khola	273450	853050	1480	87	3	1087	1200	Oct 63
647	Tama Kosi	273805	860512	849	2753	145	1661	4900	Jan 70
660	Likhu Khola	272010	861310	543	823	57	2184	3500	Mar 64
670	Dudh Kosi	271600	863950	460	4100	223	1715	4400	Mar 64
680	Sun Kosi	265230	864920	200	4917	89	552	NC	Jun 65
690	Tamur	265550	871945	276	5640	336	1879	2600	Mar 65
	Total				51440	1527	936		
	Grand Total				126083	4591	1148		

Source: HMG, Department of Irrigation, Hydrology, and Meteorology (Published and Unpublished 1976 and 1977)

Note: * In the case of both latitude and longitude, the first two digits indicate degrees, the middle two digits indicate minutes, and the last two digits indicate seconds.

Western and north central Nepal are represented by the least number of climatological stations. The analysis of climatological trends in the Central Himalayas presented here is based upon a random sample of 114 of these stations (Table 6).

Table 6: Selected Climatological Stations and Mean Annual Precipitation - Nepal

1. The Sapta Kosi Basin

NO.	NAME	LAT° °N	LONG° °E	ALT (m)	ANNUAL PPT
Bagmati Zone					
1009	Chautara	2747	8543	1660	2007
1011	Kathmandu	2742	8520	1335	1280
1012	Sundarijal	2745	8225	1380	1899
1013	Sundarijal	2746	8525	1576	2057
1014	Kathmandu	2743	8519	1324	1361
1020	Mandan	2741	8539	1370	1737
1021	Kirtipur	2741	8518	1364	1011
1023	Dolal Ghat	2738	8543	710	934
1024	Dhulikhel	2737	8533	1552	1397
1027	Barhabise	2747	8554	1220	2549
1028	Pachuwar	2734	8545	633	795
Janakpur Zone					
1102	Charikot	2740	8603	1940	2160
1103	Jiri	2738	8614	2003	2381
1104	Melung	2731	8603	1536	1827
1106	Ramechhap	2719	8605	1395	1016
1107	Sindhuli	2717	8558	1463	2547
1108	Bahun Tilpung	2711	8610	1417	2189
1109	Pattharkot	2705	8540	275	1954
1110	Tulsi	2702	8555	457	1713
1112	Chisapani	2655	8610	165	1577
1115	Nepalthok	2727	8549	1098	936
1116	Hariharpur	2720	8530	880	2683
Sagarmatha Zone					
1201	Namche Bazar	2749	8643	3450	1007
1202	Chaurikhark	2742	8643	2619	2123
1203	Pakarnas	2726	8634	1982	1769
1204	Aisyalukhark	2721	8645	2143	2604
1206	Okhaldunga	2719	8630	1810	1821
1208	Dwarpa	2713	8651	1829	1494
1209	Bhojpur	2711	8703	1524	1202
1210	Kurule Ghat	2708	8625	497	983
1211	Khotang	2702	8650	1295	1089
1213	Udayapur	2656	8631	1175	1978
1215	Lahan	2644	8030	138	1541
1216	Siraha	2639	8613	102	1234
1218	Tengboche	2750	8646	3857	979
1220	Chialsa	2731	8637	2770	1828
1224	Sirwa	2733	8623	1707	582
Kosi Zone					
1301	Num	2733	8717	1497	3079
1303	Chainpur	2717	8720	1329	1350
1305	Leguna Ghat	2708	8717	1680	672
1206	Munga	2702	8714	1317	1288
1307	Dhankuta	2659	8721	1445	912
1308	Mul Ghat	2656	8720	365	1060
1309	Tribeni	2656	8709	143	1851
1312	Haraincha	2637	8723	152	1508
1316	Chatara	2649	8710	183	2177
1317	Chepuwa	2746	8725	2590	2438
1322	Machuwa Ghat	2658	8710	158	1504
Mechi Zone					
1401	Olangchung	2741	8747	3119	1697
1402	Pangthung	2741	8749	2818	1562
1403	Lungthung	2733	8747	1780	2331
1404	Tapelthok	2729	8747	1383	2484
1405	Taplejung	2721	8740	1763	2015
1406	Memeng Jagat	2712	8756	1830	2251
1407	Ilam Tea Est.	2655	8754	1300	1575
1408	Damak	2643	8740	163	2589
1409	Arnamani	2638	8759	122	2242
1418	Angbung	2716	8745	1205	1582
1420	Dovan	2721	8736	1764	1612

2. The Narayani Basin

NO.	NAME	LAT °N	LONG °E	ALT (m)	ANNUAL PPT
0601	Jomson	2847	8343	2744	263
0609	Beni Bazaar	2821	8334	835	1187
0611	Dunai	2856	8250	2058	974

NO.	NAME	LAT* °N	LONG* °E	ALT (m)	ANNUAL PPT
0701	Ridi Bazar	2757	8326	442	1269
0702	Tansen	2752	8333	1343	1528
0703	Butwal	2742	8328	205	2510
0704	Beluwa	2741	8403	150	2536
0722	Musikot	2810	8316	1280	1281
0801	Jagat Setibas	2820	8454	1334	1200
0802	Khudi Bazar	2817	8422	823	3204
0803	Pokhara	2814	8400	866	3483
0807	Kunchha	2808	8421	997	2207
0808	Bandipur	2756	8425	1112	1935
0809	Gorkha	2800	8437	1097	1598
0902	Rampur	2737	8425	256	1693
0903	Jhawani	2735	8432	270	1786
0904	Chisapani	2733	8508	1706	2167
0905	Daman	2736	8505	2314	1466
0907	Amlekhganj	2718	8500	359	2186
0910	Nijgadh	2717	8510	244	2075
0911	Parwanipur	2704	8458	115	1150
1003	Trisuli	2755	8509	595	1968

3. The Karnali Basin

NO.	NAME	LAT °N	LONG °E	ALT (m)	ANNUAL PPT
Seti Zone					
0201	Pipalkot	2973	8052	1455	2354
0202	Chainpur	2933	8113	1304	1538
0203	Silgadhi Doti	2916	8059	1360	1127
0205	Katai	2900	8101	1388	2061
0206	Asara Ghat	2857	8127	650	1161
0208	Sandepani	2845	8055	195	1838
0209	Dhangadhi	2841	8036	170	1612
0210	Beni Ghat	2858	8107	340	1390
Karnali Zone					
0301	Mugu	2945	8233	3803	1010
0302	Thibru	2919	8146	1030	414
0303	Jumla	2918	8212	2424	665
0305	Sheri Ghat	2908	8136	1210	1473
0309	Bijayapur	2914	8138	1823	937
Bheri Zone					
0401	Pusma Camp	2853	8115	950	1660
0402	Dailekh	2851	8143	1402	1580
0404	Jajarkot	2842	8212	1220	1711
NO.	**NAME**	**LAT* °N**	**LONG* °E**	**ALT (m)**	**ANNUAL PPT**
0405	Chisapani	2839	8116	225	2142
0405	Chisapani	2839	8116	225	2142
0406	Surkhet	2836	8137	720	2402
0408	Gulariya	2810	8121	215	1184
0410	Bale Budha	2847	8135	610	906
Rapti Zone					
0501	Rukumkot	2836	8238	1560	3095
0502	Shera Gaun	2835	8249	2150	1339
0504	Libang Gaun	2818	8238	1270	1565
0505	Bijuwar Tar	2806	8252	823	1169
0511	Salyan Bazaar	2823	8210	1457	899

Source: HMG, Department of Irrigation, Hydrology, and Meteorology (Published and Unpublished 1976 and 1977)

Note: * In case of both latitude and longitude, the first two digits indicate degrees and the last two digits indicate minutes.

Topographic information is primarily from Operational Navigational Chart ONC H-9, Edition 8, 1:1,000,000, prepared and published by the Defense Mapping Agency Aerospace Centre, St. Louis, Missouri, USA. Topographic data used in this study are area-altitude relationships, obtained by planimetry of the ONC H-9 map.

Analytical Procedures

Based upon the available data, spatial and temporal variation in streamflow volume, within and among the sub-basins of Nepal, were determined. These analyses are based upon a comparison of monthly and annual mean values of streamflow volume, in m^3/s, and specific runoff, in mm.

As a first approximation, to compare input (as precipitation) with output (as streamflow or evaporation), streamflow volumes were converted to specific terms, mm/A/t;

$$Qs = \frac{(Qv \times t)}{A} \qquad (1)$$

where:

Qs = specific discharge, in mm for time, t;
Qv = measured discharge, in m^3/s; and
A = area of gauged watershed, m^2.

Time, t, may be set equal arbitrarily to any period of interest for which data are available. Here, monthly and annual values for Qs have been derived.

The majority of gauged sub-basins in Nepal have only one stream-gauge and do not receive runoff from upstream, gauged sub-basins. This is not uniformly the case, however. In those cases where more than a single gauging station exist within a single sub-basin, the discharge measurements have been corrected by subtracting the upstream values of streamflow and surface area from those of the downstream site. In this way, the data discussed here represent values of discharge and surface area for the portion of the sub-basin located between two adjacent gauges. If this correction is not applied, the basic streamflow measurements, while useful for many engineering design purposes, cannot be used for hydrological modelling.

Topographic information was obtained by planimetry of the 1:1,000,000 scale ONC map. The total surface area of each sub-basin was determined, together with the surface area between: 1) the stream-gauge and 1,000 m, 2) between 1,000 and 3,000 m, 3) between 3,000 and 5,000 m, and 4) above 5,000 m were determined by planimetry (Table 7). Based upon these data, hypsometric curves for the entire basin, as well as each gauged sub-basin, were prepared, and the mean basin altitude was determined by inspection.

Table 7: Area-altitude Relationships in the Sub-basins of Nepal

RIVER	BASIN	ABOVE 5000	3000 5000	1000 3000	TOTAL	DHM		ALT MAX	ALT MIN	ALT AVG
Surnagad	170	0	0	200	200	188	%	2650	1110	1900
Karnali	240	10420	7380	1460	19260	19260	1.00	6700	629	5200
Karnali	250	0	0	2000	2000	1980	0.99	4150	320	2200
Seti	260	1200	2620	3640	7460	7460	1.00	7000	328	3200
Bheri	270	3400	7450	1440	12290	12290	1.00	7600	246	4400
Karnali	280	0	0	1900	1900	1900	1.00	2800	191	1500
	Sum	15020	17450	10440	42910	42890	1.00	-	-	-
Rapti	360	0	0	5150	5150	5150	1.00	3560	218	-
Kali Gandaki	410	1395	2650	2600	6645	6630	1.00	8125	546	4200
Andhi Khola	415	0	0	500	500	476	0.95	2500	543	1000
Kali Gandaki	420	0	50	4250	4300	4770	1.11	4015	198	1000
Seti Khola	430	55	160	375	590	582	0.99	7880	830	3000
Marsyangdi	439	355	1120	2375	3850	3850	1.00	7880	320	4100
Chepe Khola	440	70	80	200	350	308	0.88	7850	442	2700
Burhi Gandaki	445	2180	1125	975	4280	4270	1.00	8100	485	5300
Phalankhu Khola	446	0	30	130	160	162	1.01	3500	630	2100
Trisuli	447	2450	1240	420	4110	3948	0.96	7300	600	5400
Tadi Khola	448	0	150	500	650	653	1.00	5000	475	2100
	Sum	6505	6605	12325	25435	25649	1.01	-	-	-
Bagmati	550	0	0	585	585	585	1.00	2715	1280	1600
Arun	604	26000	1200	2400	29600	28200	0.95	8500	414	6000
Bhote Kosi	610	1330	470	300	2000	2410	1.21	8000	840	5200
Balephi Khola	620	120	194	271	585	629	1.08	8000	840	3600
Sun Kosi	630	140	460	1500	2400	1881	0.78	7000	589	-
Tama Kosi	647	1400	800	600	2900	2753	0.95	7300	849	4900
Dudh Kosi	670	1500	750	1200	3450	4100	1.19	8850	460	4400
Likhu Khola	660	280	150	370	800	823	1.03	6950	543	3500
Tamur	690	1200	1050	3400	5650	5640	1.00	8590	276	-
Rosi Khola	640	0	0	87	87	87	1.00	-	1480	-
	Sum	31970	5074	10128	47472	-	-	-	-	-
	Minus Arun	5970	3874	7728	17872	-	-	-	-	-
	Grand Total	63480	30250	32780	119480	-	-	-	-	-

The relationship between specific runoff and streamflow developed for this study considers the total surface area of a sub-basin to be concentrated at the mean altitude of the basin, with the discharge from that sub-basin representing a mean value from an altitudinal belt centered on this altitude. Based upon this assumption, the streamflow volume for any sub-basin within each river system can be described by summing the calculated runoff from the altitudinal belts found within the sub-basin.

A catchment basin can be sub-divided into a series of altitudinal belts by adjacent contour lines, Z_1, Z_2,....Z_n, with surface areas A_1, A_2, ... A_n (Figure 13).

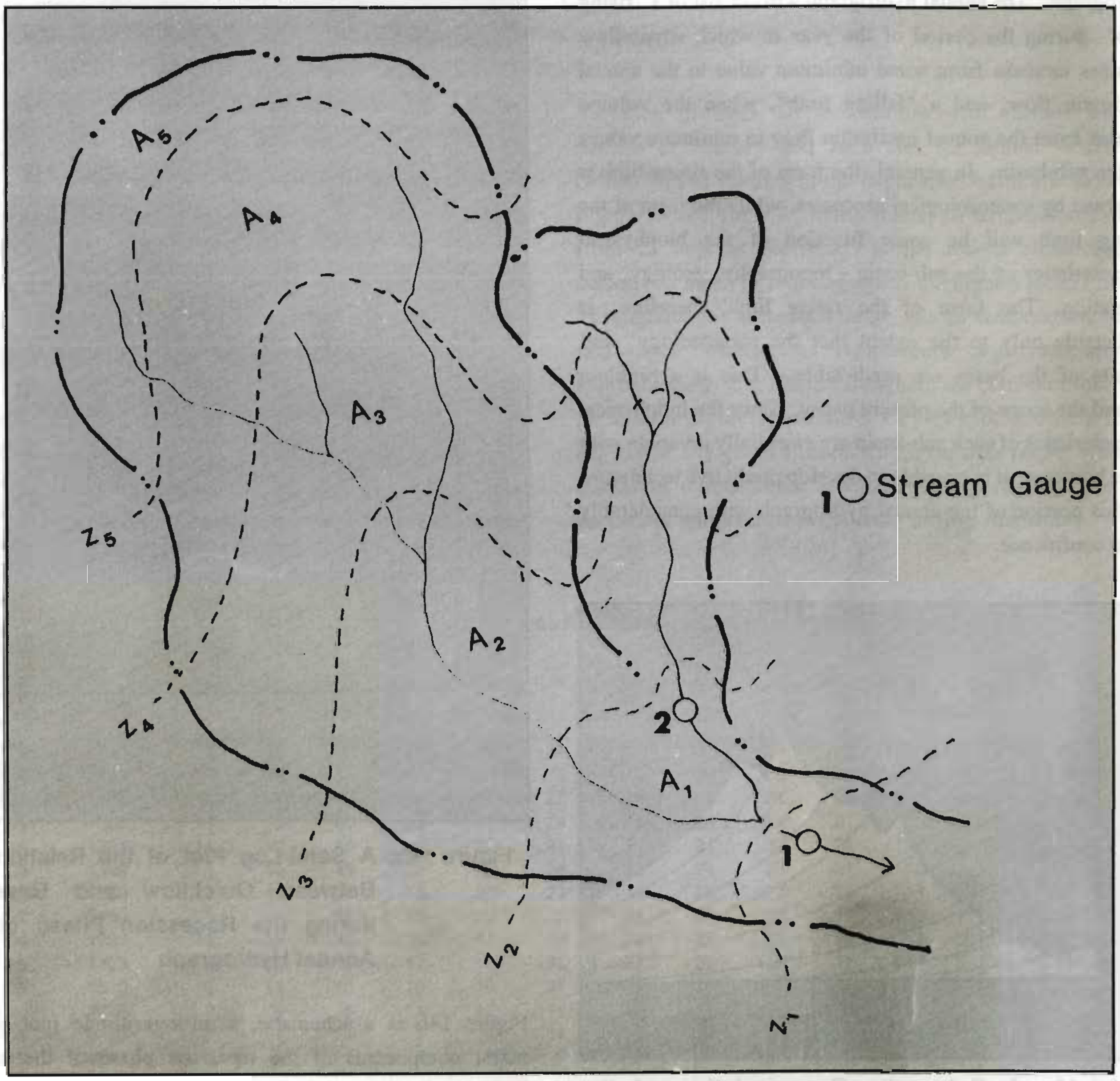


Figure 13: A Schematic Representation of the Altitudinal Zonation Used in this Study to Derive Incremental Volumes of Streamflow

The mean altitude of an altitudinal belt is:

$$Z_{mean} = \frac{(Z_t - Z_1)}{Z + Z_1} \qquad (2)$$

The area, A, within this belt was determined by planimetry and by interpolation of hypsometric curves.

The mean value of specific runoff, Q_s, for each altitudinal belt was determined by inspection of the relationship of specific runoff and mean sub-basin altitude characterising the region as a whole. The total volume of streamflow, Qv_{calc}, from a basin is the sum of the products of the specific runoff, Q_s, and surface area, A, within each altitudinal belt:

$$Qv_{calc} = Qs_1A_1 + Qs_2A_2 + \ldots\ldots\ Qs_nA_n \quad (3)$$

For gauged sub-basins, Qv_{calc} should equal Qv_{meas}, if the model duplicates accurately altitudinal variations in values of Qs within the sub-basin. Forecasting future streamflow volume is a major problem for hydrology. This is largely a problem in predicting the future form of the annual hydrograph. The annual hydrograph will consist of a "rising limb", during the period of the year in which streamflow volumes increase from some minimum value to the annual maximum flow, and a "falling limb", when the volume recedes from the annual maximum flow to minimum values for the sub-basin. In general, the form of the rising limb is governed by meteorological processes, while the form of the falling limb will be some function of the biophysical characteristics of the sub-basin - topography, geology, and vegetation. The form of the rising limb, therefore, is predictable only to the extent that the meteorology and climate of the basin are predictable. This is a problem beyond the scope of the present paper. Since the biophysical characteristics of each sub-basin are essentially invariate with time, however, it is possible to develop predictive techniques for this portion of the annual hydrograph with considerably more confidence.

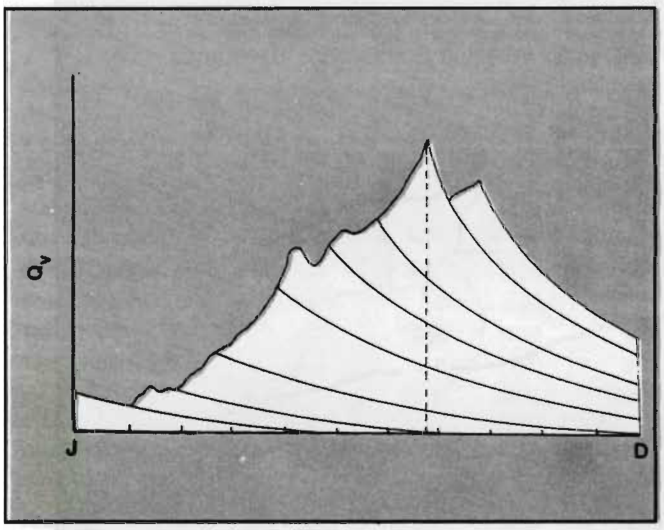


Figure 14a: A Schematic Representation of the Annual Hydrograph, Showing the Composition of the Rising and Falling Limbs

Note: The broken line marks the peak annual flow.

The major components of the annual hydrograph are shown schematically in Figures 14a and 14b. In Figure 14a, the general form of the annual hydrograph is illustrated. During the period of the rising limb, each significant increase in streamflow will immediately begin to recede at the rate characteristic of the individual sub-basin. Therefore, at any time following the onset of increasing streamflow, the volume of water flow past a point in the sub-basin will be composed of a series of runoff events, such as an individual storm or period of snowmelt, each of which is receding at a rate determined by the maximum volume produced by the event and the recession curve of the sub-basin.

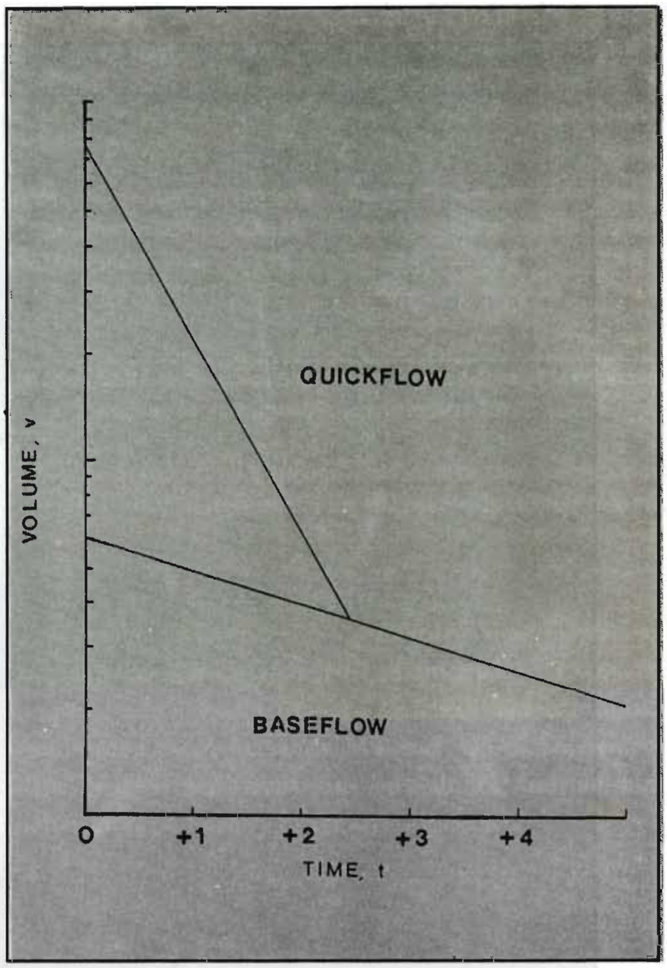


Figure 14b: A Semi-Log Plot of the Relationship Between Quickflow and Baseflow during the Recession Phase of the Annual Hydrograph

Figure 14b is a schematic, semi-logarithmic plot of the major components of the recession phase of the annual hydrograph. "Quickflow" is the component of flow composed of surface and near-surface runoff, while "baseflow" is the groundwater component. At any given moment, the hydrograph will be composed of water from a number of discrete runoff events, each receding as either quickflow or baseflow. It is only with the cessation of input from the monsoon and from snowmelt, in the autumn of each year, that a pure recession phase begins. Ultimately, the flow from a sub-basin is composed exclusively of groundwater - baseflow - lasting until the onset of the subsequent cycle of monsoon and snowmelt.

Each sub-basin will be unique with respect to the rate at which streamflow recedes from seasonal maximum values - the "recession curve" (Riggs 1963 and Riggs and Hanson 1969). The slope of the recession curve is assumed to be constant for each basin, determined by the relative contributions from surface runoff ("quickflow") and groundwater storage ("baseflow"), as they vary during the course of the year. In terms of the current understanding of Himalayan hydrology, recession curve analyses represent a method to: 1) assess semi-quantitatively the postulated impacts of various land use practices (e.g., deforestation or afforestation) on the hydrologic regime of a sub-basin by monitoring variations in the slope of the recession curve with time; and 2) develop short-term (90-180 day) forecasts of water availability during the recession phase of the annual hydrograph.

Results

The results obtained from this analysis of the hydrometeorological databases for Nepal are based upon only a portion of the total of such data available. The results are presented here largely in graphical and tabular forms. Only the most salient conclusions are drawn. It is felt that these results describe accurately the major features of the Nepal water environments, but only an analysis of all available data will provide a complete picture of these environments.

Climate

Air Temperature

Variation of mean air temperature with altitude for the months of January and June and for annual values for climatological stations in the Sapta Kosi basin are shown in Figure 15 and Table 8. Mean annual air temperatures range from 25 degrees centigrade at the lowest climatological station (90 masl) to four degrees at the highest (3,857 masl). Throughout this altitudinal range, the air temperature "lapse rate" (the change in temperature with altitude) is approximately -0.5/100 m throughout the course of the year. Mean monthly air temperatures vary by approximately 10-15 degrees at any given altitude within the data range, with the minimum temperatures recorded during January and the maximum temperatures occurring during June-July.

Table 8: Mean Monthly and Annual Air Temperatures for Eastern Nepal

STATION	ALT (m)	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
1111	90	15	17	23	27	29	29	27	28	27	26	20	16	24
1114	93	17	19	23	27	29	29	29	29	28	27	22	17	25
1003	457	15	17	20	25	27	27	26	26	24	22	20	15	22
1004	1003	14	15	20	23	24	24	24	24	23	21	18	14	21
1014	1324	11	12	16	20	22	24	24	24	23	21	16	11	18
1303	1329	14	15	19	22	23	24	24	24	23	21	18	14	20
1029	1350	10	11	15	18	20	23	24	23	22	18	14	10	17
1022	1400	9	11	15	18	20	21	21	21	19	17	13	9	16
1404	1732	13	14	18	20	21	23	23	23	22	20	17	14	19
1405	1763	9	10	15	17	18	21	21	21	19	17	13	10	18
1206	1810	9	11	16	19	19	21	21	20	19	17	14	12	16
1220	2770	2	4	8	11	12	14	15	15	14	11	7	4	10
1201	3450	-1	1	4	7	9	11	12	12	11	8	5	0	6
1218	3857	-3	-3	1	4	6	9	9	9	7	5	1	-1	4

Source: Department of Irrigation, Hydrology, and Meteorology (DIHM) 1976

There is some suggestion that a "thermal belt" (Geiger 1966) exists between 1,000 and 2,000 metres. Thermal belts, characterised by increased cloudiness, increased precipitation, and a longer growing season, are a climatological feature of many mountain regions. An interesting climatological problem for future study is the apparent altitudinal relationship between the apparent thermal belt and the zone of maximum precipitation and runoff indicated by this study.

During the winter months, freezing temperatures extend downwards to below 2,500 m, with snowfalls, while summer temperatures may exceed 10 degrees at 4,000 m. Frost action probably operates throughout this altitudinal range, with several months of freeze-thaw conditions at 2,000 m, two separate periods between 2,000 and 4,000 m (spring and autumn), above which a summer phase dwindles from approximately six months at 4,000 m to zero at 6,000-7,000 m.

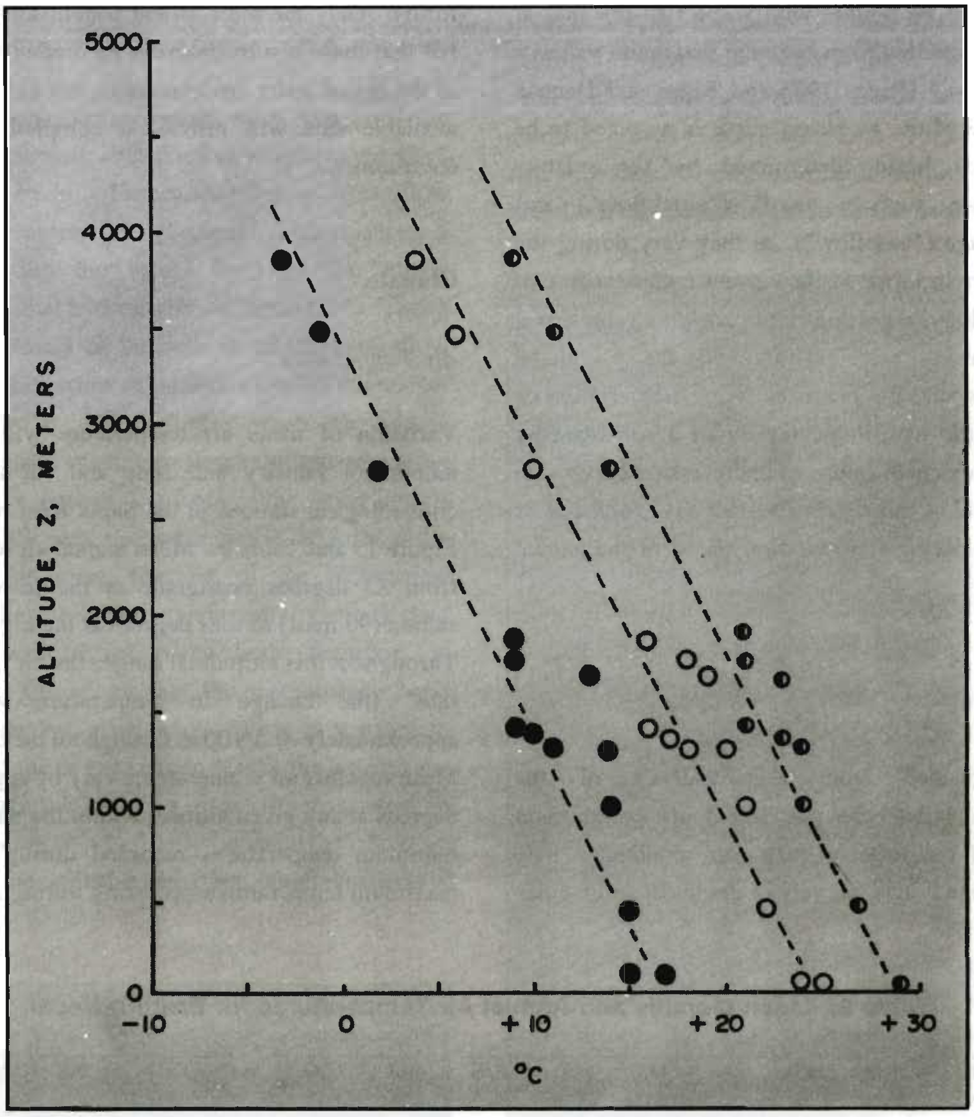


Figure 15: The Relationship between Annual and Seasonal Air Temperatures and Altitude

Note: The Lapse Rate is 0.5 C/100 metres.

Precipitation

Measured values of mean annual precipitation in Nepal range from a low of approximately 250 mm at stations north of the Great Himalayas to numerous stations exceeding 3,000 mm. The mean annual precipitation for 114 stations considered in this study is 1,627 mm. Sixty-seven of these stations are located in the Sapta Kosi basin, 22 in the Narayani basin, and 25 in the Karnali basin (Table 6).

There is relatively limited precipitation during the months from November to February throughout the region, with approximately 80 per cent of the annual total falling during the months from June to September at virtually all stations. Much of the precipitation occurs as a series of intense, localised storms, with the bulk of the total annual precipitation occurring during 30 to 40 storm events, each of which results in between 25 to 100 mm of precipitation.

The longest period-of-record for precipitation in the region is from Kathmandu, where record keeping began in 1921. The mean annual precipitation for this period is slightly above 1,300 mm, with individual annual totals ranging between 1,000 and 2,000 mm. A preliminary time-series analysis, based upon five-year running means, shows a cyclic pattern of high and low years, with the decades of the 1940s and 1970s being characterised by higher-than-average precipitation, and the 1950s and 1960s by average or slightly-below-average values (Figure 16).

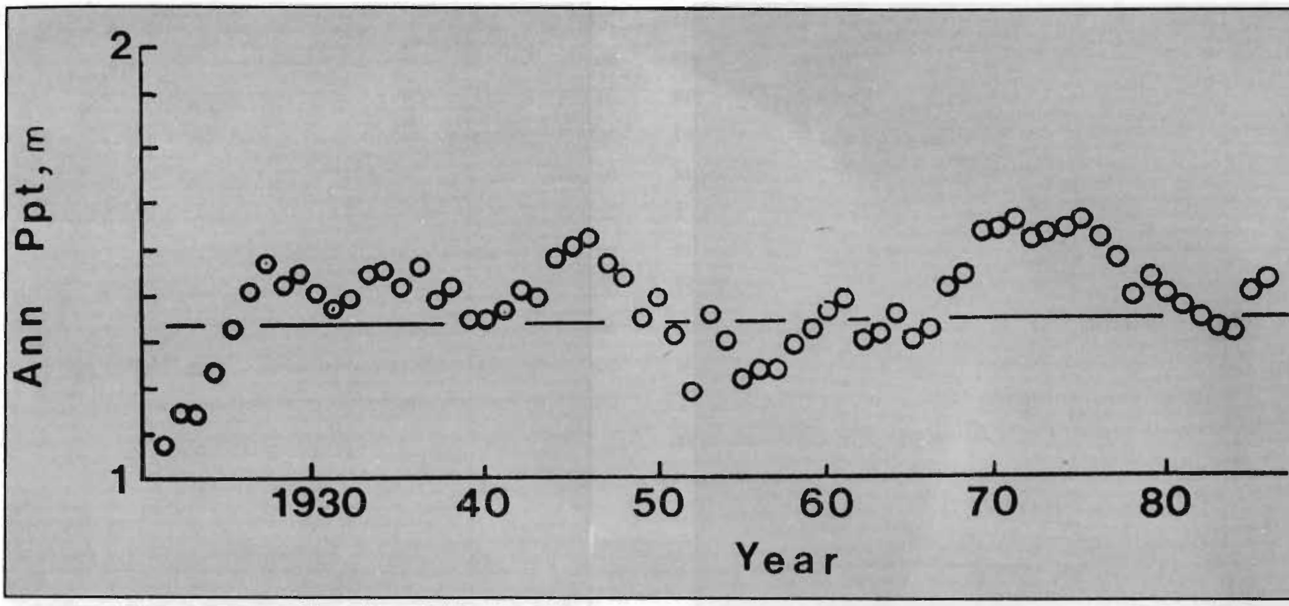


Figure 16: A Five-year Running Mean of Precipitation in Kathmandu for the Period 1921-1985

There is no clear altitudinal trend of precipitation as there is with air temperature. The relationship of precipitation and altitude in the three major river basins is shown in Figures 17,18, and 19. The data are enclosed by an envelope having no statistical significance. While there is a suggestion that maximum values occur at low to intermediate altitudes, for any given altitudinal interval there is a great deal of scatter, presumably associated with measurement errors and the existence of local topoclimates. Recent studies (Guan and Chen 1981, Higuchi et al. 1976, Yasunari 1976, and Grabs 1989) indicate that precipitation at high altitudes in the Himalayas could be greater than is indicated by these data.

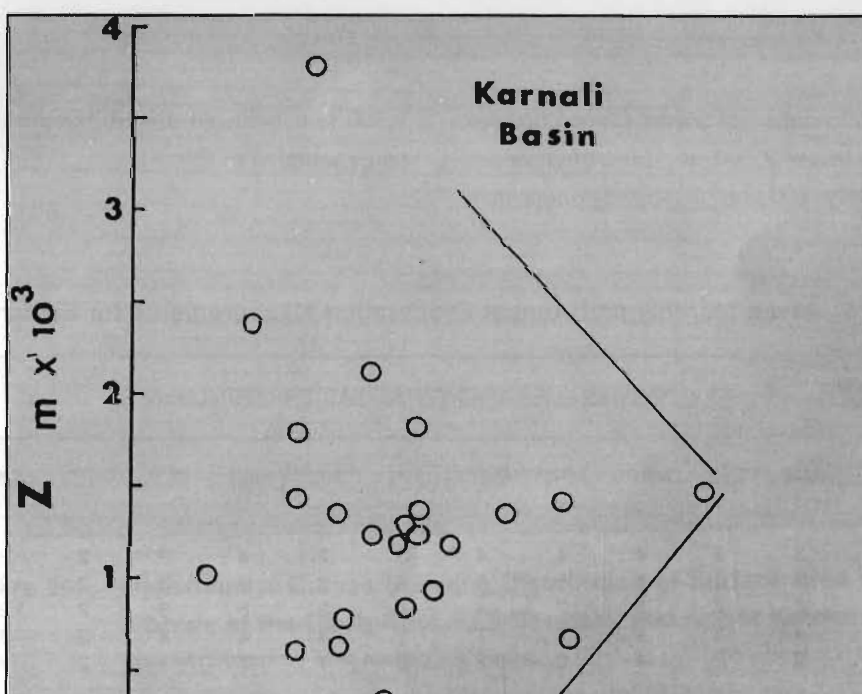


Figure 17: The Distribution of Precipitation with Altitude in the Karnali Basin Shows No Distinct Orographic Trend

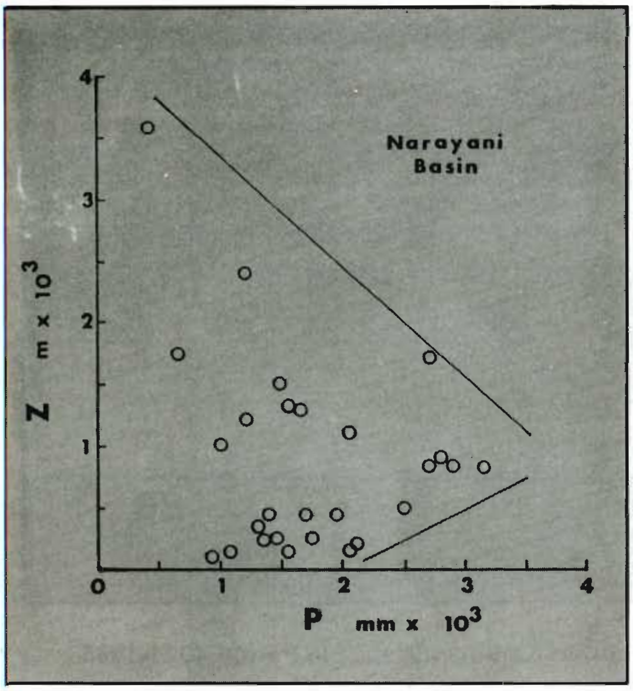


Figure 18: There is Some Suggestion of An Orographic Gradient of Precipitation in the Narayani Basin, Represented by the Formline

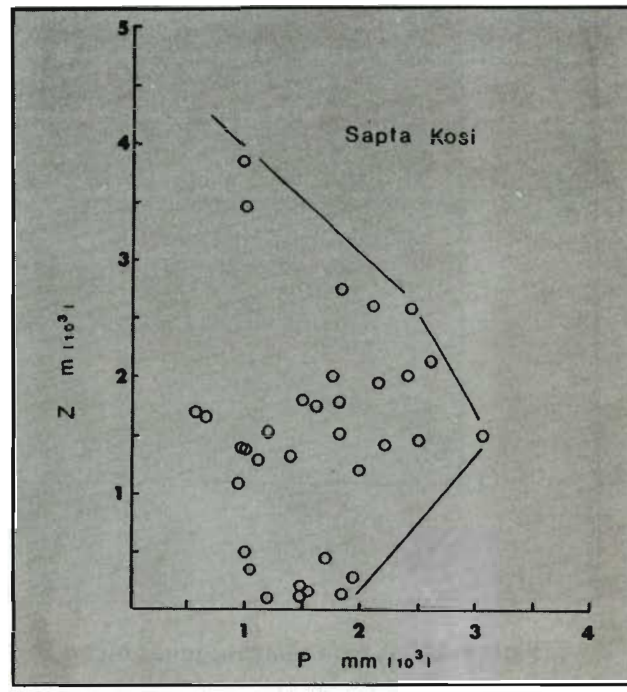


Figure 19: While There is Considerable Scatter, Maximum Values of Precipitation in the Sapta Kosi Basin Occur between 1,500-2,500 m, while Minimum Values are Recorded at the Highest and Lowest Altitudes for which Data are Available

Evaporation

A limited number of measurements of annual evaporation are available from altitudes below 2,000 m. Measured values range from approximately 800 mm to slightly more than 1,300 mm, with no discernible altitudinal trend within the range sampled (Table 9).

Table 9: Mean Monthly and Annual Evaporation Measurements for Eastern Nepal

EVAPORATION MEASUREMENTS -- EASTERN NEPAL(mm/d)

STATION	ALTITUDE	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
1007	2064	2	3	4	4	4	3	2	4	3	2	3	2	1043
1029	1350	2	3	4	5	5	4	3	4	3	2	2	1	1165
1206	1720	2	2	5	7	4	4	3	3	3	2	2	2	1186
1320	200	1	3	4	7	7	5	4	4	4	3	3	2	1363
1324	1595	2	2	4	6	2	2	1	1	1	2	2	2	803

Source: Department of Irrigation, Hydrology, and Meteorology 1976

Topography

A crucial factor in evaluating the hydrometeorological data bases for Nepal is the great disparity that exists between the range of terrain altitudes present and the altitudes at which climatological and hydrological data are obtained. Planimetry of the best-available maps suggests that the mean altitude of Nepal can exceed 3,000 m, while the mean altitude of the hydrometric stations in the region is approximately 700 masl and that of the climatological stations is slightly above 1,200m. A primary problem involved in analyses of the water budgets of both gauged and ungauged basins in the Nepal Himalayas stems more from a lack of reliable topographic maps of Nepal than from a lack of hydrometric information. Values for the mean altitude of the sub-basins used in this study, based upon planimetry of the 1:1,000,000 ONC map, are considered to be first approximations. There is no way to determine the absolute accuracy of these surface areas, but it is assumed that any errors are constant, related to the scale of the map used (Table 7).

Hypsometric curves, illustrating the relative distribution of surface area with altitude for selected sub-basins in Nepal, are shown in Figure 20. The average altitude of each sub-basin corresponds to that altitude above and below which surface area is equally distributed. The major point that Figure 19 illustrates is the non-uniform distribution of surface area with altitude in the sub-basins of the Nepal Himalayas. While altitude above sea level is obviously a major component of any model of streamflow formation in sub-basins of the Nepal Himalayas, an inspection of Figure 19 makes it apparent that altitude, used alone, will be a relatively imprecise index of that formation.

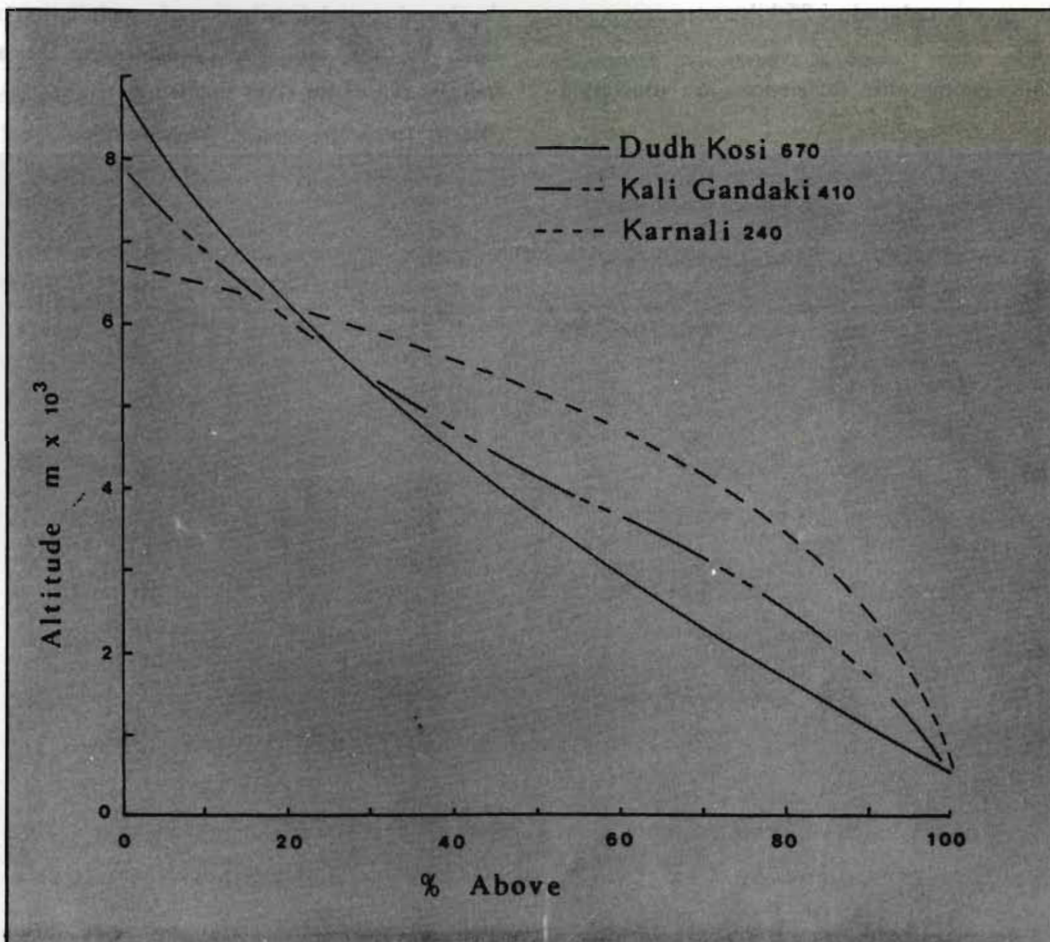


Figure 20: Hypsometric Curves Showing Distribution of Surface Area with Altitude in the Dudh Kosi, Kali Gandaki, and Upper Karnali Basins

Note: Distinct differences exist among the basins.

There are distinct differences in the geomorphology among the three major river basins. While it is beyond the scope of this paper to undertake a detailed geomorphic analysis, certain large-scale features of the terrain are considered essential to an understanding of the hydrological variations among the three basins. The most striking difference is the abrupt change occurring in the Himalayan crest at the Kali Gandaki Gorge in the Narayani basin. To the east of this gorge, there is a relatively clear division between this crest, the lowlands to the south, and the Tibetan Plateau to the north. Rivers of eastern Nepal are generally short and steep, with a north-south trend, reflecting the east-to-west trend of the Himalayan crest. To the west of the Kali Gandaki Gorge, there is no distinct Himalayan crest, but rather a strongly dissected highland, with large interfluvial areas exceeding 3,000-5,000 metres in altitude. The drainage pattern is strongly dendritic, with no clear directional trends.

In extreme eastern Nepal, the main crest of the Himalayas is located in northernmost Nepal, but, with increasing distance to the west, it trends southwards. At the longitude of Sagarmatha (Chomo Longma, Mt. Everest), the crest is separated from the Siwalik Range in southern Nepal by approximately 125 kilometres. Immediately to the east of the Kali Gandaki Gorge, at approximately the longitude of Pokhara, this distance is reduced to 75 kilometres.

These large-scale geomorphic differences are illustrated schematically in Figure 21. The horizontal scale in Figure 21 is in kilometres north of the crest of the Siwalik Range. Many of the hydrological differences among the three basins, both on the scale of the basin and on the intermediate scale of sub-basins, must be explainable in terms of the differences shown in Figure 21. Perhaps the most crucial are: 1) the orientation with respect to prevailing storm tracks, and relative proximity to the Siwalik Range, of the extreme local relief in the Narayani basin; 2) the lack of well-defined topographic trends in the Karnali basin, together with relatively subdued local relief; and 3) the greater distance to the Himalayan crest in the Sapta Kosi basin. The abruptness with which air masses are forced to rise as they encounter the Himalayan front will strongly influence the depth and spatial distribution of precipitation on the surface. This, in turn, will largely determine the availability of specific runoff for river formation.

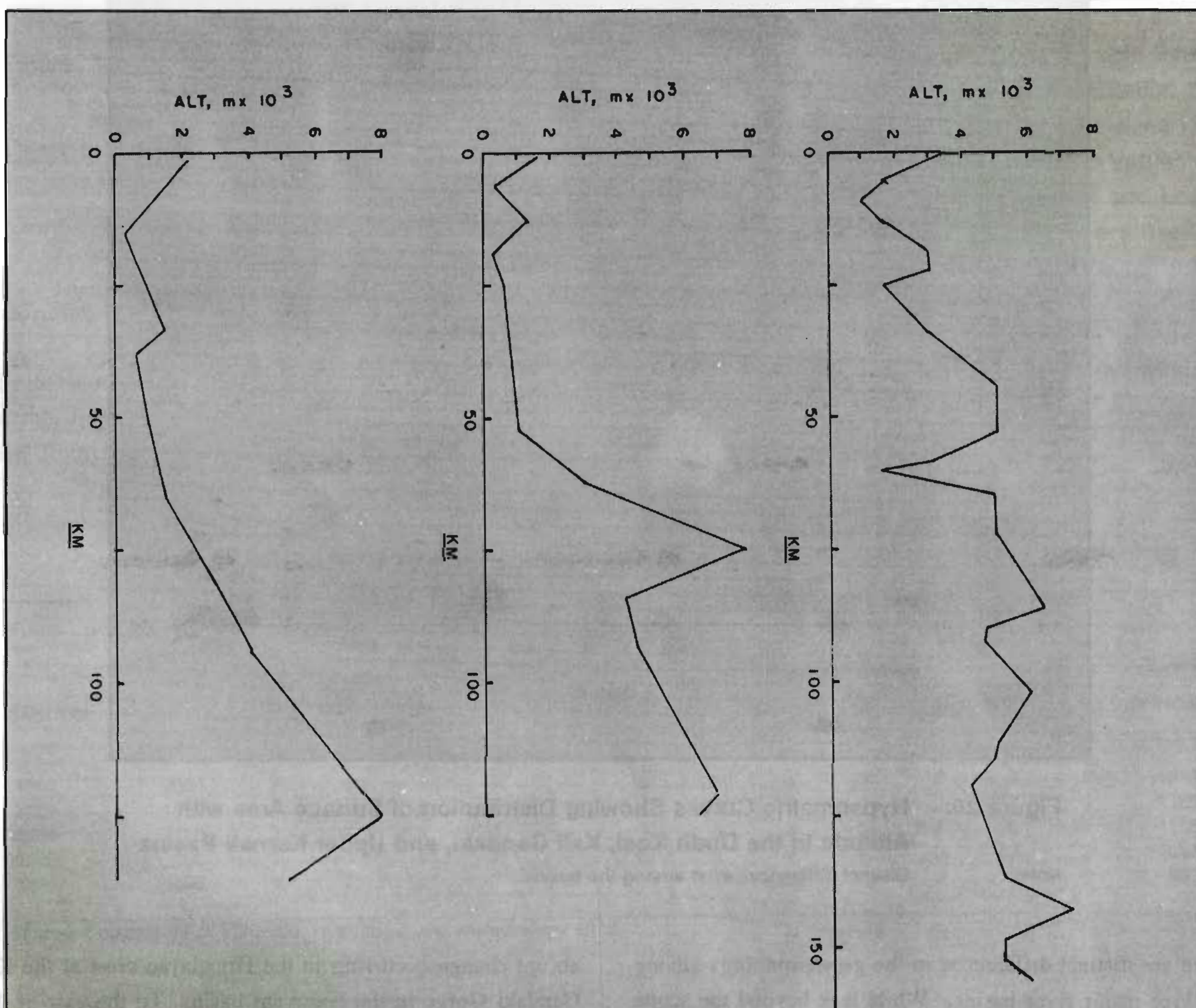


Figure 21: North-south Transects through: a. The Karnali Basin at Long. 83° 10', b. The Narayani Basin at Long. 84° 10', and c. The Sapta Kosi Basin at Long. 87° 20'

Note the major changes that occur in the major topographic alignment between eastern and western Nepal.

Streamflow and Specific Runoff

As used here, "streamflow" is the volume of discharge per unit time, Qv, m^3/s, while runoff is "specific runoff", or depth of water produced per unit area, Qs, mm (Eq. 1). Streamflow volumes vary with both space and time within and among catchment basins. In general, these variations reflect short-term changes in climate or basin storage, fluctuating about a seasonal trend - the "annual hydrograph". Streamflow is a useful index to the volume of useable water at a specific site, as well as to the energy available for sediment transport. Specific runoff is an index of water available at a specific point, within a catchment basin, to promote plant growth or cause erosion. In mountainous terrain, such as that of Nepal, the two - streamflow and specific runoff - cannot be used interchangeably, since streamflow represents an areal averaging of what is commonly a very heterogeneous spatial pattern of specific runoff.

Specific runoff ranged from a low of approximately 400 mm of water annually in the Arun basin to a high of approximately 2,780 mm in the Seti Khola, tributaries to the Sapta Kosi and Narayani river systems respectively (Tables 10, 11, and 12). The primary factor in determining the annual volume of water produced per unit area of a watershed in the eastern Himalayas appears to be the position occupied by the watershed with respect to the Great Himalayas or Mahabharat Lekh. In general, sub-basins of the Narayani River have the highest annual specific runoff values, while the Karnali sub-basins have the lowest. Both the lower Sun Kosi and Karnali basins have anomolously low values. It is not apparent from the available data if this is a result of climate or of consumptive water uses, such as irrigation, by the inhabitants.

The ratio of annual mean streamflow volume to annual mean specific runoff, Qs/Qv, varies by at least two orders of magnitude in the gauged sub-basins of the Nepal Himalayas (Table 12). These great differences are largely a reflection of the influence of surface area in the relationship between water budget environments and streamflow. This ratio indicates that fluctuations in streamflow volume, Qv, as a result of land uses on the quality or quantity of the water resources, will be most apparent in very small basins and diminish in importance directly with increases in surface area.

Streamflow and Climate

The timing of streamflow in eastern Nepal coincides closely with seasonal maxima and minima of precipitation. Maximum values generally occur in August, in coincidence with the seasonal monsoon, while minimum values occur during the months of January-May, during the intermonsoon dry period. This relationship is illustrated in Figure 22, based upon gross mean values of mean monthly streamflow and monthly precipitation for all stations within the Sapta Kosi River system.

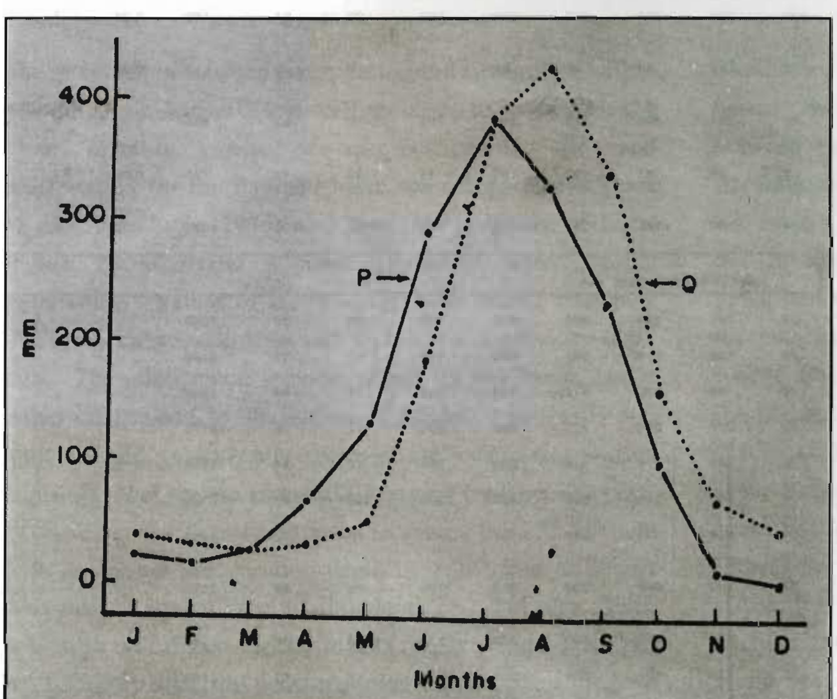


Figure 22: The Annual Distribution of Precipitation and Runoff in the Sapta Kosi Basin Follow Very Similar Trends

Table 10: Streamflow and Runoff Statistics for the Karnali Basin -- Western Nepal

STN. NO.	RIVER	AREA sq.km.	J	F	M	A	M	J	J	A	S	O	N	D	ANNUAL	1	2	3
		STREAMFLOW KARNALI BASIN WESTERN NEPAL m^3/s																
240	Karnali	19260	132	117	130	200	375	723	1170	1410	935	438	238	164	505	0.03	2	11
250	Karnali	1980	23	22	22	28	40	68	300	410	305	106	54	39	119	0.06	16	19
260	Seti	7460	72	67	75	92	131	300	736	974	677	258	128	88	302	0.04	4	15
270	Bheri	12290	97	85	83	102	152	370	1070	1470	1070	386	178	120	435	0.04	3	18
280	Karnali	1880	46	44	38	23	4	59	14	106	33	132	34	35	49	0.03	16	27
		SPECIFIC DISCHARGE mm																
240	Karnali		18	16	17	27	50	97	157	190	126	59	32	22	812			
250	Karnali		30	29	29	37	52	89	393	637	399	139	71	51	1855			
260	Seti		25	23	26	32	46	104	256	338	235	90	44	31	1250			
270	Bheri		20	18	18	22	32	78	226	310	226	81	38	25	1093			
280	Karnali		63	61	52	32	6	81	19	146	45	182	47	48	783			

Note: 1 = $m^3/S/km^2$; 2 = Qs/Qv; 3 = Qmax/Qmin

Table 11: Streamflow and Runoff Statistics for the Narayani Basin -- Central Nepal

STN. NO.	RIVER	AREA sq.km.	J	F	M	A	M	J	J	A	S	O	N	D	ANNUAL	1	2	3
		STREAMFLOW NARAYANI BASIN CENTRAL NEPAL m^3/S																
410	Kali Gandaki	6630	49	41	41	57	92	273	752	835	593	261	117	69	267	0.04	5	20
415	Andhi Khola	476	5	4	3	3	7	36	99	100	100	29	10	6	31	0.07	71	33
420	Kali Gandaki	4294	59	45	33	31	43	97	369	515	427	247	123	79	175	0.04	7	17
430	Seti	582	13	12	12	13	20	52	139	168	108	55	26	17	52	0.09	53	13
439	Marsyangdi	3542	49	42	41	55	96	229	571	607	463	210	104	66	212	0.06	9	15
440	Chepe Khola	308	5	4	4	4	6	19	63	71	59	28	13	8	24	0.08	100	18
445	Buthi Gandaki	4270	37	32	37	64	105	220	394	408	300	169	90	54	160	0.04	7	13
446	Phalankhu Khola	162	2	2	2	2	2	12	38	45	32	12	5	3	13	0.08	193	23
447	Trisuli	4110	45	39	39	60	85	231	499	565	368	163	86	57	186	0.05	8	14
448	Tadi Khola	653	9	7	5	6	8	34	101	132	97	43	22	13	40	0.06	47	26
450	Narayani	6073	78	58	47	63	104	407	1185	1544	873	383	195	120	430	0.07	5	33
		SPECIFIC DISCHARGE mm																
410	Kali Gandaki		19	16	16	22	36	107	294	326	232	102	46	27	1243			
415	Andhi Khola		27	22	16	16	38	196	539	545	545	158	54	33	2189			
420	Kali Gandaki		36	27	20	19	26	59	223	311	258	149	74	48	1248			
430	Seti		58	53	53	58	89	232	619	704	481	245	111	76	2779			
439	Marsyangdi		36	31	30	40	70	168	418	444	339	154	76	48	1854			
440	Chepe Khola		42	34	34	34	50	160	530	598	497	236	109	67	2390			
445	Buthi Gandaki		22	19	22	39	64	134	239	248	182	103	65	33	1159			
446	Phalankhu Khola		32	32	32	32	32	192	608	720	512	192	80	48	2512			
447	Trisuli		28	25	25	32	54	146	315	350	232	103	54	36	1398			
448	Tadi Khola		36	28	20	24	32	135	401	524	385	171	87	52	1893			
450	Narayani		33	25	20	27	44	174	506	659	373	163	83	51	2158			

Note: 1 = $m^3/S/km^2$; 2 = Qs/Qv; 3 = Qmx/Qmn

Table 12: Streamflow and Runoff Statistics for the Sapta Kosi Basin -- Eastern Nepal

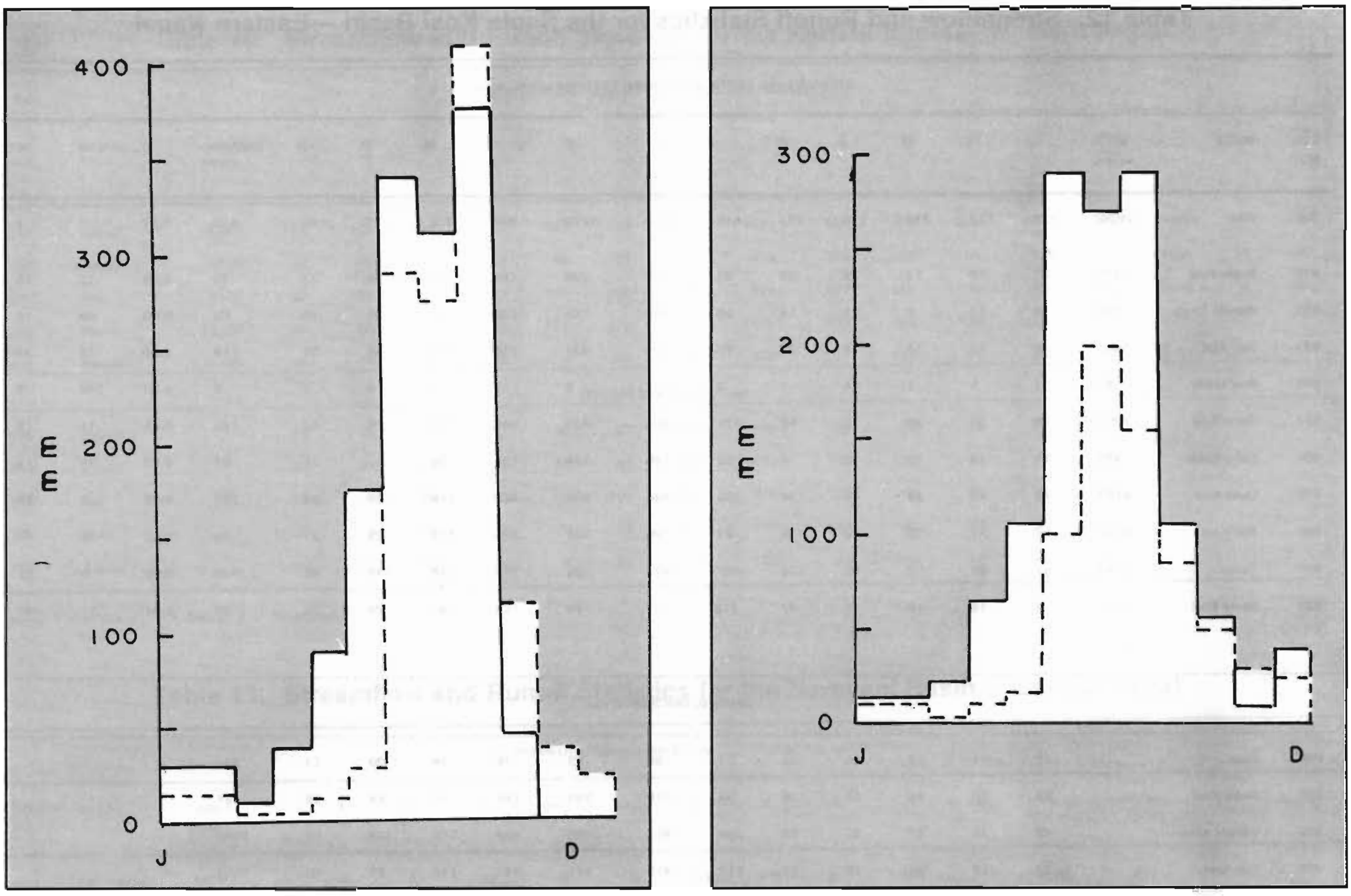
STREAMFLOW SAPTA KOSI BASIN EASTERN NEPAL m^3/s

STN. NO.	RIVER	AREA sq.km.	J	F	M	A	M	J	J	A	S	O	N	D	ANNUAL	1	2	3
604	Arun	28200	116	116	135	174	266	615	1020	1010	830	408	215	145	423	0.02	1	9
610	Bhote Kosi	2410	21	18	17	22	33	91	203	228	168	80	41	27	79	0.03	13	13
620	Balephi Khola	629	12	10	9	11	14	50	146	165	120	53	25	15	53	0.08	49	18
630	Sun Kosi	1881	24	19	18	19	27	85	329	431	266	106	58	36	119	0.06	16	24
640	Rosi Khola	87	1	1	1	1	1	2	6	8	6	4	2	2	3	0.03	348	8
647	Tama Kosi	2753	30	25	24	30	57	173	402	436	306	141	66	42	145	0.05	11	18
660	Likhu Khola	823	15	12	10	12	18	52	145	166	130	66	33	21	57	0.07	38	17
670	Dudh Kosi	4100	48	40	38	45	76	265	644	665	459	219	100	64	223	0.05	8	18
680	Sun Kosi	4917	37	37	32	20	-6	-37	185	321	275	112	28	31	89	0.02	6	10
690	Tamur	5640	67	65	52	80	176	482	921	895	704	338	149	93	336	0.06	5	17
695	Sapta Kosi	2660	-7	-18	-18	10	43	118	109	15	196	67	78	25	23	0.01	11	NC
	SPECIFIC DISCHARGE mm																	
604	Arun		11	11	12	16	24	57	94	93	76	38	20	13	464			
610	Bhote Kosi		23	19	18	24	35	98	218	245	181	86	44	29	1021			
620	Balephi Khola		49	41	37	45	58	206	602	680	494	218	103	62	2596			
630	Sun Kosi		33	26	25	26	37	117	453	594	367	146	80	50	1954			
640	Rosi Khola		30	30	30	30	30	60	179	238	179	119	60	60	1043			
647	Tama Kosi		28	24	23	28	54	163	378	411	288	133	62	40	1631			
660	Likhu Khola		47	38	31	38	57	164	457	523	409	208	104	66	2142			
670	Dudh Kosi		30	25	24	28	48	168	407	420	290	138	63	40	1684			
680	Sun Kosi		20	20	17	11	-3	-20	98	169	145	59	15	16	571			
690	Tamur		31	25	24	37	81	222	423	411	324	155	68	43	1844			
695	Sapta Kosi		-7	-18	-18	10	42	-115	106	15	191	-65	76	24	242			

NOTE: 1 = $m^3/S/km^2$; 2 = Qs/Qv; 3 = Qmx/Qmn; NC = Not Calculated

The relationship between precipitation and streamflow within individual sub-basins is less well-defined. In Figure 23, the mean monthly values of specific runoff, Qs, and precipitation for the Bagmati basin are compared for years of relatively high (1975) and low (1977) values of both. Figure 23 illustrates a basic aspect of water budget calculations - values of the ratio Q/P, the runoff efficiency of a basin increase directly with P, but at a much more rapid rate. The relationship is not constant for any basin, but is rather determined by the nature of "sinks" - primarily soil moisture and groundwater recharge and evapotranspiration demands - that remain essentially constant from year to year. In this case, the runoff efficiency increases from 55 per cent with an annual precipitation depth of 1,281 mm to 87 per cent with an annual precipitation depth of 1,444 mm. Each sub-basin will differ slightly in this respect, since each will have slightly differing geomorphological and climatological characteristics.

Because of the existence of topoclimates in the Nepal sub-basins, the problem of establishing a useful correlation between the interannual fluctuations in precipitation and streamflow becomes particularly difficult. In all probability, this is only possible on a trial-and-error basis, by comparing the discharge from a sub-basin of interest with all precipitation stations within, or in the immediate vicinity of, the sub-basin. In Figure 24, the values of mean annual runoff, Qs, and mean annual precipitation are compared for the Bagmati basin. The streamflow data are from Chobhar (550), while the precipitation data are measurements taken at the Kathmandu airport. In this particular case, correlation between these two elements of the water budget is not good. Exhaustive comparisons of values from the climate and streamflow databases will be required to establish the usefulness of precipitation as an index of streamflow. The formline is based on the relationship illustrated in Figure 23, and it has no statistical significance.



a. During 1975, A Year of Greater-than-Average Precipitation

b. During 1977, A Year of Below Average Precipitation

Figure 23: Monthly Relationship between Precipitation and Runoff in the Bagmati Basin

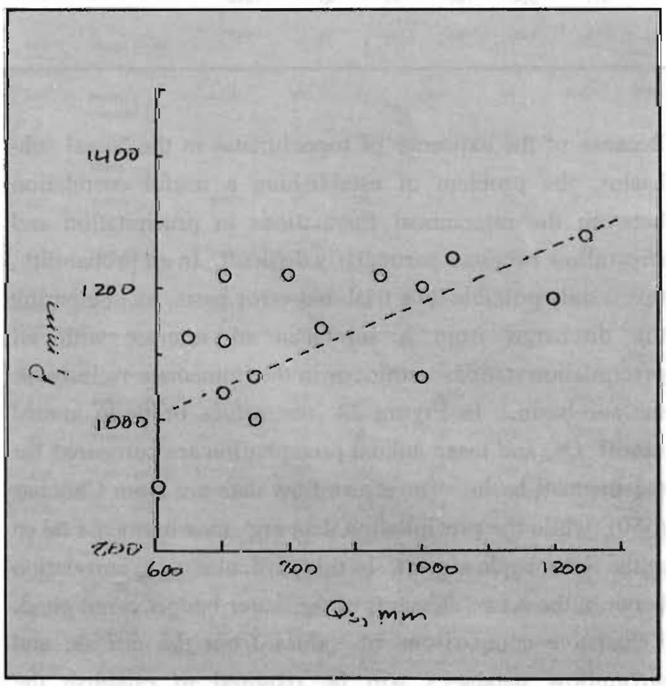


Figure 24: The Relationship between Annual Precipitation and Specific Runoff for the Bagmati Basin for the Period of Record

This lack of correlation between precipitation at individual precipitation stations within a sub-basin and annual discharge volumes from that sub-basin is characteristic of the Himalayan Region. Attempts to establish functional relationships between point-source values of precipitation, and areal averages of specific discharge as measured at hydrometric stations, must always be undertaken on the understanding of the difference in scale represented by the two types of data and the extreme climatological heterogeneity of the Himalayan environment.

Streamflow and Basin Surface Area

The volume of discharge (m^3/s) of the rivers of the Himalayas does not correlate well with the surface area above the gauging station (Figure 25), except within individual river basins. The trend towards increasing values of streamflow volume with increasing basin surface area is to be expected, given the obvious dependence of discharge on surface area under conditions of relative environmental uniformity. In the case of the sub-basins of the Karnali, Narayani, and Sapta Kosi rivers, there is considerable scatter about the mean value, suggesting a great deal of hydrological diversity among these sub-basins. Without additional analysis of the cause(s) of this diversity, the relationship shown in Figure 25 has little predictive value. The slope of the formline is 0.05 $m^3/s/km^2$, the average for all basins.

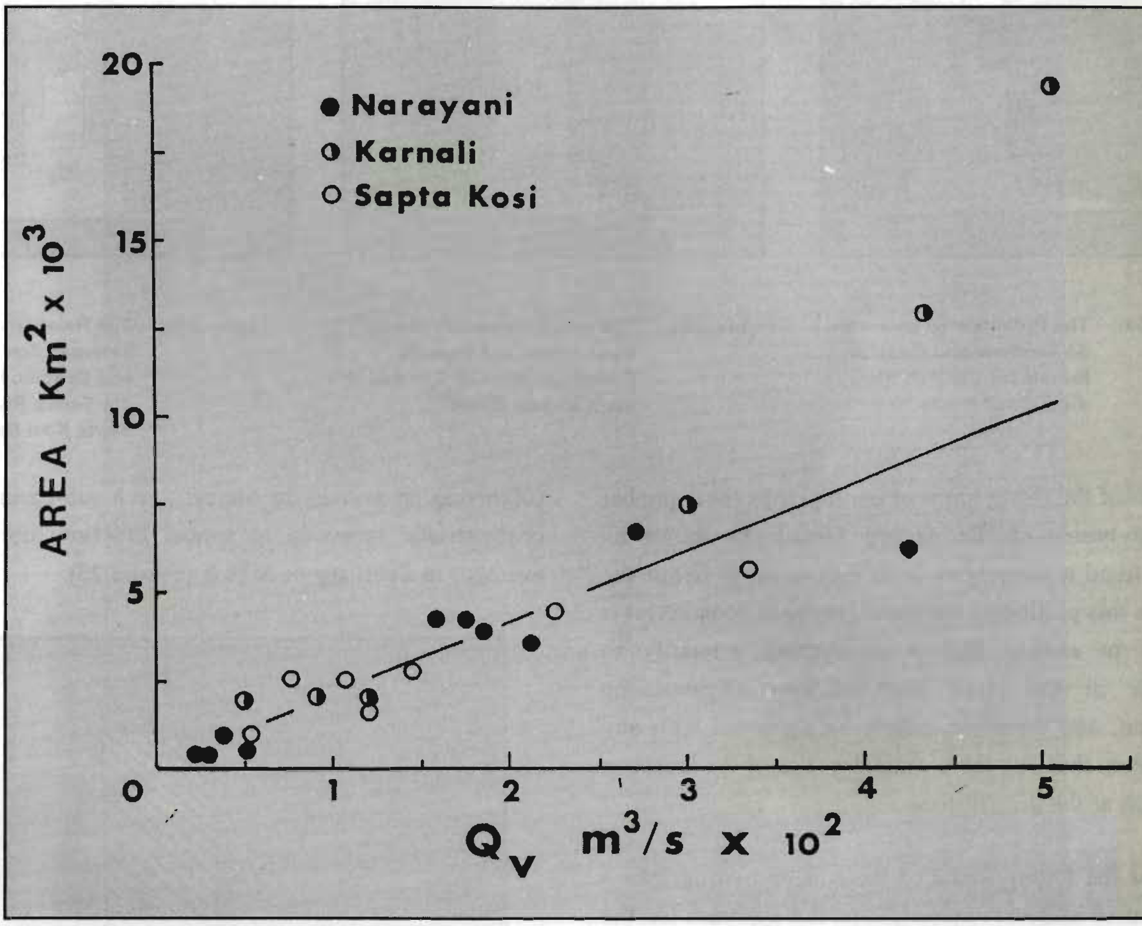


Figure 25: Basin Surface Area is Not a Good Index of Mean Annual Streamflow

The Annual Hydrographs

Hydrographs of selected Nepalese basins - graphical representations of the fluctuation of streamflow over time - based upon mean monthly values for the period-of-record, illustrate monthly fluctuations in the ratio Qs/Qv (Figures 26 and 27). These figures demonstrate some of the problems associated with developing general models of the relationship between streamflow volume and specific runoff. In Figure 26, hydrographs for three basins -- the Seti (260) in the Karnali basin, the Kali Gandaki (410) in the Narayani basin, and the Tamur (690) in the Sapta Kosi basin - in the extreme west, central, and extreme eastern Nepal, respectively, are shown. These basins were selected for an approximate correspondence in surface area - 7,460 sq.km., 6,630 sq.km., and 5,640 sq.km. respectively - to minimise the control of this factor. Grossly, the three hydrographs are quite similar. There is a close correspondence in the relationship between streamflow volume, Qv, and specific runoff, Qs, with ratios between 4 and 5 in the three basins.

In Figure 27, the relationship is compared for the Andhi Khola (415), a small (543 sq.km.) tributary of the Narayani River located immediately to the west of Pokhara, and the Arun River (604), a tributary of the Sapta Kosi River, one of the largest (28,200 sq.km.) gauged basins in Nepal, with headwaters on the Tibetan Plateau. For the Andhi Khola, the ratio between streamflow volume, Qv, and specific runoff, Qs, is approximately 70, while, for the Arun River, this ratio is one. While this great difference does not conclusively demonstrate the importance of surface area in determining the relationship between streamflow and specific runoff, it does suggest that it is a factor that must be taken into consideration in assessing the impacts of land uses on streamflow.

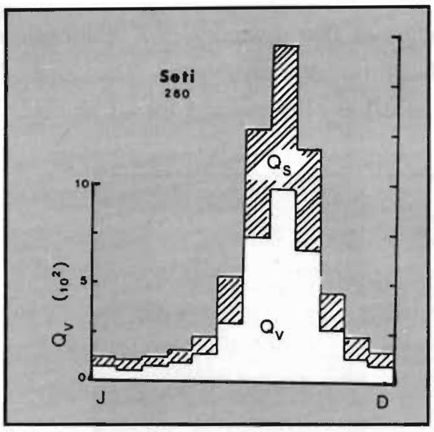


Figure 26a. **The Relationship between Streamflow and Specific Runoff for the Seti River in the Karnali Basin**

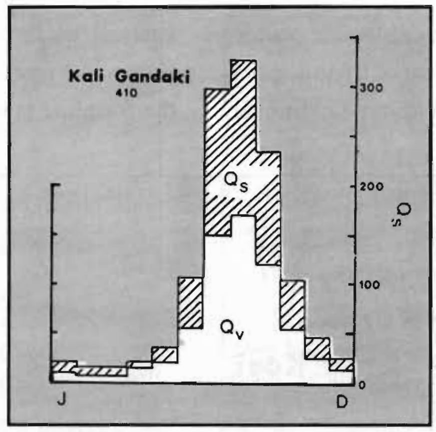


Figure 26b. **The Relationship between Streamflow and Specific Runoff for the Kali Gandaki in the Narayani Basin**

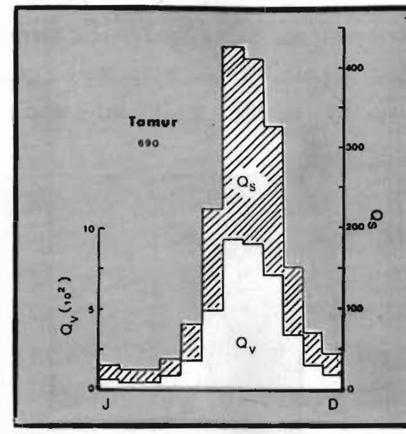
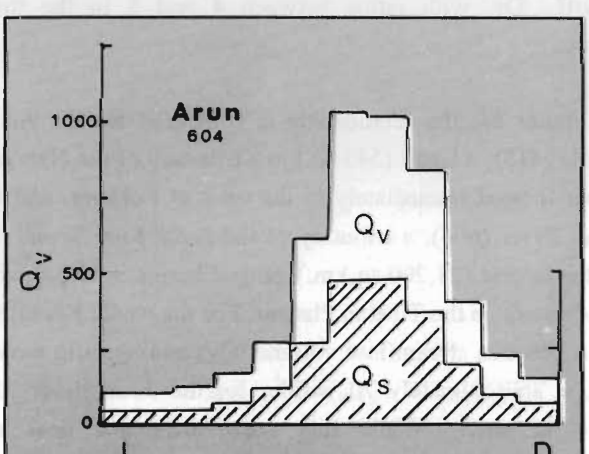


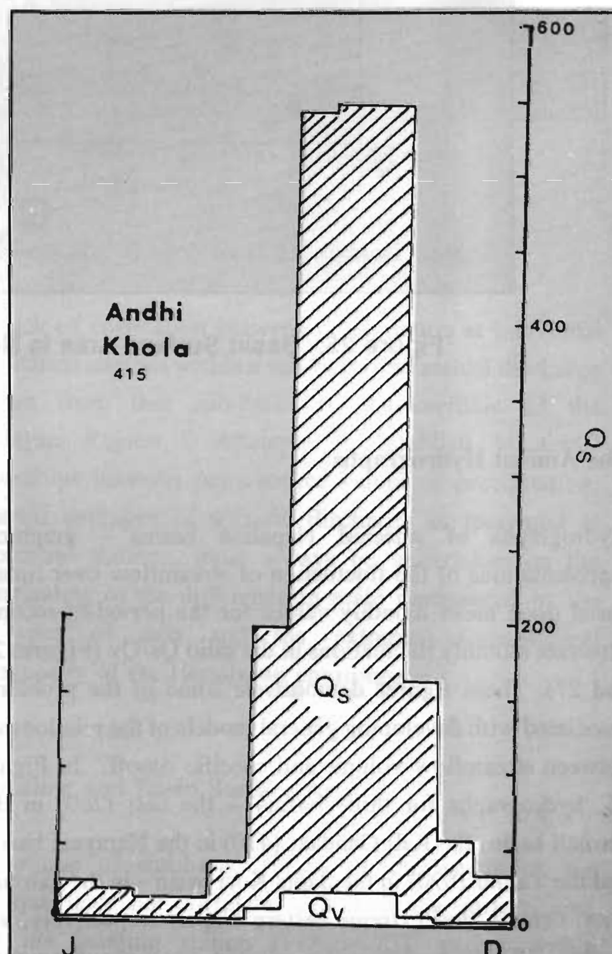
Figure 26c. **The Relationship between Streamflow and Specific Runoff for the Tamur River in the Sapta Kosi Basin**

An analysis of the rising limbs of hydrographs for a number of the sub-basins of the eastern Himalayas shows no consistent trend seasonally or from year-to-year. While the controls on this portion of the hydrograph are complex, it is reasonable to assume that it is reacting primarily to fluctuations in the onset and intensity of monsoon precipitation, and therefore cannot be predicted with any more accuracy than can these characteristics of the monsoon precipitation at the present time.

Analysis of the falling limbs of these same hydrographs - recession curve analysis - indicates that this approach has the potential to produce a streamflow forecast methodology with the least effort. Analysis of a randomly-selected sub-set of the river basins of Nepal indicates that, following cessation of the monsoon and the occurrence of peak annual flow (occurring on average in August), each sub-basin follows a characteristic recession to annual low flow, occurring, on average, in February or March (Figure 28).



a. For the Arun River (28,000 sq.km.)



b. The Andhi Khola (476 sq.km.), Showing the Control on the Streamflow-Specific Runoff Relationships Exercised by Surface Area

Figure 27: The Relationship between Streamflow and Specific Runoff, mm

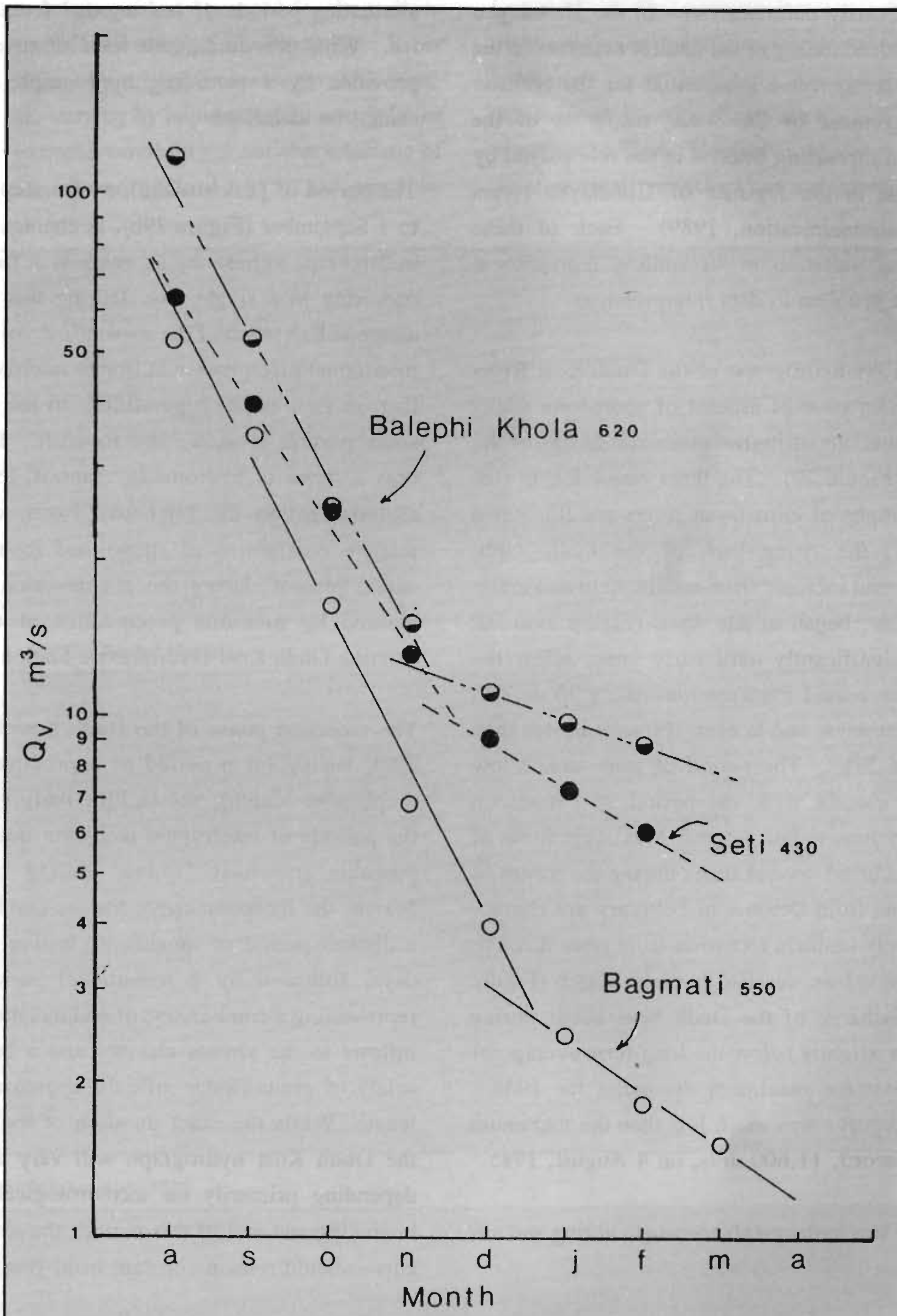


Figure 28: Recession Curves for Representative Basins in the Sapta Kosi, Narayani, and Bagmati Sub-basins

The recession curve, representing a period of between seven to eight months each year, appears sufficiently constant from year to year to permit a reasonably accurate forecast of streamflow volume for this period of each year. A much more detailed analysis than was possible for the present study is warranted to establish the statistical accuracy of such a forecasting technique.

Temporal Variations in Streamflow Volume

Trends of discharge, Qv, over time for Himalayan tributaries of the major rivers of the region have been the subject of some speculation (Bowonder 1982 and WRI 1985) but of little serious study. The primary concern has been the changes in runoff that may have resulted from unwise land use practices - primarily deforestation - in the Himalayan watersheds. An understanding of the natural extremes in the discharge of Himalayan rivers is essential for the realistic planning or management of the water resources of the region. There is an increasing interest in the role played by snow- and ice-melt in the regimes of Himalayan rivers (Grabs, personal communication, 1989). Each of these aspects of temporal variation in streamflow represents a somewhat different problem in data interpretation.

Daily variations in the hydrograph of the Dudh Kosi River for 1988 are representative of aspects of short-term (daily and seasonal) fluctuations of high-altitude sub-basins of the Nepal Himalayas (Figure 29). The three major features of the annual hydrographs of Himalayan rivers are illustrated in this figure: (1) the rising limb of the hydrograph, representing the annual increase from minimum to maximum values of streamflow, began in late April (Figure 29a) but did not increase significantly until early June, when the discharge volume increased from approximately 70 m^3/s to over 300 m^3/s in ten days, and to over 700 m^3/s in less than one month (Figure 29b). The period of peak streamflow volume coincides closely with the period of monsoon precipitation - early June to late August. Maximum flows of over 1,000 m^3/s occurred several times during the month of August. The months from October to February are characterised by a relatively uniform recession from peak flows to minimum discharge values, reached in early March (Figure 29a). Average discharge of the Dudh Kosi River during 1988 was 209 m^3/s, slightly below the long-term average of 223 m^3/s. The extreme maximum discharge for 1988 - 1,750 m^3/s on 1 August - was much less than the maximum for the period-of-record, 11,600 m^3/s, on 4 August, 1985.

Several features of this hydrograph are worth noting and are discussed below.

The rising limb of this hydrograph (Figures 29a and b), lasting for approximately four months (Apr-Jul), is irregular, reflecting the intermittent nature of inputs (as precipitation or snowmelt) to runoff.

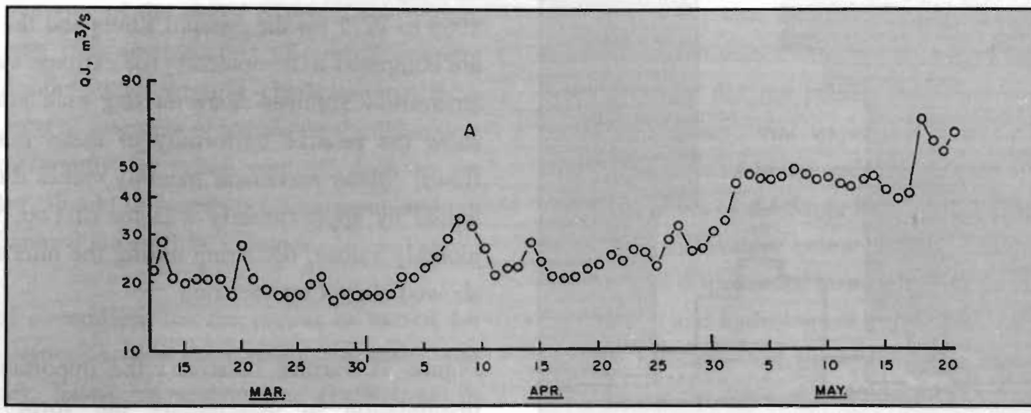
Based solely upon daily mean values of streamflow, it is not possible to separate the snowmelt component of the hydrograph. While it is reasonable to assume that much of the increase in streamflow volume, occurring between 1 April and 1 June (Figure 29a), is the result of this factor, only a continuous trace of streamflow would establish this. The characteristic feature of streamflow, resulting from snow- or ice-melt, is a sharp diurnal cycle, reflecting alternating periods of melting and freezing of the snow or ice. Without a continuous trace of streamflow, such as is provided by a recording hydrograph, this diurnal cycle cannot be identified.

The period of peak streamflow, from approximately 1 June to 1 September (Figure 29b), is characterised by variations in discharge volume by as much as a factor of three, often occurring in a single day. During this period, it must be assumed that much of the streamflow volume is produced by monsoonal precipitation at low to intermediate altitudes, but that, in view of the high altitude of the 0 degree isotherm, some portion is snow- and ice-melt. During this period, only a series of hydrometric stations, located at increasing altitudes within the catchment basin, could establish the relative contibution of snow- and ice-melt. The diurnal cycle, present during the pre-monsoon period, would be masked by monsoon precipitation at the altitude of the existing Dudh Kosi Hydrometric Station.

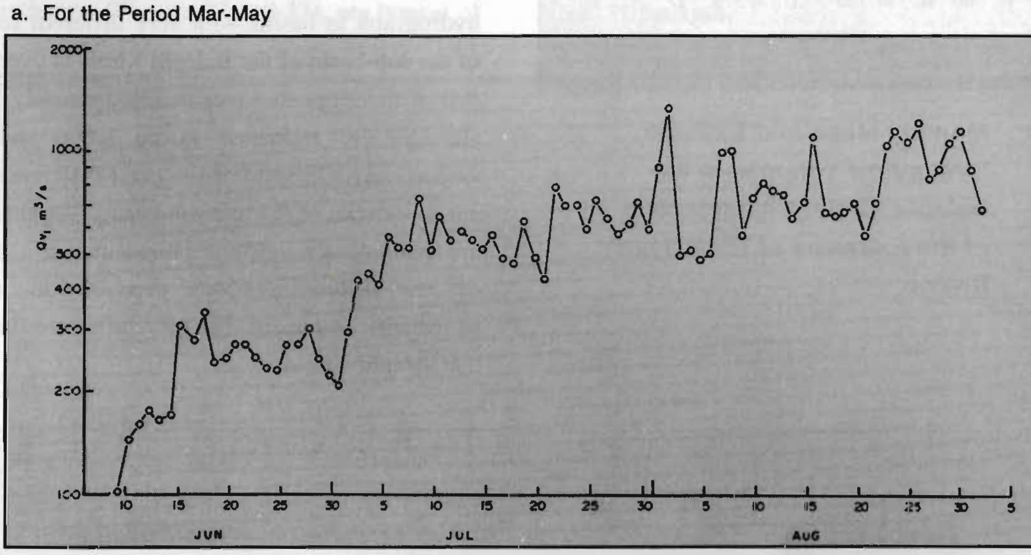
The recession phase of the Dudh Kosi hydrograph (Figure 29c), lasting for a period of approximately seven months (September-March), shows little daily variation. Excluding the periods of interrupted recession during September and probable snowmelt "spikes" during late February-early March, the recession curve for the Dudh Kosi River shows a distinct period of quickflow, lasting approximately five days, followed by a transitional period of "interflow", representing a combination of soil moisture and groundwater inflows to the stream channel and a baseflow, composed solely of groundwater inflows, approximately 120 days in length. While the exact duration of the recession phase of the Dudh Kosi hydrograph will vary from year to year, depending primarily on meteorological conditions at the beginning and end of this period, the slope of the recession curve should remain constant from year to year.

Except for special studies, such as snow hydrology or the derivation of storm hydrographs, it is most common to discuss streamflow variations in terms of monthly or annual means, in order to reduce the amount of data that must be considered to manageable proportions. For the purposes of planning most water resources' projects, monthly mean streamflow values are sufficient.

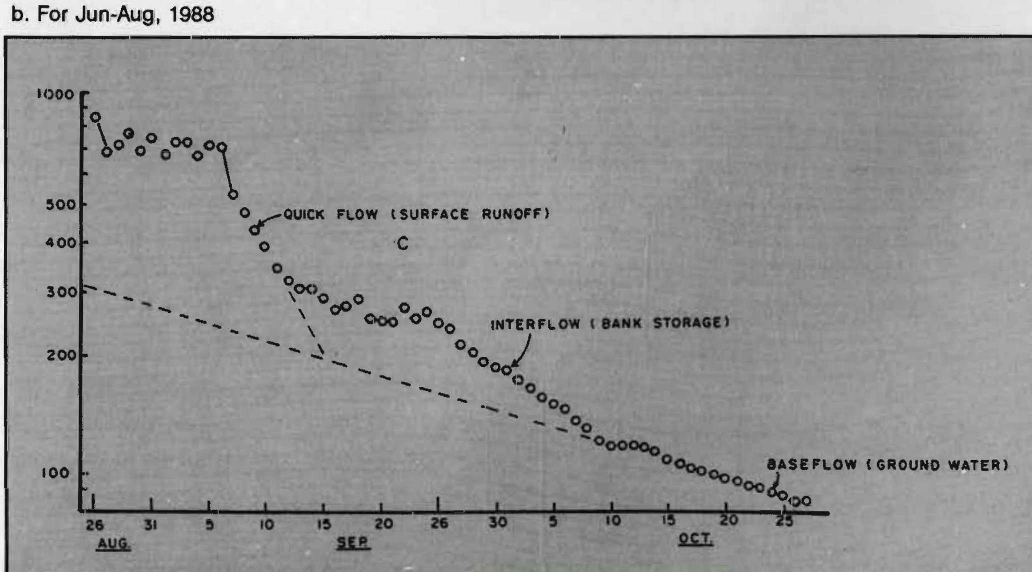
A particularly difficult problem associated with water resources' development in the Himalayan Region involves the extreme variability of streamflow volume in the rivers of the region. This is illustrated in Figure 30, comparing maximum, mean, and minimum monthly values of streamflow volumes for the period of record for the Balephi Khola, a relatively small tributary of the Sapta Kosi River system. The total range of discharge volumes for the period-of-record is extreme, varying by approximately one order of magnitude. Such extreme variability is not characteristic of snow-fed mountain rivers (Alford 1985) and must be assumed to be associated with variations in monsoon precipitation in the Himalayan Region. The greatest monthly variations occur during the months from June to October, approximately coinciding with the period of monsoon. The baseflow period, November to May, is characterised by relative small variations among extreme flows.



a. For the Period Mar-May



b. For Jun-Aug, 1988



c. For Aug-Oct, 1988

Figure 29: The Hydrograph of the Dudh Kosi River

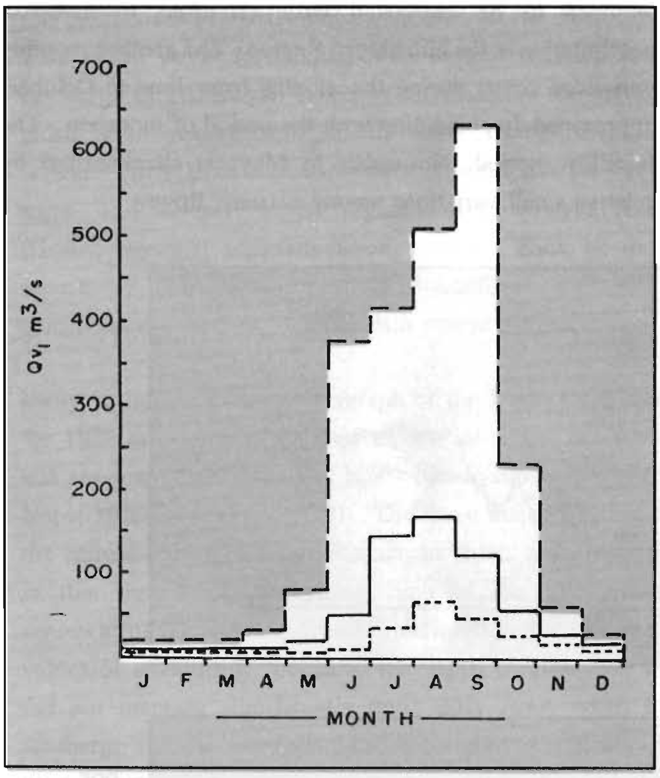


Figure 30: Monthly Mean and Extreme Streamflow Volumes in the Balephi Khola, Characteristic of the Extremes of Himalayan Rivers

The extreme variability of Himalayan rivers is further illustrated by a comparison of mean monthly streamflows. Mean monthly streamflow values smooth the longer-term extremes as illustrated in Figure 30 and show, instead, the year-to-year variation in monthly values that can be expected. In Figure 31, annual hydrographs, based upon monthly mean values of streamflow, for the period from 1963 to 1977 for the Balephi Khola and the Bagmati River, are compared to demonstrate the extreme variations in peak streamflow volumes characterising each year, as well as to show the relative uniformity of mean minimum monthly flows. Mean maximum monthly values during this period varied by approximately a factor of two, while minimum monthly values, occurring during the intermonsoon period, showed almost no variation.

Figure 31 further illustrates the importance of monsoon precipitation in determining the form of the annual hydrograph in basins with very different relief. The relief of the sub-basin of the Balephi Khola is over 7,000 m, while that of the Bagmati River is approximately 1,000 m. Mean altitudes are estimated to be 3,600 and 1,600 metres respectively. In spite of the great difference in topographic characteristics of the two sub-basins, the annual hydrographs are qualitatively similar. This demonstrates the importance of low altitude monsoon precipitation, relative to any snowmelt component that may influence the hydrograph of the Balephi Khola.

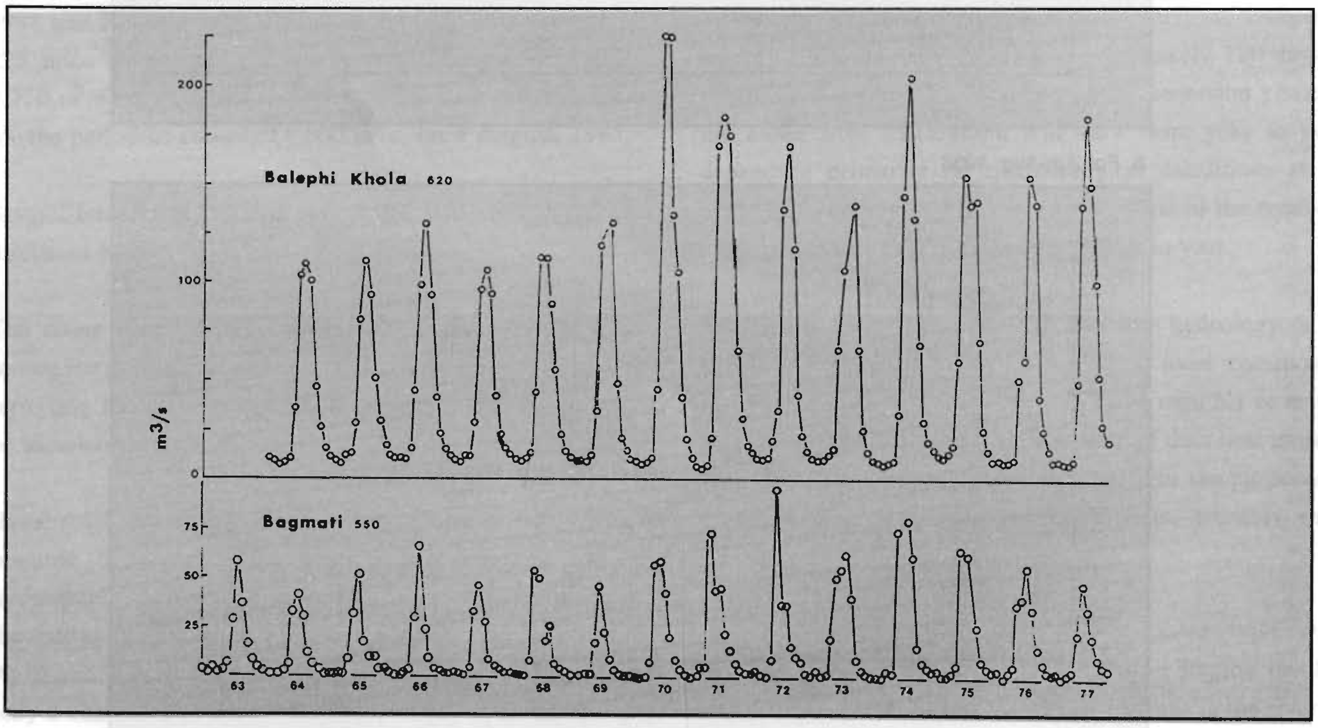


Figure 31: Average Monthly Streamflow Volume for the Balephi Khola and Bagmati River, Showing the Extreme Range of Flows Characterising Individual Years

Questions concerning the impact of land use practices, or the long-term availability of water for such uses as agriculture or urban supply, are best considered from the perspective of fluctuations in mean annual values of streamflow. If human uses of Himalayan watersheds are having any impact on the streamflow from these watersheds, this should be revealed by the long-term trend of mean annual discharge volumes. If Himalayan tributaries of the major rivers of the region, such as the Ganges, play an important role in determining the cycles of flooding and drought characterising these rivers, a comparison of interannual variations should reflect this role. Water supply for urban centres, such as the Kathmandu Valley, should be based upon minimum, and not mean, values of annual streamflow volumes.

Annual trends of streamflow for the period of record for several gauging stations within the Karnali, Narayani, and Sapta Kosi basins, based on year-to-year fluctuations in mean annual discharge (Figures 32 and 33), are typical of gauged basins in Nepal. For the sub-basins illustrated here, there is no apparent increase or decrease of mean annual values with respect to the long-term mean flow from the respective basins, although year-to-year variations are often 50 per cent of the mean flow for the period of record. The decade of the 1970s, during which time the concern for the impact of human use on the watersheds of the Himalayas was at a peak, was one of generally higher-than-average streamflow, but values from the decade of the 1980s suggest that this trend did not persist in all sub-basins of Nepal. Some sub-basins, that experienced a small increase in streamflow volume in the mid-1980s, such as the Dudh Kosi and Arun rivers of the Sapta Kosi system (Figure 33), ended the decade with values below the long-term average. While this does not disprove the many suggestions of environmental degradation and hydrological impairment referred to above, it does indicate that these land-use impacts cannot be discerned on the scale of individual gauged sub-basins of the Nepal Himalayas.

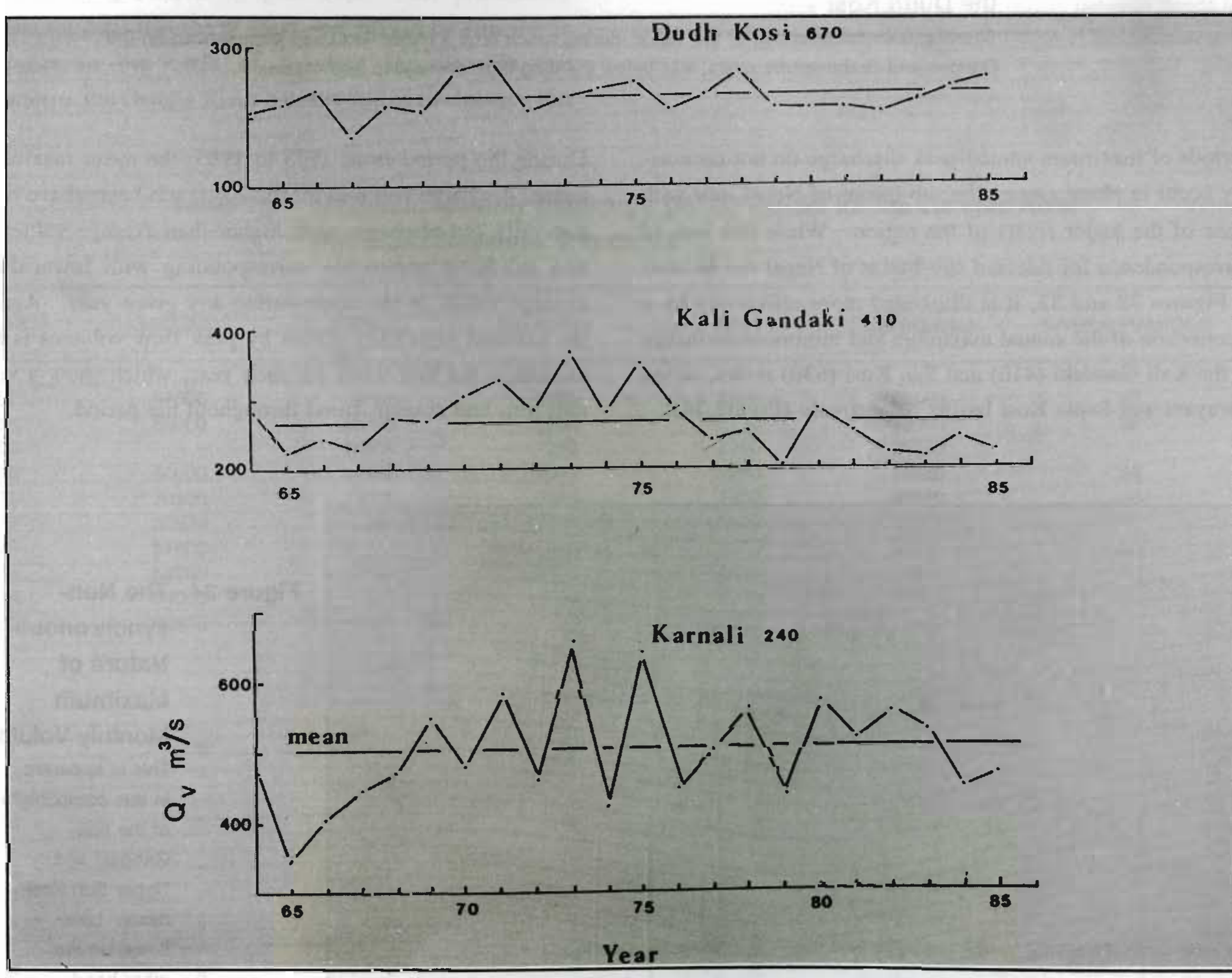


Figure 32: Average Annual Streamflow Volume for Three Representative Basins
Showing: 1) the absence of any long-term trends that might be associated with land use; and 2) the lack of uniformity in high and low streamflow years

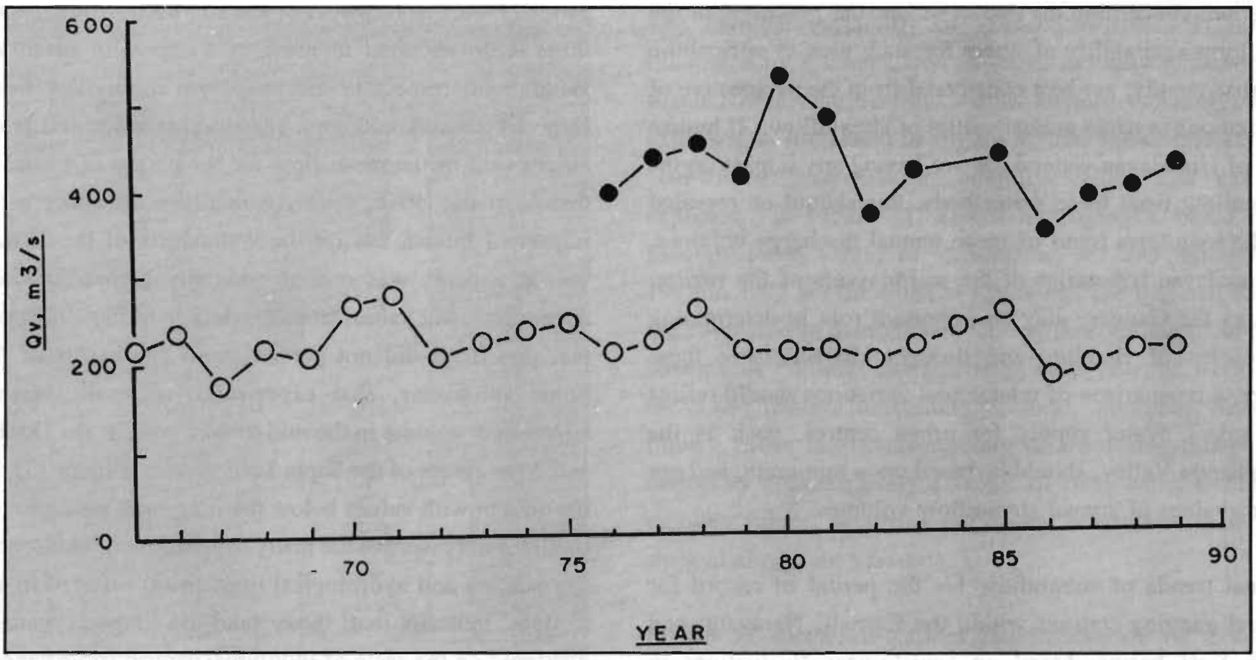


Figure 33: Average Monthly Streamflow Volumes for the Arun River (closed circles) and the Dudh Kosi

Showing that the latter half of the 1980s, during which time a major flood was experienced on the Ganges and Brahmaputra rivers, was below the long-term average in both basins

Periods of maximum annual peak discharge do not necessarily occur in phase among the sub-basins of Nepal, nor with those of the major rivers of the region. While this lack of correspondence for selected sub-basins of Nepal can be seen in Figures 32 and 33, it is illustrated more effectively by a comparison of the annual maximum and minimum discharge of the Kali Gandaki (410) and Sun Kosi (630) rivers, in the Narayani and Sapta Kosi basins respectively (Figure 34).

During the period from 1965 to 1985, the mean maximum annual discharge volumes for these two sub-basins have been generally out-of-phase, with higher-than-average values in one sub-basin commonly corresponding with lower-than-average values in the other during any given year. Again, the extreme variability shown by peak flow volumes is not present in the low flows for each year, which show a very uniform, and similar, trend throughout the period.

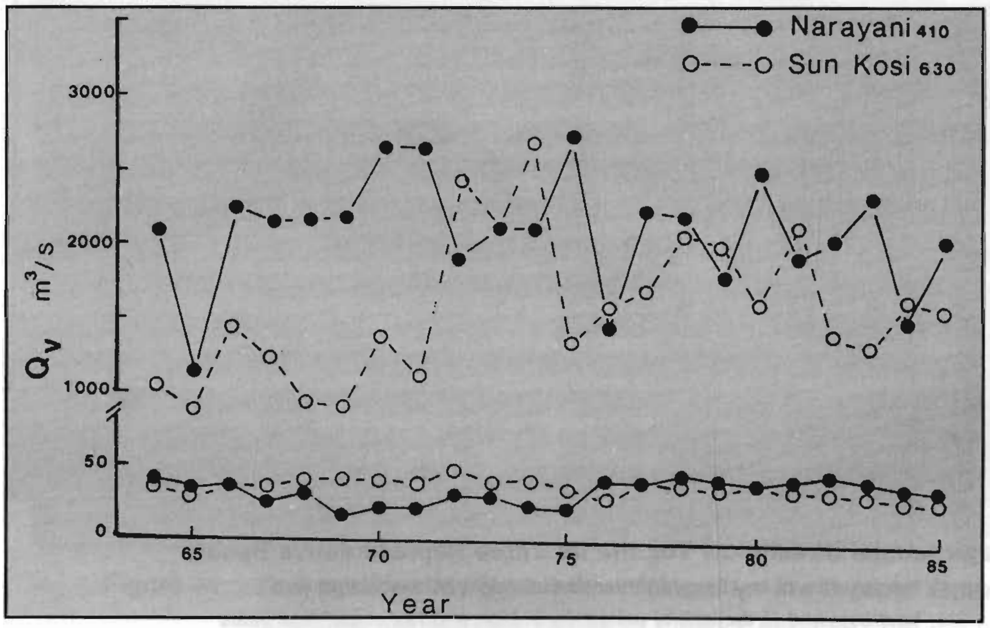


Figure 34: The Non-synchronous Nature of Maximum Monthly Volumes

This is apparent in this comparison of the Kali Gandaki and Upper Sun Kosi rivers. Low flows, on the other hand, show little year-to-year variation

A similar lack of correspondence of annual trends of discharge volume characterises the annual flood peak, Qm - the highest discharge measured annually - of the Ganges River (as measured at the Farrakha Barrage (Rao 1984); and the sum of the annual flood peaks of the Karnali, Narayani, and Sapta Kosi basins. This relationship for the period 1967-1976 is illustrated in Figure 35. The data on which Figure 35 are based are given in Table 13. It can be seen that, during the period from 1967 to 1976, maximum flood peaks on the Ganges River occurred during the years 1971 and 1976, while the cumulative maximum peak discharge of the three Nepal basins occurred in 1970 and 1974. The years 1971 and 1976 were characterised by a lower-than-average cumulative discharge from Nepal.

While there is considerable scatter, the correlation between the Himalayan and Ganges river floods and droughts appears to be negative, with maximum percentage contributions from the Himalayas occurring during years of minimum discharge from the Ganges River (Figure 36). This preliminary analysis suggests that the primary role played by Himalayan tributaries in the cycle of flooding and drought that characterise the Ganges River basin is that of modulating this cycle.

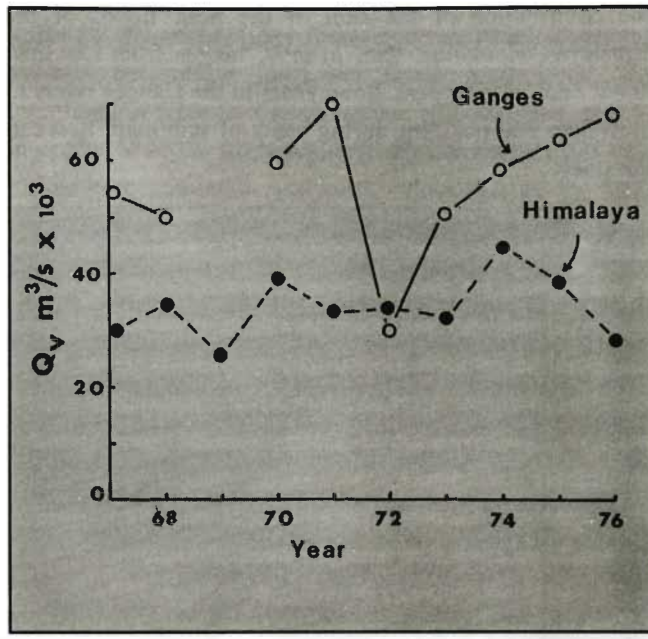


Figure 35: Based Upon the Sum of Peak Annual Flows for the Major Rivers of Nepal
There is no apparent correlation between floods in Himalayan headwaters and those of the main Ganges River

Table 13: Maximum Monthly Discharge (m^3/s) Values for the Ganges River and Major Nepalese Tributaries

YEAR	GANGES	KARNALI	NARAYANI	KOSI	SUM (NEPAL)	%NEPAL/GANGES
1967	54500	9780	8790	6990	25560	47
1968	50000	10700	10200	12790	33690	67
1969	--	10500	7270	7360	25130	--
1970	60000	14400	12900	11260	38560	64
1971	70500	14800	9760	7950	32510	46
1972	30500	10900	13800	8700	33400	110
1973	51600	10700	12800	8230	31730	62
1974	59000	8980	25700	10910	45590	77
1975	64000	16000	15100	7320	38420	60
1976	68500	7450	--	6070	-----	--
			RANK OF MAXIMUM ANNUAL DISCHARGE			
1967	6	7	8	9	8	
1968	8	5	6	1	3	
1969	-	6	9	7	9	
1970	5	3	4	2	2	
1971	1	2	7	6	6	
1972	9	4	3	4	5	
1973	7	5	5	5	7	
1974	4	8	1	3	1	
1975	3	1	2	8	4	
1976	2	9		10	-	

Note: Values for the Kosi System are sums of stations 680 (Sun Kosi) and 690 (Tamur). Data for the entire Sapta Kosi basin are not available for this period. Ganges data are measurements at the Farrakha Barrage.

Source: DHM Nepal, unpublished and Rao 1984

The contribution of the sum of the peak floods of the Himalayan tributaries, Qm, in m³/s, ranges from less than 50 per cent, during peak flood years in the Ganges river, to more than 100 per cent during years of minimum flows in that river.

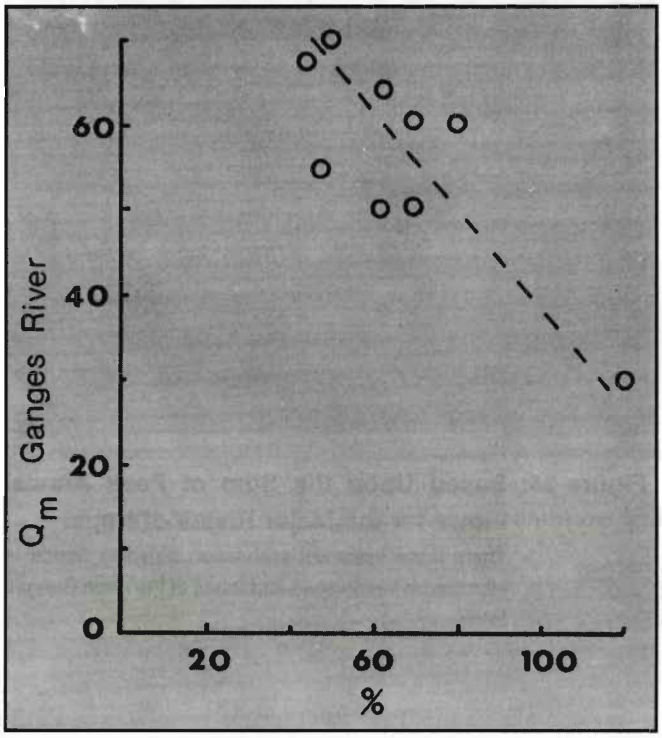


Figure 36: While there is considerable scatter, the correlation between per cent contribution of Nepali tributaries to the peak annual flow of the Ganges River appears to be negative. This suggests that the Nepali rivers modulate, rather than contribute negatively to, the flow of the Ganges

The annual maximum flood peaks for the Himalayan rivers of Nepal do not correspond in time to any greater extent than do the other defining characteristics of streamflow from the region. This is, for example, the reason that it is possible for the contribution of Nepalese headwaters to exceed 100 per cent of the flood peak of the Ganges River. In 1971, a year with the highest flood peak during the period represented in Figure 35, the Karnali River peaked on the 10th of September, the Narayani River peaked a month earlier, on the 8th of August, the Sun Kosi peaked on 12th of June, and the Tamur peaked on the 7th of August. The date of peak flow in the Ganges River was not available. It is clear that both extreme flood events in the Himalayan tributaries, and the coincidence in time of these events, are necessary for a direct correlation to exist between the tributaries and floods in the Ganges basin. It is a general lack of coincidence in time, rather than a lack of total volume of streamflow, that makes the contribution of Himalayan tributaries. Maximum annual peak discharge is a reasonable index to the total volume of streamflow during any given year, as indicated by a comparison of maximum peak flows and mean annual flows. Based upon a larger, random sample of the Himalayan rivers than was used to define the relationship shown in Figure 35, the relationship between Qv and Qm is compared in Figure 37. While there is considerable scatter in this relationship, it is clear that a correlation exists between peak and mean annual streamflow for a majority of Nepalese rivers. It is probable that much of the scatter is related to the variations in the factors determining variations in the slope of the recession curve - primarily climate, geology, and topography. This further demonstrates that it is timing, rather than total volume, that is crucial in determining the importance of Himalayan tributaries to floods in the Ganges or Brahmaputra basins.

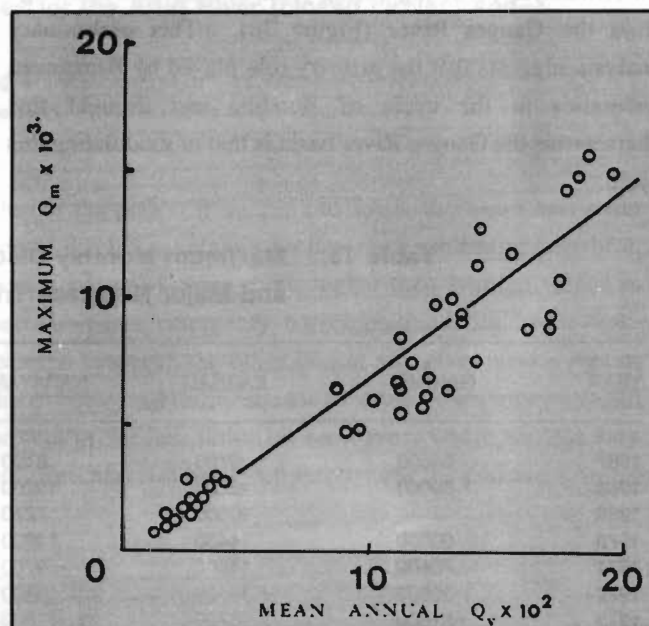


Figure 37: The relationship between peak annual flows and mean annual flows is positive, suggesting that the latter may be used as an index to the contribution of Nepali tributaries to the flood-drought cycles of the Ganges basin

Snow Hydrology

Serious studies of the snowmelt component of the annual hydrograph of Himalayan basins in Nepal is very recent (Grabs, Personal Communication, 1989). Some indication of the probable contribution from this source is provided by studies conducted by the Japanese (Higuchi et al. 1976) and, more recently by the German Technical Assistance Programme (GTZ) in collaboration with the Nepalese Department of Hydrology and Meteorology (Grabs 1989).

Data for four small, high-altitude basins in the upper Dudh Kosi basin - the Imja Khola, and unnamed tributaries at Gokyo, Pheriche, and Dingboche - for 1984 - are given in Table 14. Nineteen eighty-four was a year of approximately average streamflow from the Dudh Kosi basin. The hydrology of these four small basins, all with mean altitudes in excess of 5,000 m, is undoubtedly dominated by a cycle of snow accumulation and melt, while that of the lower Dudh Kosi is assumed to be largely produced by monsoon precipitation.

Table 14: Streamflow and Runoff Statistics for Glacierised Basins of the Upper Dudh Kosi River -- 1984

GAUGED WATERSHEDS OF THE DUDH KOSI BASIN -- 1984

BASIN	AREA (sq.km.)	AVG ALT(m)	Q m^3/s	Q mm	Q(ANN) $mx10^9$
Imja Khola	692	5289	32	1490	1.0
Gokyo	275	5339	14	1560	0.4
Pheriche	144	5570	6	1330	0.2
Dingboche	147	5478	12	2540	0.4
Dudh Kosi	4100	4000	233	1700	7.3

Source: W. Grabs, Personal Communication 1989 and DHM unpublished

An inspection of the total annual volume of streamflow for the four in Table 14 shows that they produced nearly 2,000 million cubic metres in 1984, 27 per cent of the flow of 7,000 million cubic metres produced by the entire Dudh Kosi basin. This is consistent with the relative surface area involved, 1,258 sq.km., or 30 per cent of the total surface area of the Dudh Kosi above the DHM hydrometric station (670). While these data cannot be generalised (Alford 1985, unpublished), it is probable that they provide a better than order-of-magnitude estimate of the percentage contribution of snowmelt to the annual hydrographs of many Himalayan sub-basins.

Variations in Runoff with Altitude

Much of the diversity of hydrological environments, described to this point, clearly is associated with the "characteristic irregularities of topography", referred to by the International Association of Hydrological Sciences (IAHS 1982). A primary research goal for the region should be development of quantitative conceptual models, relating streamflow to topography and geographical location within the region, in an attempt to resolve some of the uncertainties now associated with these relationships.

For this study, it is assumed that the range of hydrological environments is primarily a result of two factors:

(1) the orographic control exerted by the Great Himalayas on air masses moving across them and

(2) the altitudinal distribution of surface area present in individual sub-basins.

If it is assumed that the hydrologic regimes of the high-altitude watersheds of the Nepalese Himalayas are responding primarily to orographic controls, it is possible to construct a simple model to predict the water budget of any given sub-basin in the region, given an accurate topographic map and some measurements of streamflow in the general vicinity of the area of interest.

This assumption implies that the macro-scale meteorological environment of the Himalayas - the atmospheric processes determining precipitation, evaporation, and snow-ice-melt - is relatively uniform over large portions of the region, and that variations among individual sub-basins are caused primarily by geomorphic (topographic) differences among these sub-basins, primarily the distribution of surface area with altitude and aspect. The hydrologic regime of each individual sub-basin should be determined by the interaction between a heterogeneous meso-scale topography and the more homogeneous macro-scale meteorological regime of the region.

To test the hypothesis with respect to altitudinal controls, empirical curves, relating specific runoff to mean sub-basin altitudes for the Karnali basin (Figure 38), Narayani basin (Figure 39), and the Sapta Kosi basin (Figure 40), were plotted.

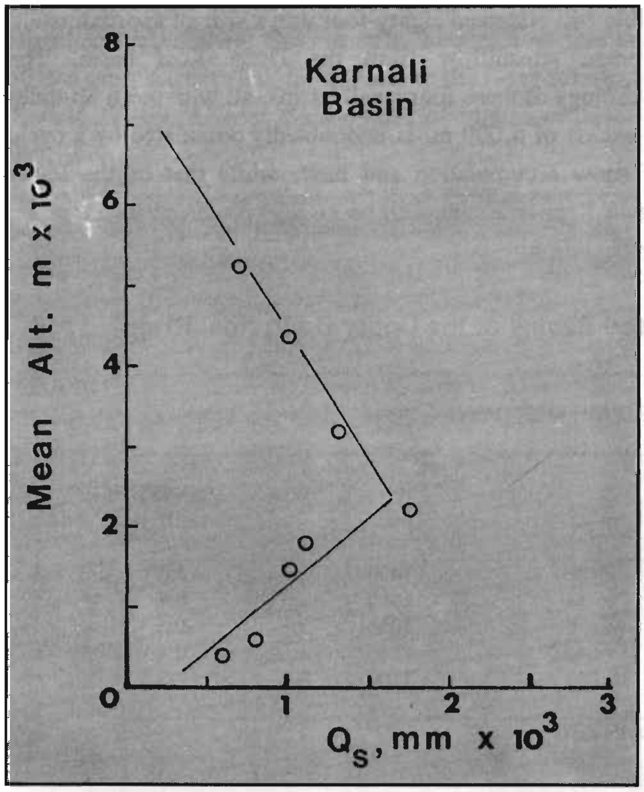


Figure 38: The Relationship between Mean Basin Altitude, Z, m, and Specific Runoff, Qs, mm, for the Sub-basins of the Karnali River

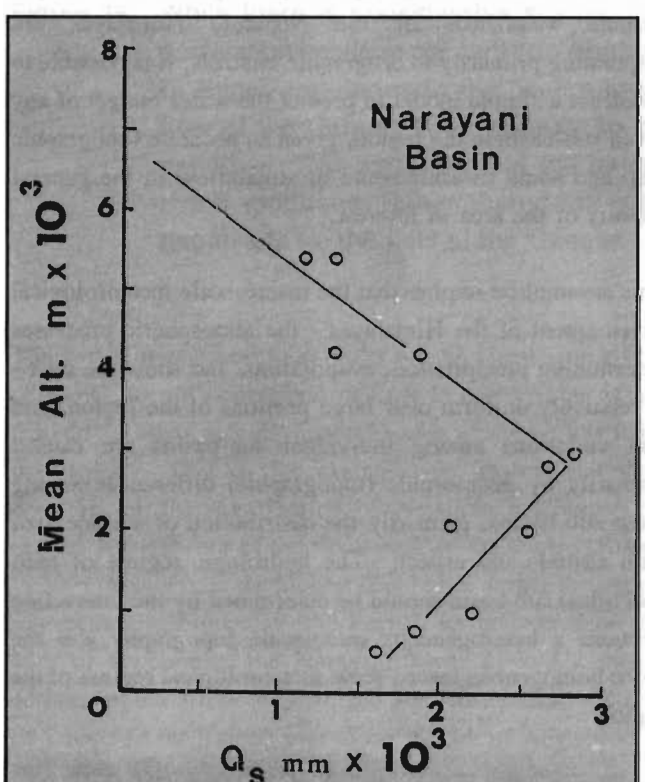


Figure 39: The Relationship between Mean Basin Altitude, Z, m, and Specific Runoff, Qs, mm, for the Sub-basins of the Narayani River

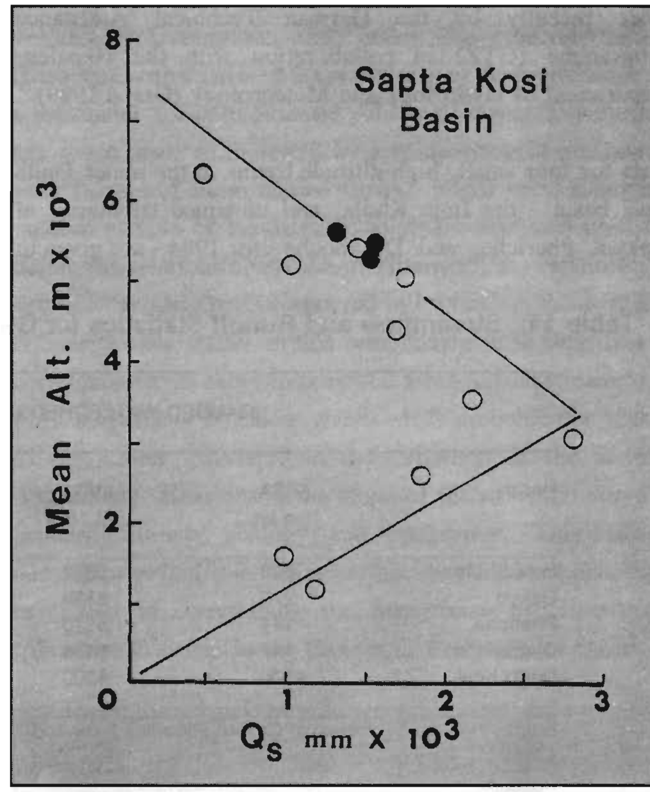


Figure 40: The Relationship between Mean Basin Altitude, Z,m, and Specific Runoff, Qs, mm, for the Sub-basins of the Sapta Kosi River

Closed circles represent runoff from small basins in the Upper Dudh Kosi River, 1984 (Grabs, personal communication 1989)

From the relationships shown in Figures 38, 39, and 40, at least three separate hydrological environments related to altitude can be identified.

1. A low-altitude belt, between approximately 0 and 4,000 masl, representing primarily sub-basins with low to intermediate mean altitudes on the southern slopes of the Great Himalayas and within the Mahabharat Lekh.
2. A high-altitude belt, between approximately 4,000 and 7,000 masl, representing sub-basins with high mean altitudes on the south slopes of the Great Himalayas in Eastern Nepal.
3. A high-altitude belt, between approximately 5,000 and 7,000 masl, representing those portions of catchment basins north of the Great Himalayas on the Tibetan Plateau.

As a first approximation, each of these environments may be described in terms of simple linear equations, relating specific runoff to discrete altitudinal belts:

for low-altitude sub-basins: $Qs = kZ + Qs_o$ and (4)

for high-altitude sub-basins: $Qs = Qs_o - (Z - Z_o)\,k$ (5)

where,

k is the rate of change of specific runoff with altitude, Qs_o is the value of specific runoff at the minimum altitude for the respective curve, Z is the altitude for which Q_s is calculated, and Z_o is a base altitude for each curve.

Based upon the empirical relationships between specific runoff and mean basin altitudes, equations (4) and (5) were evaluated as follows.

for Eastern Nepal -

$$Q_s = 0.45Z + 1500 \quad (6)$$
$$Z_o = 0$$

$$Q_s = 2900 - (Z\text{-}Z)\,(-0.65) \quad (7)$$
$$Z_o = 3200$$

for the Tibetan Plateau -

$$Q_s = 2000 - (Z - Z\ )(-2.00) \quad (8)$$
$$Z_o = 4500$$

for western Nepal -

$$Q_s = 0.45Z + 425 \quad (9)$$
$$Z_o = 0$$

$$Q_s = 1550 - (Z - Z\ )(-0.3) \quad (10)$$
$$Z_o = 2250$$

Equations (6), (7), (8), (9), and (10) were tested against eight sub-basins in the Sapta Kosi basin, six sub-basins in the Narayani basin, and one sub-basin in the Karnali basin. In general, agreement between calculated and measured streamflow volumes is good, but these results are considered tentative, largely due to the scale of the available topographic information (Tables 15 and 16).

Of more interest at this preliminary stage of model development, however, are the boundaries at which it became necessary to shift from the "eastern" to the "western" form of the model (from equations [6] and [7] to equations [9] and [10]) and which basins required the use of equation (8) (for the Tibetan Plateau). These shifts are interpreted as indicating a transition between distinct hydrological environments, given the great difference in the constants used to drive the three sets of equations. The preliminary results indicate that the boundary between "eastern" and "western" Nepal, for hydrological purposes, is in the vicinity of the Kali Gandaki River. Only those sub-basins with more than approximately 50 per cent of their surface area on the Tibetan Plateau (i.e., the Arun, Bhote Kosi, Trisuli, and Burhi Gandaki) required the use of the "Tibetan" form of the model (Figure 41).

Table 15: Calculated and Measured Values of Streamflow

Selected Sub-basins of the Nepalese Himalayas

Sub-Basin	Equations	Calculated mcm*	Measured mcm*	%C/M
Dudh Kosi	(6)(7)	7000	7300	96
Tamur	(6)(7)	11000	11000	100
Likhu Khola	(6)(7)	1700	1800	96
Arun	(6)(8)	14000	13000	103
Sun Kosi (630)	(6)(7)	10000	8200	125
Bhote Kosi	(6)(8)	2700	2500	106
Balephi Khola	(6)(7)	1300	1600	77
Tama Kosi	(6)(8)	4400	4400	97
Phalankhu Khola	(6)(7)	370	410	90
Tadi Khola	(6)(7)	1400	1300	111
Trisuli	(6)(8)	6300	5900	108
Burhi Gandaki	(6)(8)	5100	5000	103
Marsyangdi	(6)(7)	7200	6700	108
Seti Khola	(6)(7)	1300	1600	123
Kali Gandaki	(9)(10)	7400	8400	114
Karnali	(9)(10)	1600	1600	103

*mcm = Million Cubic Metres. Measured values from DHM, unpub.

Clearly, there is an altitudinal component in the annual runoff from Nepalese sub-basins. The requirement for a "Tibetan" form of the model indicates the existence of a strong aspect gradient as well. The fact that these topographic irregularities can be described in relatively simple terms on the scale of discrete altitudinal belts within individual sub-basins indicates that the goal of modelling Himalayan hydrologic regimes is achievable. On the regional scale, the work of Russian scientists (Dreyer et al. 1982) suggests a strong possibility that the entire western Hindu Kush-Himalayan Region may be described by an equation similar to the equation (6) used in this study. Similar relationships between altitude and runoff exist in the mountains of western North America (Alford 1985). The possibility of developing a general model of meso-scale mountain hydrologic systems is good, and attempts to do this should be a high priority among those concerned with water resources in regions such as the Hindu Kush-Himalayas.

Table 16: Representative Calculations, Distribution of Runoff with Altitude in Selected Sub-basins of the Nepalese Himalayas

Altitude Belt (m)	Area sq.km.	%	Q m	Q m^3	%
DUDH KOSI 670					
500	584	0.18	1.75	1.0e+09	0.15
1500	876	0.27	2.20	1.9e+09	0.28
2500	681	0.21	2.60	1.8e+09	0.25
3500	380	0.12	2.75	1.0e+09	0.15
4500	380	0.12	2.00	7.6e+08	0.11
5500	227	0.07	1.50	3.4e+08	0.05
6500	130	0.04	0.75	9.7e+07	0.01
TOTAL	3244	1.00			
	CALCULATED			6.96e+09	0.96
	MEASURED			7.28e+09	
TAMUR RIVER 690					
500	790	0.15	1.75	1.38e+09	0.13
1500	1356	0.26	2.20	2.98e+09	0.27
2500	1243	0.24	2.60	3.23e+09	0.30
3500	565	0.11	2.75	1.55e+09	0.14
4500	518	0.10	2.00	1.04e+09	0.09
5500	340	0.07	1.50	5.1e+08	0.05
6500	340	0.07	0.75	2.6e+08	0.02
TOTAL	5152				
	CALCULATED			1.10e+10	1.01
	MEASURED			1.09e+10	

Altitude Belt (m)	Area sq.km.	%	Q m	Q m^3	%
KALI GANDAKI 410					
500	100	0.02	0.65	6.5e+07	0.01
1500	800	0.12	1.10	8.8e+08	0.12
2500	1750	0.26	1.55	2.7e+09	0.36
3500	1450	0.22	1.30	1.9e+09	0.25
4500	1200	0.18	1.00	1.2e+09	0.16
5500	900	0.14	0.65	5.9e+08	0.08
6500	375	0.06	0.35	1.3e+08	0.02
7500	80	0.01	0.00	0.0e+00	0.00
	6655	1.00	CALCULATED	7.5e+09	0.89
			MEASURED	8.4e+09	
ARUN RIVER 604					
500	850	0.03	1.75	1.49e+09	0.11
1500	1487	0.05	2.20	3.27e+09	0.24
2500	1487	0.05	2.60	3.87e+09	0.28
3500	744	0.03	2.75	2.04e+09	0.15
4500	744	0.03	2.00	1.49e+09	0.11
5500	15244	0.52	0.10	1.52e+09	0.11
6500	9000	0.30	0.00	0	0.00
TOTAL	29555				
	CALCULATED			1.37e+10	1.03
	MEASURED			1.33e+10	
KARNALI RIVER (240)					
500	193	0.01	0.65	1.3e+08	0.01
1500	963	0.05	1.10	1.1e+09	0.07
2500	1540	0.08	1.55	2.4e+09	0.15
3500	2504	0.13	1.30	3.3e+09	0.21
4500	3563	0.19	1.00	3.6e+09	0.23
5500	5008	0.26	0.65	3.3e+09	0.21
6500	5394	0.28	0.35	1.9e+09	0.12
TOTAL	19165	1.00			
		CALCULATED		1.6e+10	0.98
		MEASURED		1.6e+10	

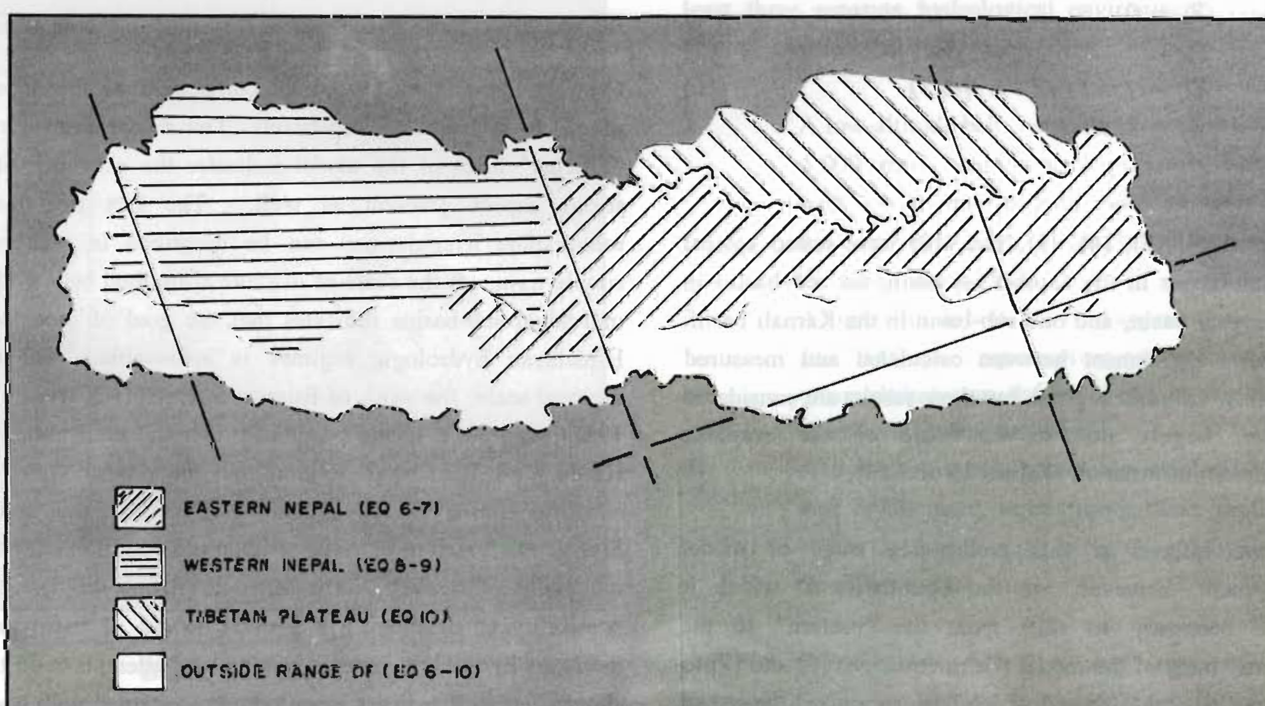


Figure 41: The Three Major Hydrological Environments Described by Equations (6)-(10) in the Text