DISSERTATION

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IMPACT OF LAND-USE AND CLIMATIC CHANGES ON HYDROLOGY OF THE HIMALAYAN BASIN: A CASE STUDY OF THE KOSI BASIN

BY
KESHAV PRASAD SHARMA

DOCTOR OF PHILOSOPHY
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GLOSSARY OF ABBREVIATION

α	Significance level
AA	Agriculture area (km^2)
AG	Alpine grazing land (km^2)
asl	Above sea level
C	Cyclic component
CBS	Central Bureau of Statistics
CG	Cold-tropical grazing land (km^2)
CSRC	Complex Systems Research Center
cdf	Cumulative distribution function
CF	Conifer forest (km^2)
CSRC	Complex Systems Research Center
CWC	Central Water Commission
D	Detention storage (mm)
d	Fraction of vegetative area of a catchment
DCW	Digital Chart of the World
DD	Degree decimal
DEM	Digital Elevation Model
DEM30	Digital Elevation Model with 30 Arc-Sec Resolution
DHM	Department of Hydrology and Meteorology
DTED	Digital Terrain Elevation Data
E	Total loss that includes ET and interception (mm)
ELV	Elevation (m)
F	F-Statistics
FAO	Food and Agriculture Organization
e	Evaporation fraction
e_s	Saturation vapor pressure (mb)
ET	Evapotranspiration (mm)
FAO	Food and Agriculture Organization
FRISP	Forest Resource Information System Project
GCM	Global Climate Model(s)
GDS	German Development Service
GELV	Grid elevation (m)
GEN	Glaciological Expedition in Nepal
GLOF	Glacier Lake Outburst Flood
GTZ	German Agency for Technical Cooperation
HF	Hardwood and mixed forest (km^2)
HMG	His Majesty's Government

I	Irregular component
ICIMOD	International Centre for Integrated Mountain Development
IA	Intense agriculture area (km^2)
IMD	India Meteorology Department
IS	Ice and snow area (km^2)
KM1	Area between 500 m to 1 km (km^2)
KM2	Area between 1 km to 2 km (km^2)
KM3	Area between 2 km to 3 km (km^2)
KM4	Area between 3 km to 4 km (km^2)
KM5	Area between 4 km to 5 km (km^2)
KM6	Area between 5 km to 6 km (km^2)
KM9	Area between 6 km to 9 km (km^2)
L	Lake (km^2)
LA	Light agriculture (km^2)
LAT	Latitude
LRMP	Land Resources Mapping Project
LON	Longitude
LT	Local Time
LT500	Area less than 500 m (km^2)
MA	Medium agriculture (km^2)
MAB	Man and Biosphere
N	Number of observation
ns	Nonsignificant
P	Precipitation (mm)
p	Precipitation fraction
PET	Potential Evapotranspiration (mm)
p-value	Probability
R^2	Coefficient of determination
RB	Rock and boulders (km^2)
S	Seasonal component
S	Shrub (km^2)
SAINDX	Slope-aspect index
SG	Sub-tropical grazing land (km^2)
SGHU	Snow and Glacier Hydrology Unit
S_y	Sediment yield (million ton)
T	Temperature (°C)
t	t-statistics
TU	Tribhuvan University
u/s	Upstream
UNEP/GRID	United Nations Environmental Program/Global Resource Information Database
UNDP	United Nations Development Program
UNH	University of New Hampshire
Var	Variance

w	Runoff ratio
WEC	Water and Energy Commission
WMO	World Meteorological Organization
Z	Elevation (m)

ABSTRACT

IMPACT OF LAND-USE AND CLIMATIC CHANGES ON HYDROLOGY OF THE HIMALAYAN BASIN: A CASE STUDY OF THE KOSI BASIN

By

Keshav Prasad Sharma
University of New Hampshire, May 1997

Land-use and climatic changes are of major concern in the Himalayan region because of their potential impacts on a predominantly agriculture-based economy and a regional hydrology dominated by strong seasonality. Such concerns are not limited to any particular basin but exist throughout the region including the downstream plain areas. As a representative basin of the Himalayas, we studied the Kosi basin (54,000 km^2) located in the mountainous area of the central Himalayan region. We analyzed climatic and hydrologic information to assess the impacts of existing and potential future land-use and climatic changes over the basin.

The assessment of anthropogenic inputs showed that the population grew at a compound growth rate of about one percent per annum over the basin during the last four decades. The comparison of land-use data based on the surveys made in the 1960s, and the surveys of 1978-79 did not reveal noticeable trends in land-use change. Analysis of meteorological and hydrological trends using parametric and nonparametric statistics for monthly data from 1947 to 1993 showed some increasing tendency for temperature and precipitation. Statistical tests of hydrological trends indicated an overall decrease of discharge along mainstem Kosi River and its major tributaries. The decreasing trends of streamflow were more significant during low-flow months. Statistical analysis of homo-

geneity showed that the climatological as well as the hydrological trends were more localized in nature lacking distinct basinwide significance. Statistical analysis of annual sediment time series, available for a single station on the Kosi River did not reveal a significant trend.

We used water balance, statistical correlation, and distributed deterministic modeling approaches to analyze the hydrological sensitivity of the basin to possible land-use and climatic changes. The results indicated a stronger influence of basin characteristics compared to climatic characteristics on flow regime. Among the climatic variables, hydrologic response was much more sensitive to changes in precipitation, and the response was more significant in the drier areas of the basin. Rapid retreat of glaciers due to potential global warming was shown to be as important as projected deforestation scenarios in regulating sediment flux over the basin.

CHAPTER I

INTRODUCTION

Two thousand and four hundred kilometers long and 150 to 400 km wide, the Himalayan ranges are the biggest and the tallest mountain structure on Earth. These high mountains not only provide the sources for several perennial rivers but also influence the climate, water cycle, and energy budget of the region. Along with the Tibetan plateau, massive mountains of the Himalayas, extending up to the tropopause, play major role in the generation of monsoons (Hahn & Manabe, 1975; Murakami, 1987), the most extensive and the most dynamic weather system on Earth. The agriculture-based socio-economy of the region is vulnerable to any unfavorable climatic change over the Himalayas (Swaminathan, 1987). Such impacts have the potential for directly affecting the lives of almost one tenth of the world's population living in the Himalayas and its adjacent plains.

Influence of population pressure on land resources coupled with the potential impacts of global climate change on regional water cycle is a major concern; however, the nature of such impacts has been a subject of debate among scientists. There are large uncertainties regarding the scale of water cycle impacts due to changes in land use (Bosch & Hewlett, 1982) as the impacts depend on several governing factors and forcing functions. Similarly, a significant uncertainty lies in the estimate of climatic trends particularly at regional levels (Lamb, 1987; Mitchell & Qingcun, 1991).

Considerable concern has been expressed in the past about the degradation of the Himalayan environment due to land use changes in the mountains (Eckholm, 1975; Bruijnzeel, 1989). Likewise, effects of global climate change on the Himalayan region as a whole have been drawing the significant attention of scientists. A particular concern is the predicted rise in temperature in the central Himalayas which is generally greater than the adjacent areas under different global warming scenarios (Bhaskaran et al., 1995; Schneider & Rosenberg, 1989). The 'Himalayan dilemma' (Ives & Messerli, 1989) as a result of land-use changes has, hence, become a more complex dilemma with the additional issue of global climatic changes.

This study considers one aspect of climate change: the water cycle. Within this broad topic we focus upon climatic trends and riverine transport in a selected Himalayan drainage basin: the Kosi River basin. The selection of this basin is based on the following factors:

1. Location and representativeness

- The basin lies in the central Himalayas.
- Almost half of the basin lies in the southern part of the Himalayas and the remaining half lies in the Tibetan plateau. These are the two distinct Himalayan environments representing humid and steep topography of the South and dry plateau of the North.

- Relatively longer climatologic records are available for this basin as compared to other similar basins of the Nepal Himalayas.
- The size of the basin is suitable for meso-scale hydrological study (Ives, Messerli, & Thompson, 1987).

2. Environmental concerns

- The anthropogenic influence in this basin is considered to be severe among similar Himalayan basins of the region.
- There are currently no major structural changes, such as inter-basin water transfer or dam construction, to the flow regime of the Kosi River and its major tributaries.
- The river system includes some of the most sediment laden rivers of the world.
- The basin has high potential economical significance through future hydropower development. The basin has higher hydro-power and irrigation potential (Sharma, 1977; Thapa, 1993) than any other basins in Nepal.

Background

Despite narrations on environmental degradation because of serious damage to forests in the Nepalese mountains are available (Collier, 1928) long before the onset of the population explosion (Karan, 1987) in the region, the general conception of the government and people of Nepal supported the view that the country was rich in forest resources. The government of Nepal even encouraged deforestation for more agricultural land, for commercial exploitation of timber, and for reducing depredations of wild animals (Bajracharya, 1983; Collier, 1928). A closed agrarian society, high illiteracy rate, and nonexistence of proper governmental or nongovernmental organizations to deal with the environment were some of the reasons behind a lack of consciousness towards environmental conservation.

Udyog Parishad (Development Board), constituted in 1935, was the first organized government agency to be charged with several development activities including agriculture and forest. It was followed by the establishment of specialized agencies, such as, *Krishi Parishad* (Agriculture Board) and *Kathmal Report Adda* (Forestry Report Office). Despite these developments, little happened regarding the development of land-use inventory and land-use policy until 1956 when government announced the first five year plan (Shrestha, 1968).

The following are some of the major developments that followed as a result of the establishment of responsible government agencies (Bajracharya, 1985; Carson, Nield, Amatya, & Hildreth, 1986; Department of Forest, 1973).

- Nationalization of the forest in 1957.
- Forest Act 1961 with recognition of *Panchayat* (local community) and private forest.
- Establishment of the Forest Resources Survey office in 1963 that initiated the development of a forest inventory as a part of its responsibilities.

- National Parks and Wildlife Protection Act of 1973 that resulted in the establishment of several national parks in the nation including Sagarmatha National Park in the Kosi basin.
- *Panchayat* Protected Forest Law of 1978 which laid down the rules and regulations for the *Panchayat* forests.
- Community Forest Development Project of 1979 with assistance from UNDP and FAO.

The above list shows that there were several changes in forest policies within a period of two decades. These subsequent changes in forest policy were the result of failure of some of the implemented programs. Particularly, the nationalization of forest in 1957 is believed to be a major debacle in the forest history of Nepal (Bista, 1992). The nationalization of the forests is blamed for the anarchy created from the transfer of community and private forest into government forest (Carson et al., 1986; Messerschmidt, 1987). Present policies of the government of Nepal are directed towards community forest development programs. In the process, the Department of Forest developed a master plan in 1989 and implemented the Forest Act of 1993 and the Forest Regulation of 1995. All these policies and programs promote the extension of community forests.

As described in the previous paragraphs, little information exists about the history of land-use change over the Kosi basin before 1950s. Some available historical accounts of land-use change in the Kosi basin indicate that most of the potential agricultural lands were already exploited by farmers long before this century to support the needs of the population (Lionel, 1970; Applegate & Gilmour, 1987). Lack of agricultural land is believed to be the main reason behind massive migration of Nepali citizens to India, Bhutan, and Sikkim particularly after the Nepal-Britain treaty in 1918 that ended the war (Lionel, 1970).

In contrast to the issues of land-use changes in the Himalayan mountains, the issue of global climatic changes is relatively new. Furthermore, the issue of global climatic changes has not yet received wide publicity in the region and hence the populace is generally unconcerned. It has been an issue mainly within the scientific community both inside and external to Nepal.

Although meteorological observations for the Indian Himalayas are available since the last quarter of nineteenth century (Sharma, 1982), no meteorological time series data are available for the Nepalese Himalayas before 1921. The history of secular meteorological records in Nepal started with the establishment of a precipitation gauging station in Kathmandu. The sole station at Kathmandu served to represent Nepal until late 1940s during which a network of precipitation gauging stations was initiated in the Kosi basin. The hydrological and meteorological network was upgraded in the 1960s after the establishment of the Department of Hydrology and Meteorology (DHM) in 1962. The department is the sole agency in Nepal responsible for maintaining and upgrading the hydrological and meteorological network, and it has been compiling, processing, and publishing hydrological and meteorological data since its fist publication in 1966 (DHM, various years). This study is the first assessment of the DHM data base for analyzing basin scale climatic trend and water balances.

Objectives

The main goal of this research is to analyze (1) the climatic trends in the Himalayas on the basis secular meteorological and hydrological data and (2) the impact of land-use and climatic changes on hydrology. The Kosi basin is chosen as representative of the central Himalayan region. The major objectives of the research work are the assessment and evaluation of the following:

- Land-use changes within the basin particularly during the period of secular hydrological and meteorological data.
- Climatic changes within the secular period.
- Overall impact caused by land-use and climatic changes on the hydrology of the basin.
- Trends in land-use and climatic changes in the basin and their possible impact on hydrology and sediment flux.

Research Questions

This research is directed towards addressing the following major scientific questions

1. Have there been significant changes in land-use area and land-use pattern in the past?
2. What are the characteristics of such changes?

3. Do available climatic data reveal any trend?

4. Do available hydrological and sediment data reveal any trend?

5. Has the yield of any river, stream or spring increased or decreased during low-flow or high-flow season?

6. What differences the land-use practices bring to the sediment yield characteristics of the main river and its major tributaries?

7. What type of basin scale hydrological responses can be expected in future in the different scenarios of potential climatic changes and projected land-use changes?

An implicit objective is an assessment, from the perspective of environmental change, of the DHM sampling network.

Scope and Limitations of the Study

The study is based on the analysis of most of the available information on environmental changes as a result of anthropogenic changes. It fills a significant gap existing in such study of highly fragile mountain environments of the world. The study attempts to answer several environmental questions on the basis of scientific indicators such as climate, river discharge and sediment yield of the basin. The outcome of the study is not only relevant to the scientists involved in the Earth sciences but also to policy makers and general public of the region.

The Kosi basin with an area of about 54,000 km^2 represents a major region of the Himalayas. Although the study falls in a category of meso-scale for the general classification of hydrological modeling scales, we can consider it a study of regional nature. Despite the heterogeneity of mountain environment in the Himalayan region, most of the meso-scale basins share many similarities in terms of physiography, bio-diversity, and anthropogenic activities. For instance, not only the drainage basin of Narayani (32, 000 km^2) and Karnali (42,000 km^2), the other two major rivers of Nepal, are comparable but also are monthly and annual discharges from these rivers (Sharma, 1993). The study has, hence, a significant scope to extend results to other meso-scale Himalayan basins with additional consideration of few eco-climatological differences.

Since the study deals with an environmental issue of relatively long temporal dimension and highly heterogeneous mountain environment, it has several obvious limitations. The followings are brief account of some of the limitations that directly affect the results of the study.

• *Record length and missing records.* Very little historical information of land-use and climate is available before the initiation of Kosi Project in 1947. Hence, almost all the analysis is based on relatively recent information. Besides length of the records, most of the data suffers from missing records.

• *Inadequate spatial sampling.* More than half of the basin lies 4,000 m above sea level. Except for three stations in Tibetan plateau of China, virtually no hydrological and meteorological data is available for this region.

• *A dearth of sediment information.* Although sediment transport by rivers is an important indicator of environmental changes within a basin, the sediment data base for the Kosi basin is poor for proper assessment.

• *Complex nature of the study.* The complex characteristic of land surface-atmosphere interaction under the influence of anthropogenic changes results in a wide range of uncertainties. These processes can not be studied in isolation. However, integrated application of available GIS tools and hydrological models has contributed towards reducing such shortcomings in recent years.

CHAPTER II

STUDY AREA

The Kosi River with its immeasurable historic, cultural and religious value (Pande & Goel, 1992) originates in the Tibetan plateau and the Nepalese high-lands. The river has seven major tributaries: Indrawati, Sunkosi, Tamakosi, Likhukhola, Dudhkosi, Arun, and Tamor (Figure II-1).

The Kosi River is known by several names in Nepal and India. The river is generally known as Saptakosi, meaning seven Kosis, in Nepal. In India, it is also known as Mahakosi meaning the great Kosi and Saharsadhara, meaning several currents as the river spreads into several currents when it merges out of the Mahabharat mountains at Chatara (Plate 1). Kosi is also synonymous with large river in the eastern Nepal; hence most of the major tributaries are called Kosi, for example, Sunkosi.

Although there are several explanations about the name of the Kosi River (Zollinger, 1979), it is believed to be derived from the name of a great *rishi* (hermit) Kaushik who used to live on the bank of this river. The river is referred to as Kaushika in Sanskrit literature.

The two major tributaries of the Kosi River, coming down into Nepal, are known by different names in Tibet. The Bhotekosi (upstream of Sunkosi) and the Arun are known as Poiqu and Pumqu in Tibet. The Bhotekosi (upstream of the Tamakosi) also

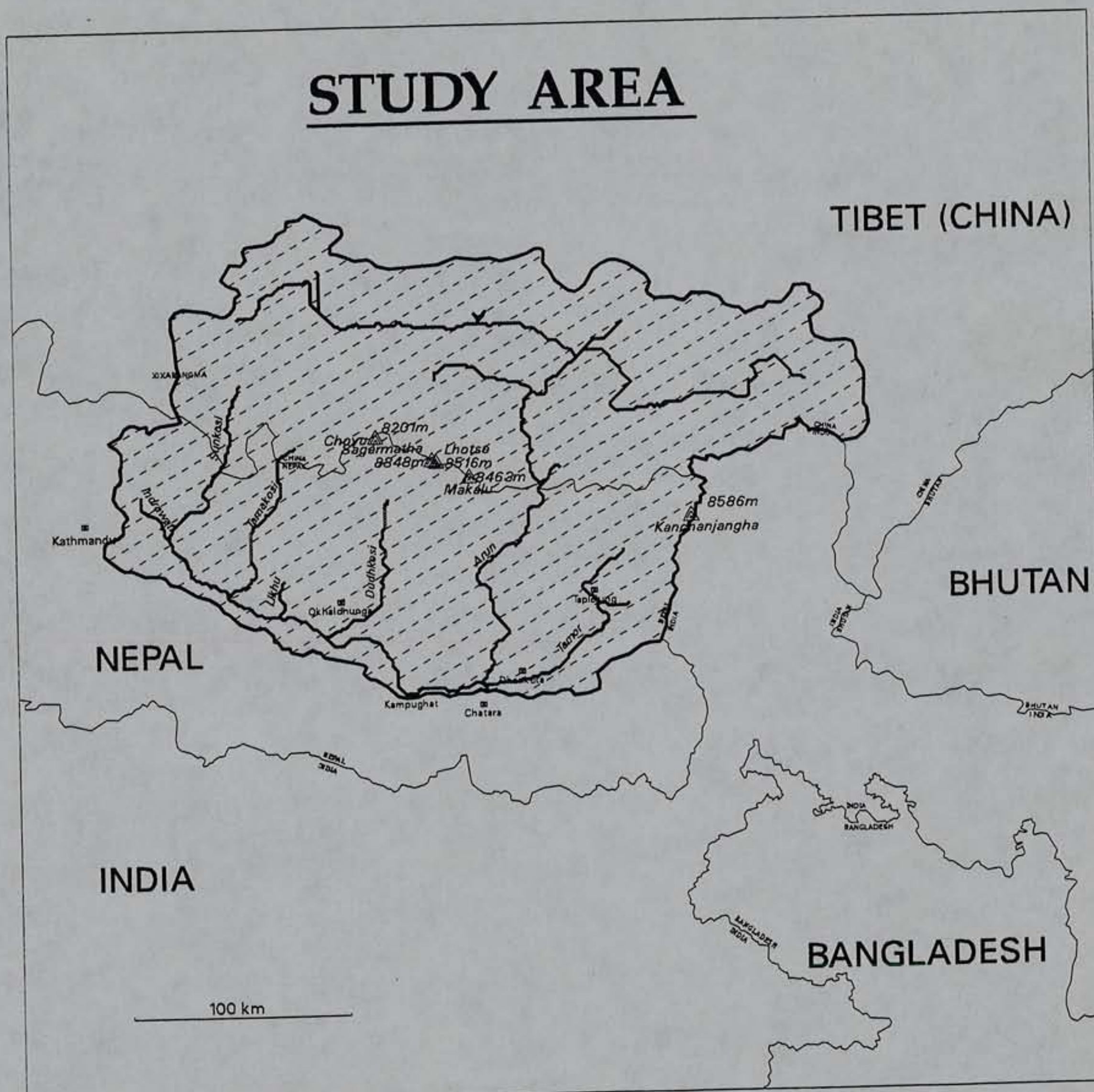


Figure II-1. Study area showing geographical locations and major tributaries of the Kosi River. The Kosi River forms and enters into the Gangetic plain at Chatara.

Plate 1. The Kosi River spreads in several channels when it enters into the Gangetic plain. (Looking downstream)

originates in Tibetan glacier close to the Nepal-China border. These rivers are called Bhote Kosi in Nepal as they originate in Bhot (commonly known name of Tibet in Nepal).

Basin Characteristics

The area considered in this study is the Kosi River basin upstream of Chatara lying in the mountainous region of the eastern Nepal and the southern Tibet (Figure II-1). The study area includes all the mountainous region of the Kosi basin. The area lies within the latitudes 26° 51' and 29° 79' and the longitudes 85° 24' and 88° 57'.

Three major river systems of the world originate in the Himalayas: Ganga, Brahmaputra, and Indus. Based on the river discharge, the Brahmaputra and the Ganga rank fourth and fifth respectively among the major rivers of the world (van der Leeden, Troise, & Todd, 1990). The amount of sediment transported to the ocean by the Ganga-Brahmaputra River system is the highest among the rivers of the world (van der Leeden et al., 1990). The Kosi is the third largest river in the Himalayas based on discharge and drainage area, with the Brahmaputra and the Indus rated first and the second. The Kosi is the biggest river system in Nepal. Table II-1 gives some major hydrological and sediment delivery characteristics of the Kosi River, its major tributaries, other major Himalayan rivers and compares these to the largest and the longest river systems of the world. Figure II-2 illustrates a comparison of the hydrology of the Kosi basin with the regional and the global hydrology.

Table II-1. Comparative chart showing the average annual hydrological and sediment delivery characteristics of the Kosi River, major Himalayan rivers and the largest (the Amazon), the longest (the Nile) and the most sediment laden (the Huanghe) river of the world.

	Kosi	*Ganga*	*Brahma-putra*	*Indus*	*Huanghe*	*Nile*	*Amazon*
Drainage Area ($*10^3$ km^2)	53.7	1060	935	927	673	3000	5800
Length (km)	520	2510	2900	2900	5460	6650	6400
Discharge (km^3/yr)	49.5	589	625	175	104	89	6700
Runoff (mm/yr)	922	556	668	189	154	30	1160
Sediment load (million tonnnes/yr)	135	520	540	250	1100	120	1200
Sediment yield (tonnes/km^2/yr)	2514	491	578	270	1634	40	207
Sediment per unit runoff ($*10^{-3}$)	1.95	0.63	0.62	1.02	7.59	0.96	0.13

Data for the Kosi basin were derived from this study. Data for other basins are from: drainage area, length, and discharge (van der Leeden, Troise, & Todd, 1990) and sediment load (Milliman & Syvitski, 1992).
Assumption: one cubic meter of sediment = 1.4 tons of sediment

Combined, the three major Himalayan rivers: Ganga, Brahmaputra, and Indus contribute to about 3.6 percent of the global river discharge and 9.3 percent of the global sediment discharge to the ocean (Figure II-2 and Table II-1). The Kosi River in the mountainous areas of the Himalayas flows with about 0.4 percent of the runoff and eight percent of the sediment delivered to the oceans by the three major rivers originating in the Himalayas (Figure II-2 and Table II-1). Although the sediment:discharge ratio of the Kosi River is lower than that of the Huanghe River (Yellow River) of China (Table II-1), the sediment yield is the highest of the rivers of the world with similar or larger basin area (Milliman & Syvitski, 1992).

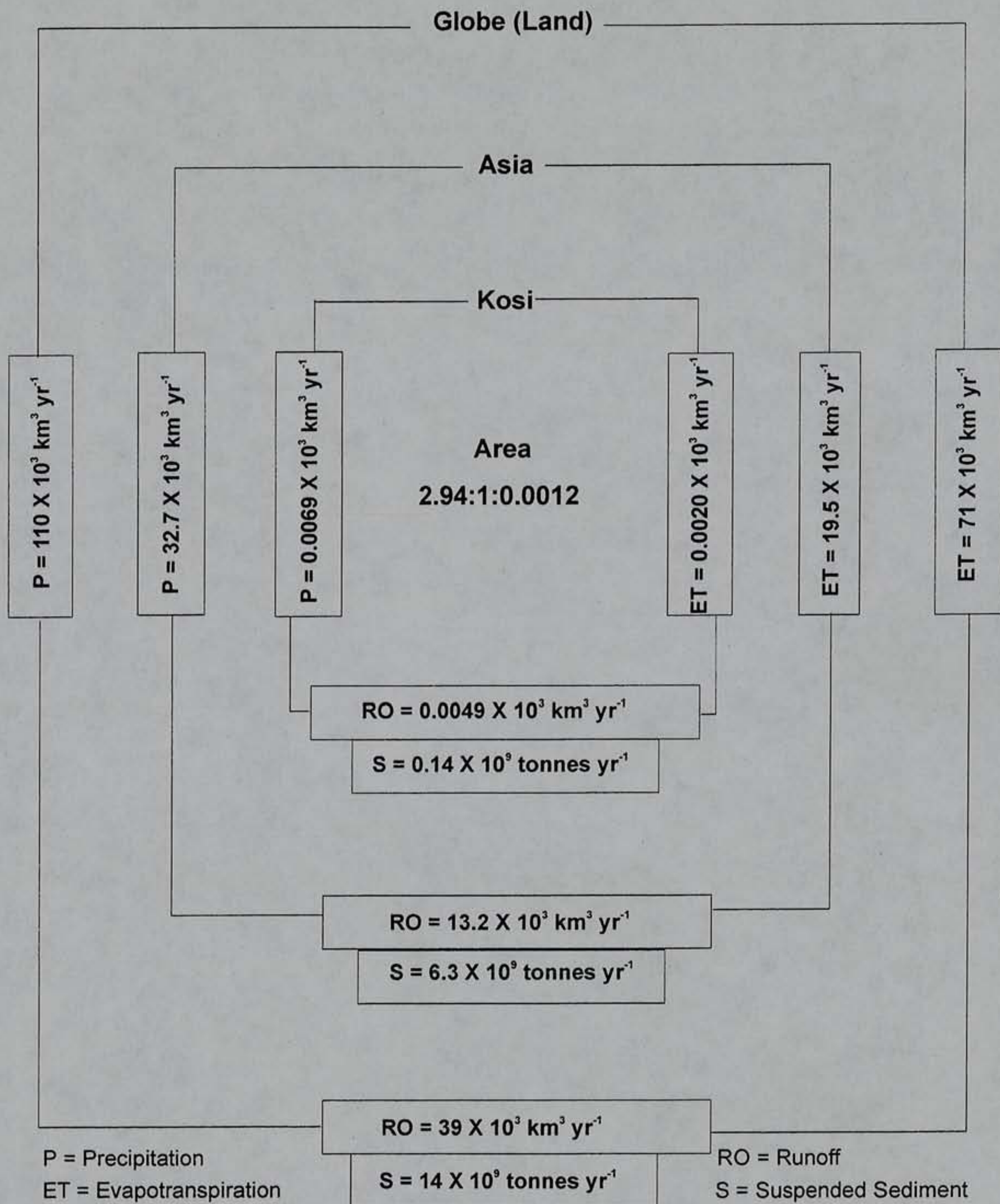


Figure II-2. Major components of annual hydrological cycle of the Kosi basin in relation to the continent and the globe.

Data from Chapter IX (the Kosi) and van der Leeden, Troise, and Todd (1990).

Geologically, the basin is a part of the region uplifted since the Pliocene Epoch (Sharma, 1990). The age of geological units, found in the higher Himalayan part of the Kosi basin, is estimated as pre-Cambrian to Mesozoic and those in the middle mountains are pre-Cambrian to upper Paleozoic (Morrison-Kundeson, 1991). The region is still believed to be geologically active (Jhingran, 1981). Bhotekosi and Arun, the two major tributaries of the Kosi River, are considered antecedent (Holmes, 1965; Wager, 1937).

The Kosi River at Chatara drains the highest and the steepest mountain system of the world. The average elevation of the basin is 3,800 m but varies from 140 m at Chatara to more than 8,000 m in the great Himalayan range. Figure II-3 and Figure II-4 illustrate the topographic pattern and the relief of the Kosi basin respectively. Sagarmatha (Mt. Everest), the highest peak of the world, lies close to the center of the basin. More than 60 percent of the basin lies within a circle of 100 km radius from Sagarmatha. The basin drains the head-water area of six (Figure II-1) of the ten highest peaks of the world including Kanchanjangha (8,598 m), Lhotse (8,516 m), Yalungkang (8,505 m) next to Kanchanjangha, Makalu (8,463 m), and Chooyu (8,201 m). There are about 500 peaks exceeding 6,000 m in the basin (Pandey, 1987). Southern half of the basin provides a high relief topography within a short distance of about 200 km (Figure II-3). Figure II-5 illustrates the profile of the seven major tributaries of the Kosi River system.

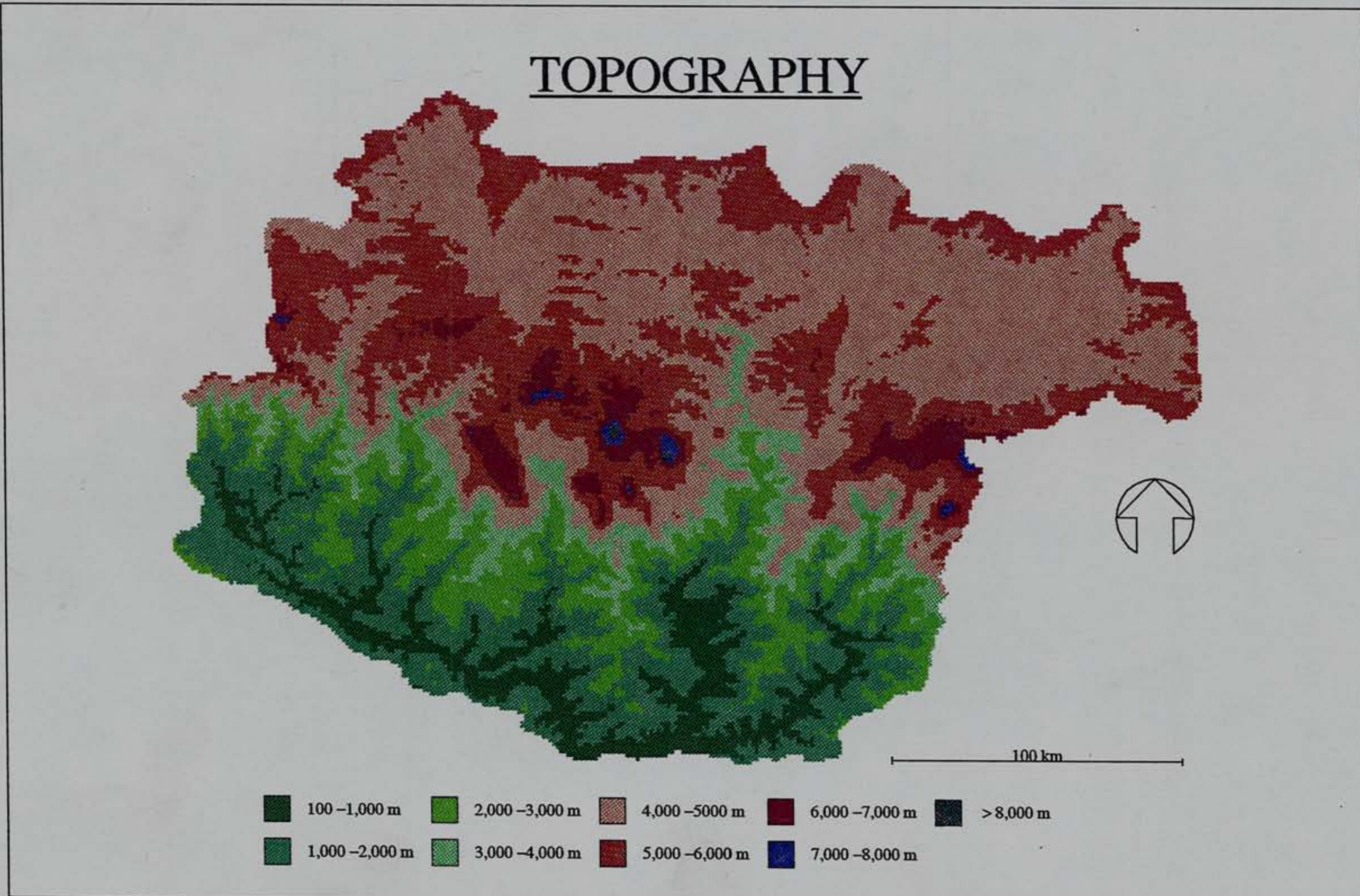


Figure II–3. Topographical variation in the Kosi basin.

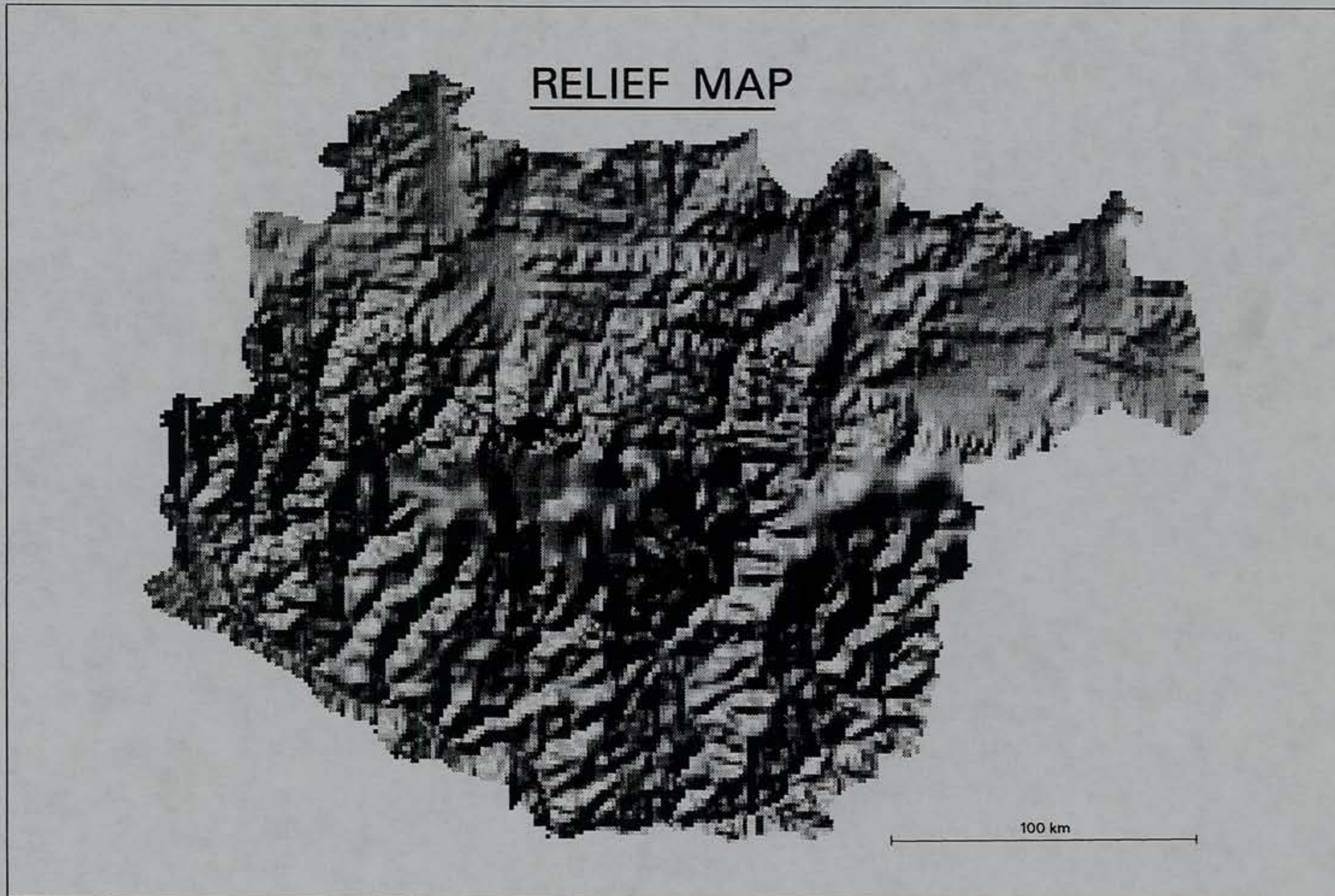


Figure II-4. Relief map of the Kosi basin derived from DEM.

The Kosi River has a predominantly southerly direction of flow to Chatara and beyond to the Ganga River. Flow patterns of the Arun River in its head area and flow patterns of the Sunkosi and the Tamor rivers before their confluence are influenced by the Greater Himalayan and the Mahabharat range, respectively. Longitudinal diversion of the Kosi River by Mahabharat range results in a funnel effect. The Sunkosi and its major tributaries are believed to have diverted by the upliftment of the Mahabharat range due to tectonic activities during the recent geological period (Sharma, 1977).

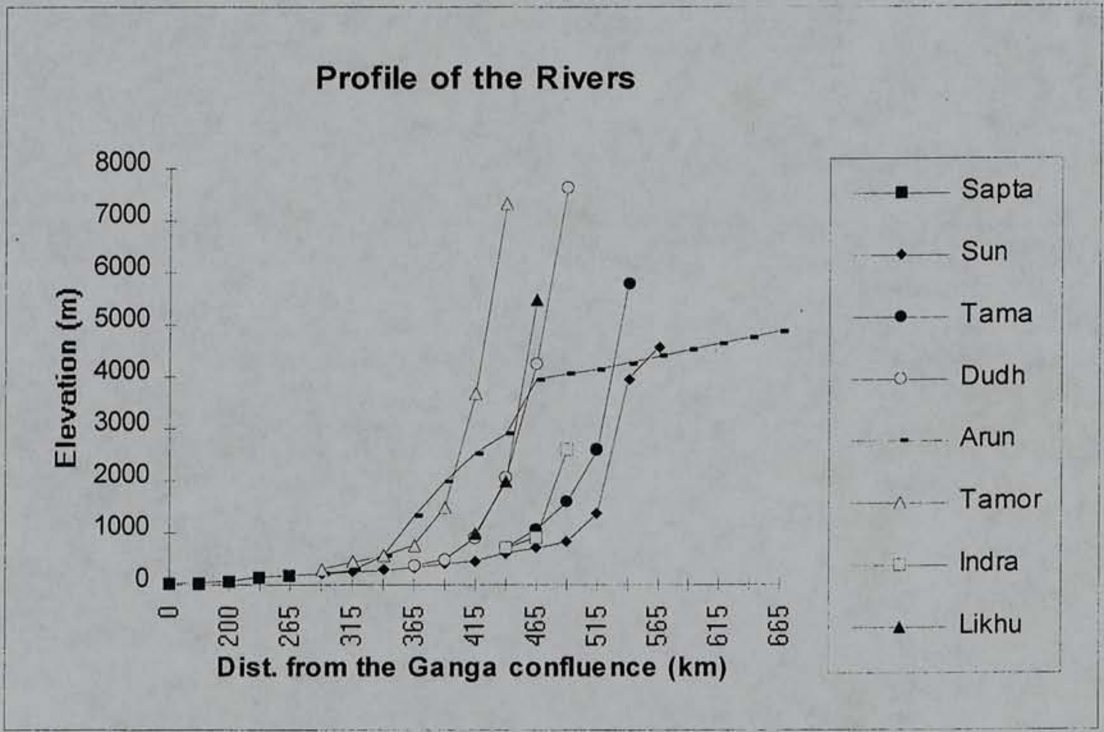


Figure II-5. Profile of the Kosi River and its tributaries.
Data from Defense Mapping Agency Aerospace Center (1986)

Table II-2. Characteristics of the major physiographic divisions of the Kosi basin.

	Mahabharat	*Middle Mountains*	*High Mountains*	*Himalayas*	*Tibetan Plateau*
Elevation (m)	140 - 3,000	200 - 4,000	1,000 - 4,000	4,000 - 8,848	3,500 - 6,000
Land System	Mountain chain in east-west direction	Complex series of ridges and valleys	Steep and long slope	Glaciated valleys and high ridges	Glacial and alluvial fans
Geology	Mainly soft rocks	Mainly soft rocks	Mainly hard rocks	Mainly hard rocks	Tethys's sediment up to 10 km thick
Climate Koppen's Class (Trewartha, 1954)	Temperate (Cwag)	Temperate, (Cwag-Cwbg)	Temperate (Cwb)	Alpine and tundra. (EFH, ETH)	Arctic and arid (Dwb)
Vegetation	Chir pine, chestnut, oaks, rhododendron, banmara, Sal in valleys	Chir pine, oak, bluepine, rhododendron, banmara	Fir, birch, juniper, oak, rhododendron, blue pine and meadow	Birch and rhododendron in lower part. Alpine meadow in higher parts	Meadow and some alpine vegetation
Soil	Moderately deep dark grayish and brown gravely sandy loams or loamy sand	Mostly deep dark yellowish brown clay loam soil with gravel and boulders	Mostly deep dark brown stony and fine sandy loams with boulders	Shallow and loose soil with sandy gravel and cobbles in valleys. Rocks above 5,500 m.	Shallow pockets (10-15 cm thick) of loams mixed with rocks and glacial drift
Agriculture	Maize, rice, wheat, millet, barley, potato	Maize, rice wheat, barley, sugarcane, potato, herb	Oat, barley, wheat, potato, yams, herb		Barley, wheat, rapes, and peas in low land (<4,200 m)
Population pattern	Moderate population density	Population density ranges from 65 to 150 per sq km.	About 10 per sq km	Very low population density	Very low population density (<1/sq km)
Environmental concern	Growing deforestation and agriculture activities	Deforestation, grazing and development activities	Deforestation in few slopes of Dudhkosi and Arun valleys	Growing tourism and grazing	Grazing and some deforestation
Sediment	High sediment delivery with gullies and landslides	High sediment delivery with several landslides	High sediment delivery with avalanches and landslides	Avalanches	Sediment mainly deposited in wide valleys

Information from (Ekvall, 1968; Hagen, 1980; Majupuria, 1985; Nelson, Laban, Shrestha, & Kandel, 1980; Pandey, 1987; Sharma, 1988, Shrestha, 1989)

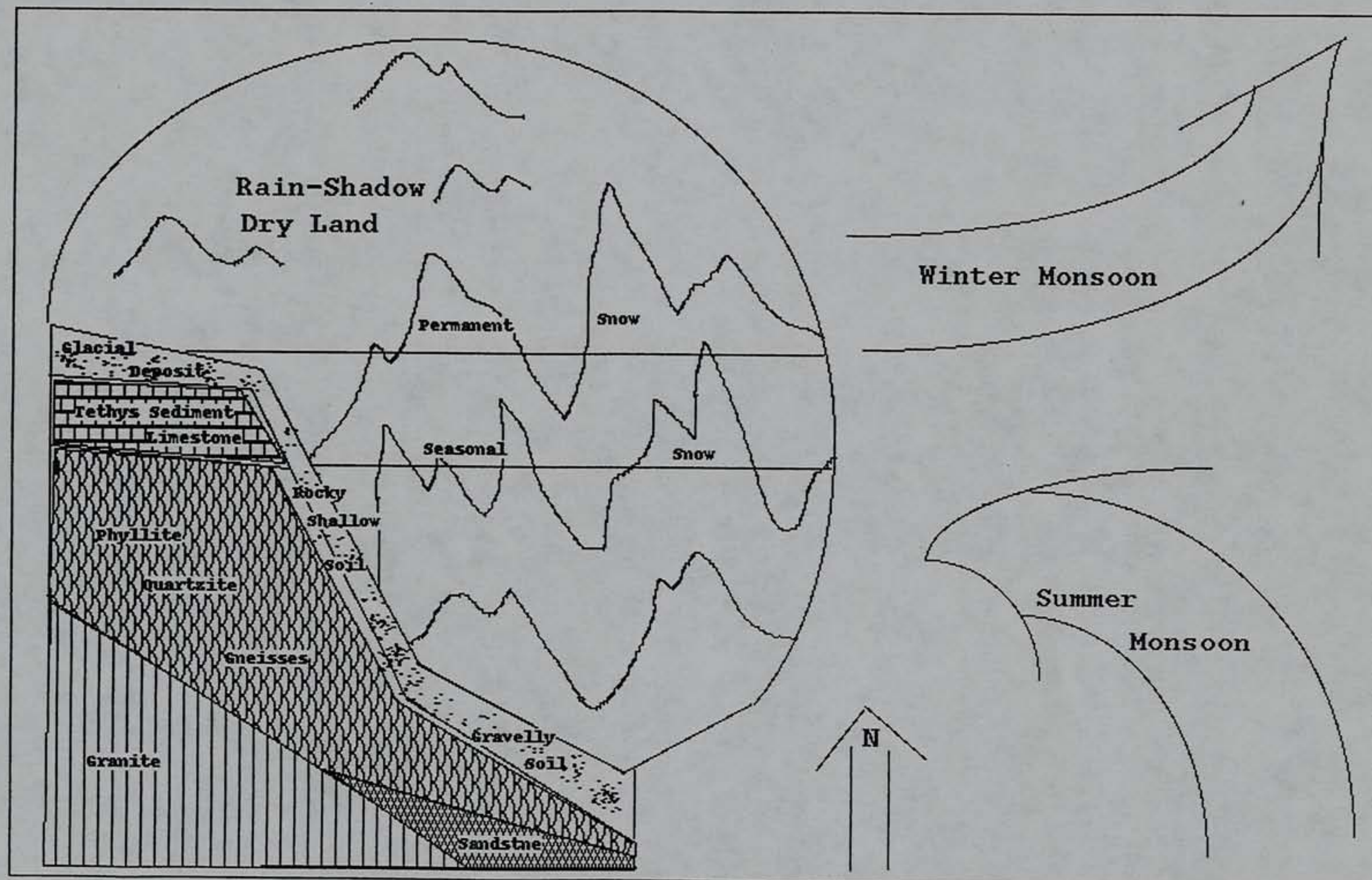


Figure II-6. Simplified schematic diagram of hydrometeorological, topographical, and geological characteristics of the Kosi basin.

The study area can be divided into five major geographic units: (a) Mahabharat (b) Middle Mountains (c) High Mountains (d) Himalayas and (e) Tibetan plateau. The salient features of these divisions are described Table II-2. Figure II-5 illustrates the profile of the seven major tributaries of the Kosi River system.

Table II-2 shows that the high topographical variation within the basin has resulted in several extremities in physiographic, climatic, and demographic patterns within the basin. Under this extreme variation of climatic factors and moisture conditions, the basin breeds numerous flora and fauna (Shrestha, 1989; Wenhua, 1993) and varieties of social and cultural practices (Pandey, 1987).

Hydrometeorological Characteristics

The climatology of atmospheric circulation, variations in topography, and rain-shadow effect of the Himalayas are the three major factors influencing hydrometeorological characteristics of the Kosi basin. The following weather systems play a major role in bringing precipitation over the basin:

- Summer monsoon brings several wet spells widespread over the basin. Almost 80 percent of the annual precipitation over the basin occurs during monsoon. Monsoon generally sets-in over the basin during the first half of June and withdraws towards mid-September. The period from June to September is considered the monsoon season.
- Winter monsoon period is dominated by westerly wind with westerly jet stream in the higher troposphere. The weather systems develop as westerly disturbances; hence enter into the Kosi basin from the West. Precipitation

amount, although insignificant compared to monsoon precipitation, contributes to significant snow accumulation in high elevation areas.

- The transitional times, before and after the monsoons, are referred to as pre-monsoon and post-monsoon period respectively. Local weather systems, such as convective activities, are highly dominant particularly during the pre-monsoon period.

Annual precipitation within the basin under the influence of topography varies from less than 250 mm to more than 4000 mm. There are several instances of maximum daily precipitation exceeding 300 mm in high precipitation areas of the basin; but these are rare above 3000 m.

The seasonal distribution of precipitation has a strong influence on the hydrological characteristics of the basin (Figure II-6). The period of summer monsoon is also the period of high flows. The lowest flows are generally observed during the first three months of a calendar year (Appendix E). Streamflows begin to rise in spring with rising temperatures and increasing snowmelt in high altitude zones. Most of the areas of the basin above 6000 m are covered by permanent snow as the temperature remains below freezing point throughout a year. The areas between 2500 m to 6000 m experience seasonal snow accumulation that melts along with the rise in temperature during spring and summer.

Despite the significant role of snowmelt in generating runoff in high elevation areas, its overall contribution to the Kosi River is less than ten percent of the total runoff (Sharma, 1993). This observation is different from findings in the western Himalayas

(Kashmir and Hindu-Kush region) where contribution of snowmelt to major rivers is estimated at 50 percent (World Bank, 1968).

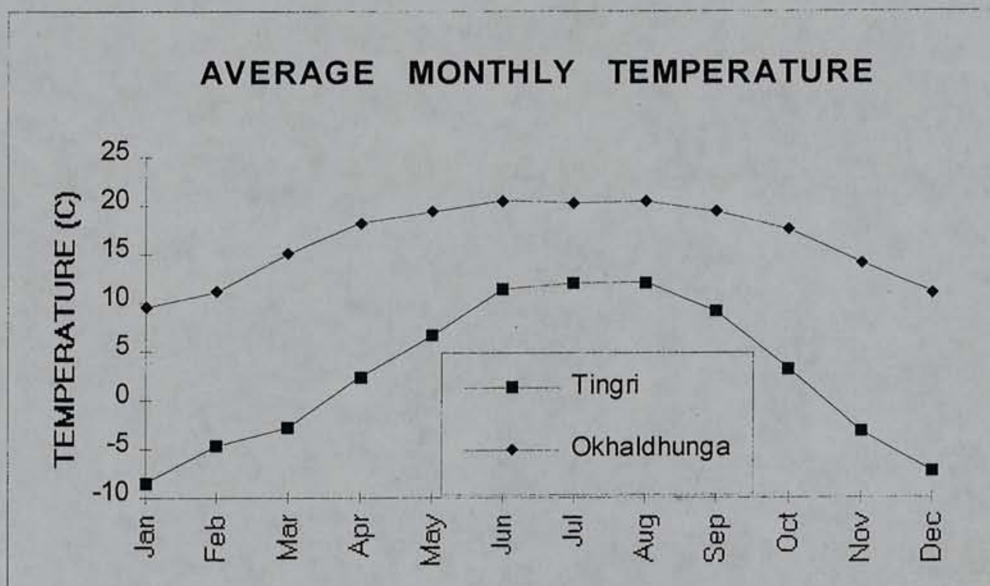


Figure II-7. Average monthly temperature pattern at selected station of the southern Himalayas (Okhaldhunga) and the Tibetan plateau (Tingri).

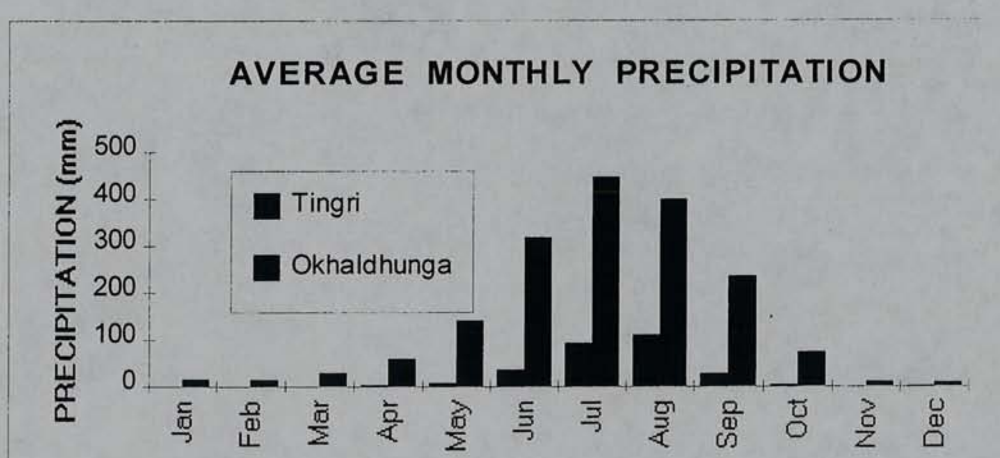


Figure II-8. Average monthly precipitation pattern at selected station in the southern Himalayas (Okhaldhunga) and the Tibetan plateau (Tingri).

Figure II-7 and Figure II-8 illustrate typical temporal patterns of temperature and precipitation over the basin at selected stations on the southern and northern side of the

Himalayas. The average monthly precipitation (Figure II-8) shows a similar temporal pattern of moisture regime on both sides of the Himalayas under the influence of monsoon; but the absolute amounts of rainfall vary significantly.

CHAPTER III

REVIEW OF RELATED LITERATURE

Most of the available literature related to the environmental aspects of the Himalayas deals with deforestation and its linkage to climatic variables, such as, floods, droughts, and precipitation pattern. This chapter reviews the literature concerning land-use changes, climatic changes, and the sensitivity of the watershed to such alterations. The review has a greater focus on the Himalayan region for land-use aspect and the monsoon region for climatic aspect.

Land-use Changes in the Himalayas

Land-use change in the Himalayas and its impact over the region are the most publicized Himalayan environmental issues. Most of the available literature concerned with this subject, deals with the issue of large scale land-use changes as a result of rising population. In addition, some available literature relates the increasing occurrence and severity of natural disasters in the downstream Gangetic plain areas to the massive deforestation in the Himalayas.

Most of the publications regarding environmental degradation in the Himalayas are available in international and national popular press. In addition, there are some specialized publications such as, Bruijnzeel and Bremmer (1989), Ives and Messerli (1989), and Lall (1981) that deal with several aspects of the problem. A general review of the literature shows the existence of a great debate not only on the nature of human impact but also on the scale of such activities in the Himalayas. The majority of the available literature deals with one or more of the following three major hypotheses related to environmental degradation.

Catastrophic Degradation

This category is generally referred to as the 'Theory of Himalayan degradation.' The picture of the Himalayas presented by several authors (Claire, 1976; Denniston, 1993; Eckholm, 1975; Messerschmidt, 1987; Modie, 1981; Reiger, 1981; World Bank, 1984) can be summarized as:

- Mountain deserts of the western Himalayas are moving eastward.
- The trend of forest loss indicates total loss of accessible forest by the end of this century.
- People have already exploited most of the potential arable land.
- Existing agriculture land has lost its fertility due to washing away of top soil.
- Natural disasters, such as 1987 and 1988 floods of Bangladesh (Jacobson, 1988; Smith, 1988), are increasing every year due to increasing magnitude of floods and droughts.

Such assessments and predictions are based on the following observations made in the Himalayan region:

- Documentation of a rapid rise in population (two per cent or more per annum) during post 1950 period
- Severe deforestation

- Receding tree-lines and browning hills
- Most of the hill districts running under food and fuel deficiency
- Shifting cultivation and existence of abandoned lands.

The theory of Himalayan degradation is focused on the forest situation of Nepal in 1960s and 1970s during which time people were less concerned about protecting the nationalized forests. Furthermore, eradication of malaria and construction of highways encouraged the subsistence level farmers of the hills and mountains to migrate towards the foothills (areas in *Tarai* close to the hilly region) and *Tarai* (Central Bureau of Statistics [CBS], 1987). Such movements of people led to a great deal of deforestation of the intact forests of foot hills, commonly known as *'Char Kose Jhadi'* (Eight miles Strip of Dense Forest). Population growth rate exceeding eight per cent per annum in some *Tarai* districts during 1971-81 (CBS, 1987) and more than 24 per cent reduction in forest cover in *Tarai* during 1964-78 (Gilmour, 1991) support the theory of large scale deforestation. Hence, the term 'Himalayan Degradation' is, in fact, a misnomer as the land-use changes occurred mainly in *Tarai*, not in the mountains. A general conception about Nepal being synonymous to the Himalayas may have contributed towards such a terminology.

Normal Processes

Several authors have challenged the 'Theory of Himalayan degradation' (Bajracharya, 1983; Bruijnzeel & Bremmer; Gilmour, 1981; Ives & Messerli, 1989; Kattelmann, 1990). The major points presented by them against the degradation theory can be summarized as:

- Decrease of forest cover in the Himalayas is not significant except some reduction of forest density.
- Land-use pattern in the Himalayas is not the result of post-1950 population explosion but is over a much longer time frame.
- Models used by authors, supporting the hypothesis of environmental degradation, are not suitable due to high uncertainties in the evaluation of processes related to deforestation.
- Scale of human activities is insignificant when compared with the dimension of natural processes in the Himalayas.
- People-farm-forest relationship might have already led to a sustainable environment.
- Large-scale floods in Ganga-Brahmaputra plains are not usually linked with the Himalayan hydrology (Alford, 1992; Brammer, 1990; Kattlemann, 1987, 1990).

The theories of nonsignificant changes in the Himalayas are established through a better information base. Land-use surveys of Nepal made in the 1970s did not validate the hypothesis of large scale deforestation in the Himalayas. Similarly, a lack of relation between precipitation in the Himalayan watersheds and floods and droughts in the Ganga-Brahmaputra basin did not support the 'Theory of Himalayan Degradation' proposed earlier.

Although the literature supporting nonsignificant changes is based on data and facts, we may still ask "Are there enough evidences?" or "Are not the increasing food, fuel, and fodder demands creating negative impacts on the environment?" Recent studies of some of the districts (Dahal, 1994) and microcatchments (ICIMOD, 1995) in the Kosi basin contradict the theory of historical deforestation concluding the deforestation being post-1950 phenomena. Similarly, some available hydrological studies are difficult to interpret, such as, "Nepali rivers modulate rather than contribute negatively to the flow of the Ganges." (Alford, 1992, p 58), although these rivers are the major tributaries of the Ganga River.

Comparison of the two contradictory theories on the Himalayan environment would suggest that there is neither catastrophic degradation of the Himalayas nor no-worry situation. On the other hand, some new facts put forward by some researchers (next paragraph) indicate an increasing trend in forest extent in Nepal.

Greening Trend

Recently, some researchers have been pointing out towards the greening of the Himalayas, that is, observation of a trend in forest increase. Carter and Gilmour (1989), Fox (1993), and Gilmour (1991) report up to three-fold increases in forest in some local areas of the Kosi basin during two decades in the recent past. Similarly, the success stories of community forest development policy of the government of Nepal are (User Group, 1995) indicating a significant increase of community forest. A. Tuladhar (personal communication, September 22, 1995), a research student at Clark University, after his preliminary assessment of satellite pictures over Nepal, finds statistically significant trends of increasing forests in most of the Himalayan region.

Greening trends, reported for several parts of the Kosi basin are the success stories of forestry programs; nevertheless, we did not find any plausible explanation for a greening trend in the entire Himalayan range. Attempts to explain the greening trend may lead to other questions, such as, "Are the forestry programs very successful and widespread over the Himalayas," "Are there any climatic changes in the region influencing positively to the vegetation growth?" Spreading of *Banmara* (Eopatorium adenophorum) in the middle mountains of the eastern Nepal since the 1950s (Shrestha, 1989) is another puzzle that may directly affect the assessment of forest cover. These plants are found to be invading abandoned cultivation lands.

Realities

The last three sections of this chapter describe completely different perspectives on the same environmental issue. The obvious questions are hence: what are the truths?

The major reason behind such discrepancies by different authors can either be due to the lack of information on environmental assessment in the region or the lack of synthesis of available information. The reasoning can further be verified by recent information that shows that the earlier predictions of deforestation rate as well as the population growth rate are grossly overestimated (Bajracharya, 1983; Gurung, 1991).

Since the inadequacy of environmental information is a reality throughout the developing world, the remote areas of the Himalayas are no exception. Our major emphasis in this study is, hence, on the evaluation of the most appropriate environmental indicators, such as climatic variables to determine the trend of changes. In addition, the analysis of hydrological variables such as discharge and sediment flux, provides an indication of the integrated impact of environmental changes in the region.

Land-use Change and Climate

Land-use changes result in the alteration of hydrological and meteorological conditions of affected areas. Obvious hydrological impacts of deforestation include: overall increase in yield and change in temporal variation of runoff, decrease in evapotranspiration, change in soil moisture characteristics, and increase in soil erosion. Similarly, meteorological responses to deforestation are associated with increases in: surface albedo, wind speed, turbulence, maximum air temperature, and net radiation loss. Opposite effects are expected when land-use change occurs as a result of afforestation.

Bosch and Hewlett (1982), Bruijnzeel (1990), and Whitehead and Robinson (1993) have compiled and reviewed the results obtained from several empirical studies related to hydrological impacts, described above, as a result of land-use changes. Studies concerning meteorological impacts have indicated micro-meteorological changes whereas the regional, continental and global scale impacts are still a topic of debate. Several studies conducted for the Amazon basin using Global Climate Model (GCM) simulation indicate increase in temperature from one to three degree Kelvin (Dickinson & Henderson-Seller, 1988; Shukla et al., 1990) and decrease in evapotranspiration up to 30 per cent (Shukla et al., 1990). On the other hand, the GCM based studies have many discrepancies and disagreements among modelers, especially when the results are interpreted at regional levels (Lamb, 1987; Mitchell & Qingcun, 1991).

Impact of land-use change on precipitation, one of the three major components of hydrological cycle, has been less understood as compared to other two components: evapotranspiration and runoff. Although studies have been conducted since the first quarter of this century (Brooks, 1928), no acceptable relations have been established so far (Ward & Robinson, 1990). Some evidence of the effects found at the local scale (Anthes, 1984) lacks sufficient empirical justification. Despite such insufficient theoretical and empirical evidence, there exists strong perception not only among people and policy makers but also among scientists about the role of deforestation in decreasing precipitation. Such perception is primarily based on some literature that justifies such observation on the basis of observed data including those of south India where strong influence of summer monsoons is experienced (Meher-homji, 1991). Some other examples, showing evidence of decreasing precipitation because of deforestation, include several parts of the world: China (Zhang, 1986), Ghana (Mann, 1987), Panama (Windson & Rand, 1985 as quoted in Meher-homji, 1991) and Costa Rica (Fleming, 1986). Length of record for such assessment and difference in catch efficiency of rain gauges in forested and non-forested environment are some of the questions that still do not have satisfactory answers for accepting the hypothesis.

Sensitivity of Himalayan Climate

Examples of decreasing precipitation as a result of increasing deforestation, presented by Meher-homji (1991) consider several places in the Indian subcontinent including Cherrapunji that lies in the eastern Himalayas. Similarly, Kothyari and Singh (1996) show increasing temperature and decreasing precipitation trends over the Ganga basin since mid-1960s and relate these to deforestation. Similar trends of increasing temperature and decreasing rainfall in different parts of the Indian subcontinent and China, south and north of the Himalayas respectively, have also been reported by Denniston (1993), Hingane, Kumar, and Murty (1985), Myers (1986, 1988), and Hingane (1996). Several studies also indicate that the decreasing precipitation trend as a result of deforestation is more distinct in mountainous areas than in coastal regions (Meher-Homji, 1991).

Some studies indicate decreasing trend of temperature even in the areas of heat island effects such as Delhi (Lal, 1993). Similar decrease can also be expected in some areas contiguous to the Kosi basin on the basis of extrapolated results of Hingane et al. (1985). Despite such observations in different parts of the Himalayas and its adjacent plains, there is less dispute about recent trend of temperature rise in the northern hemisphere including the Himalayas.

In contrast to the general agreement of an increasing temperature trend among scientists, there is less agreement about the declining precipitation trend described above. For instance, the results presented by Parthasarathy and Mooley (1978) and Mooley and Parthasarathy (1984) on the basis of all India monsoon rainfall data for the period of about 100 years does not reveal any trend that could be related to global warming. Several other studies in the region that do not support the hypothesis of decreasing trend of precipitation in the region include: Rogers, Lydon, and Seckler (1989), and Srivastava et al. (1992).

How sensitive are the monsoonal circulation and the monsoon activities to climatic changes? Attempts have been made to relate the monsoon variabilities to regional anomalies, such as, El Nino (Ju & Singo, 1995) and snow cover in central Asia (Shukla, 1987; Walsh, 1995). Although the inverse relation of El Nino and Eurasian snow cover to the strengthening of monsoons looks promising, the results are not consistent (Shukla, 1995(b); Walsh, 1995). Predictions of monsoon sensitivities on the basis of such connections are at a primary stage of research. Additionally, the intensive monsoon activities in India may not correspond to active monsoon in the Himalayan region since the region generally experiences strong monsoon activities during the periods of inactive monsoon in India ('monsoon breaks'; Dhar & Narayanan, 1966; Dhar, Soman, & Mulya, 1982).

Existence of a vast amount of water as ice and snow is an additional aspect behind sensitivity of the Himalayas to possible climatic changes. More than ten per cent of the Kosi basin is covered by snow throughout a year (Sharma, 1977). Receding glaciers, which may provide some evidence of warming (Barry, 1981, 1992) have been observed in the Himalayas in recent past. Kadota and Ageta (1992) report the receding of Shorong glacier in the Dudhkosi tributary of the Kosi River by about 30 m within a decade ending 1989. Yamada et al. (1992) report accelerating rate of retreat of almost all the studied glaciers in the Kosi and other adjacent Himalayan basin since 1980. Relating these glacier retreats to the reported global warming is not straightforward as the Himalayan glaciers have been retreating at least for the last 140 years (Mayewski & Jeshcke, 1979).

In the preceding paragraphs, we discussed the literature dealing with the sensitivity of the Himalayas to the land-use and climatic changes on the basis of observed climatic variables. In addition, some literature is also available that deals with the sensitivity of the Himalayas to the predicted global warming on the basis of GCM results.

The size of the Kosi basin is less than or close to the size of a single grid of most of the available GCM experiments. Extrapolation of results to the size of the Kosi basin is hence subject to higher uncertainties. Nevertheless, the results of GCM simulations, obtained in areas covering the central Himalayas, are less ambiguous than in many other regions (Hansen et al., 1988; Meehl, 1994). The scale of predicted warming, however, varies significantly among different models.

Since the monsoons are analogous to land breeze and sea breeze at a seasonal scale, their activities are highly related to the differential heating of the Indian subcontinent and the Tibetan plateau (Trewartha, 1954). In a scenario of predicted global warming, the thermal gradient is likely to steepen due to higher warming of continent than ocean and a lowering of albedo as a result of reduction in snow area. In the background of these physical processes, GCM results indicate intensification of monsoons in the scenarios of global warming bringing more precipitation over the region (Pioneering Study, 1994, 4). The monsoon precipitation is expected to be enhanced further in a scenario of deforestation (Shukla & Mintz, 1982; Meehl, 1994) because of drier soil conditions before the onset of monsoon. Lower heat loss in drier soil causes increased thermal gradient between land and sea surface resulting in the intensification of the monsoons.

Discussion

The Himalayan region of Nepal is probably one of the most studied regions of the world; however, it does not imply that it is the best studied nor does it imply that it has been adequately studied. The general survey of literature regarding the relationship between anthropogenic changes and climatic changes, presented above, exemplifies the complexities involved in meteorological, hydrological, and anthropogenic processes and their interaction. These processes have been analyzed by scientists and journalists on the basis of observation, judgment, reasoning, and modeling. The studies have provided valuable insight about the biospheric environment, but the diversity of the conclusions has added more uncertainties and confusion.

The large number of variables involved in environmental processes and the complex nature of their interactions are likely to be a challenge to the scientific communities for several years. The existing knowledge base is adequate neither for scientific explanation of the environmental processes nor for predictions. In general, the literature review does not lead us towards conclusive facts, but rather leads us toward making recommendation to develop a reliable time series data base of the land surface conditions and atmospheric environment. Standard time series data for land-use, water cycle, and sediment flux are the most critical aspect for environmental studies in the region as several disparities exist in the available information. For instance, Shrestha (1989), finds the reported agriculture area of three districts in the Arun River basin differing by 80 to 140 per cent in two different authenticated sources.

The research trends indicate that the Himalayan regions have attracted regional and international scientific communities during the last three decades. Unfortunately, the emphasis of research works seems to be biased more on using limited information and less on improving the available data base. Since a reliable data base provides higher confidence in explaining processes, there is an urgent need to change the emphasis of the Himalayan research from an existing principle-based approach to information-rich approach.

Fortunately, we are equipped with simple instruments that have been used to monitor environmental indicators, such as, precipitation and temperature. Similarly, the available measurement of river discharge is an excellent indicator that can be monitored at a single location for the whole basin. These data can be replaced neither by scientific knowledge nor by computer simulation or modeling. Despite some shortcomings in the length of the records, areal representation, and data quality we will rely heavily on this available information for assessing the environmental trends in the Kosi basin.

CHAPTER IV

COLLECTION AND ANALYSIS OF DATA

This study is based on three types of basic information: hydrological and meteorological data, land-use data, and a digital elevation model. This chapter contains a description of nature, source, and quality of the data sets used in this study.

Meteorological and Hydrological Data

Meteorological and hydrological data, available at the Department of Hydrology and Meteorology (DHM) in Nepal, are the major source of information used in this study. Very little meteorological and hydrological information is available for the Tibetan part of the Kosi basin. We obtained some records for the Tibetan part mainly from the World Weather Records (various years) and Nepal-China joint glacial study report (LIGG/WECS/NEA, 1988).

Various organizations are involved in collecting hydrological and meteorological information in the Kosi basin as a part of gathering information for implementation of certain projects. Among them, Central Water Commission (CWC) of the government of India was the only organization involved in regular hydrological and meteorological data collection on regular basis before the establishment of DHM in Nepal. CWC established and maintained a regular gauging station on the Kosi River at Barahksetra, about two km downstream of the confluence of Arun, Tamor, and Sunkosi (Figure II-1), in 1947. CWC also established one station on each of the two major tributaries of the Kosi; the Sunkosi

River at Kampughat and the Tamor River at Tribeni (confluence of three rivers) in 1948. All these stations were discontinued in the 1970s after the establishment of new stations by DHM. The present DHM station on the Kosi River is about 5 km downstream of the CWC site whereas the location of DHM station on the Tamor River is about 15 km upstream of the CWC site. Although these represent a small difference in basin area, we combined these records for trend analysis as the F-statistics did not reject the hypothesis of their belonging to same population. Streamflow and sediment discharge data obtained by CWC have not been published. Only the monthly and annual summaries of these data are available in hydrological reports, such as, WEC(1982).

Along with the initiation of hydrometric survey, India Meteorology Department (IMD) established several climatological stations in the Kosi basin in the late 1940s and 1950s. The Government of India made available all the daily precipitation and temperature data collected by IMD to DHM when it transferred all the meteorological and hydrological stations to the government of Nepal after the establishment of DHM. Later, DHM either closed the IMD stations or replaced with a new system following the standard procedures and instruments as recommended by the World Meteorological Organization (WMO, 1981).

DHM has published the hydrological and meteorological data regularly since its first publication in 1966. The publications include monthly precipitation through 1990 and other monthly climatic summaries through 1986. Hydrological data have been published through 1977 and the rest have been documented in various stages of processing as internal publications or in a computer data base at DHM. DHM introduced digitization of the hydrological and meteorological records using micro-computers in the 1980s. Several historical data are still in the process of digitization. Most of the sediment data are yet to be digitized and processed.

A major task of the research program was to collect, compile, and review all the existing processed data and expand the digital data base to include the latest information. Collection of some supplemental data, such as sediment concentration of the major rivers was also necessary to analyze existing unprocessed sediment data of the Kosi River and its tributaries. We accomplished these tasks on the basis of a proposal submitted to the concerned institutes (Sharma, 1994). The task involved the following activities:

- Collecting, processing, and updating meteorological and hydrological data
- Computerization of data in suitable formats for data analysis and modeling software
- Processing of sediment data with additional measurements at major gauging sites for developing sediment ratings
- Review of the whole data set for its applicability in climate change studies and hydrological modeling

We established a data base with information available at the central office in Kathmandu and the Kosi Basin Field Office in Dharan during the monsoon and the post-monsoon period of 1994. The data base consists of all the discharge and precipitation values at a daily time step for Nepali side of the Kosi basin. Other climatological data that were digitized at monthly time steps include: temperature, relative humidity, sun-shine hours, evaporation, and wind. The recent five year climatological data including all the variables described above are digitized at a daily time step.

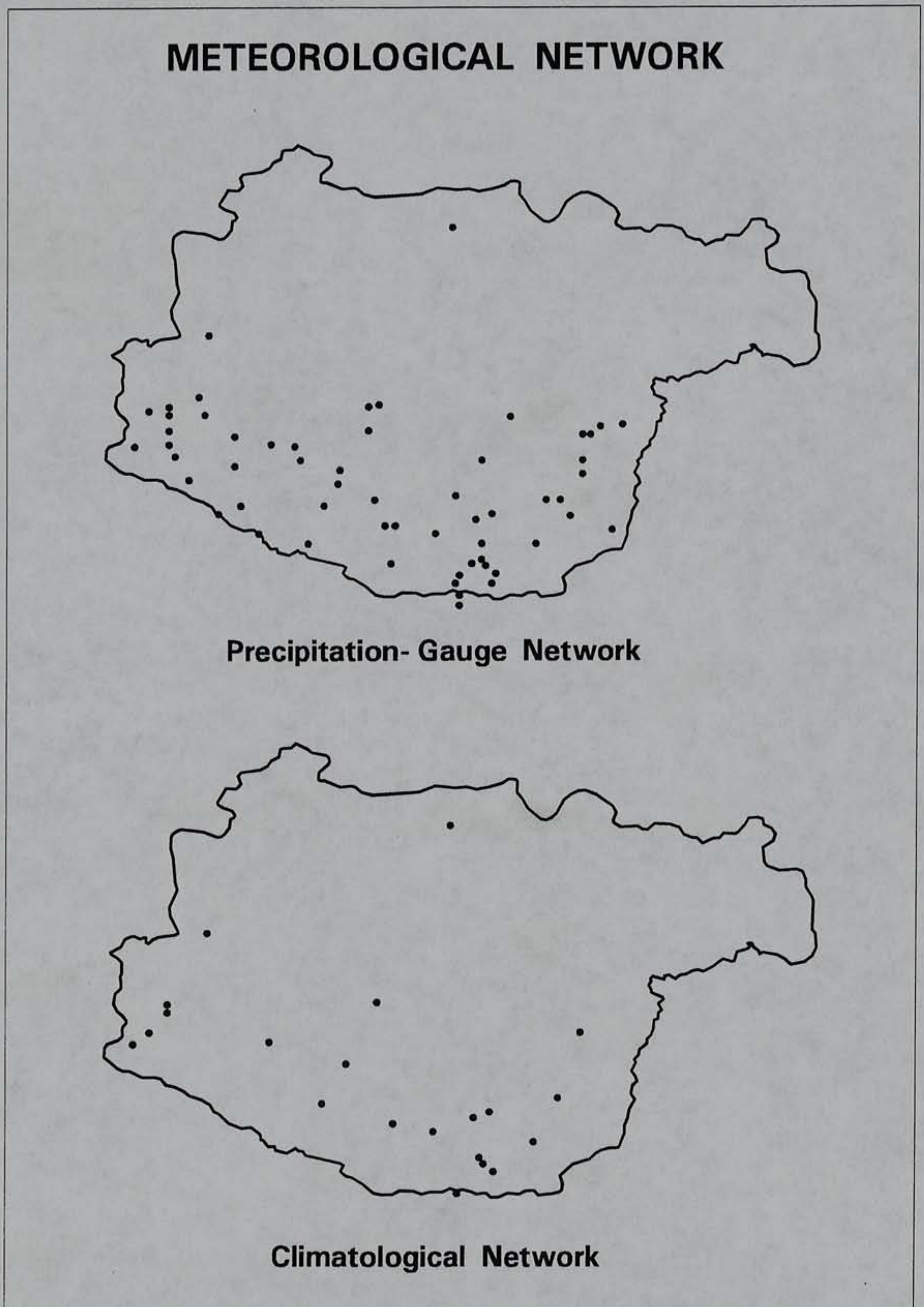


Figure IV-1. Meteorological network in the Kosi basin. Appendix A contains the list of the stations.

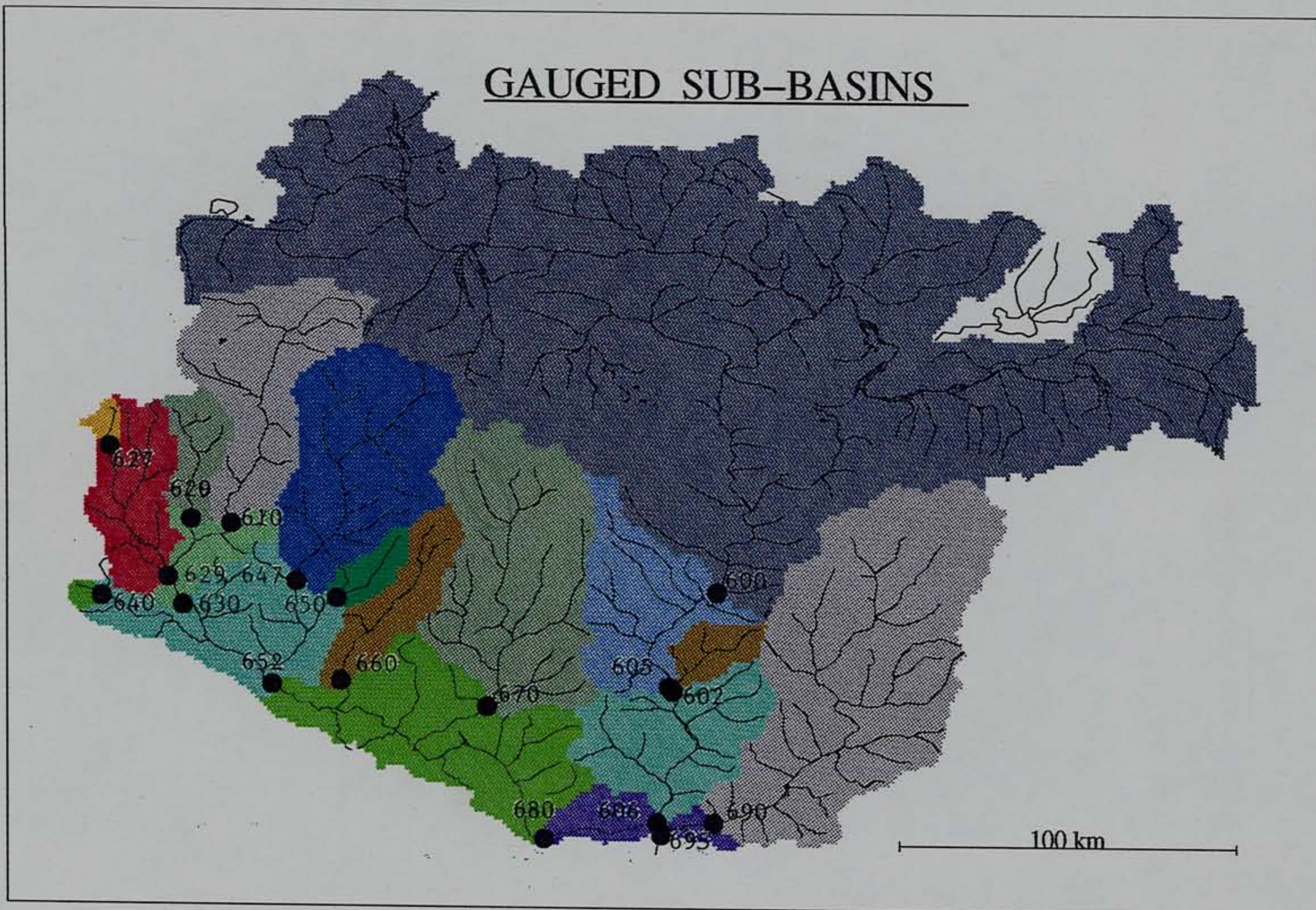


Figure IV–2. Gauged sub–basins that contribute to the Kosi river. Appendix B contains the station description.

Appendix A and Appendix B list the meteorological and hydrological stations and Appendix C to Appendix H contains a summary of the processed records (Sharma, 1996) used in the study. Figure IV-1 presents the location of precipitation gauging stations and climatological stations. The climatological stations are the stations equipped with at least maximum, minimum, wet-bulb, and dry-bulb thermometers besides precipitation gauge. Some of these climatological stations are equipped with Class A evaporation pan, sunshine recorder, and anemometer (Appendix F, Appendix G, and Appendix H). Figure IV-2 shows the gauged sub-basins of the Kosi River system. Both of these figures clearly illustrate the disparities of gauging network density between the southern half and the northern half of the basin; the northern half showing very sparse network.

Land-use and Anthropogenic Data

Unlike meteorological and hydrological data, no time series of land-use data is available for the Himalayan region. Basic sources of land-use data are the two major surveys carried out in late 1950s in the hills of Nepal (Department of Forest [DOF], 1973) and in late 1970s covering the whole Kingdom. The land-use data, prepared by the later project, known as the Land Resources Mapping Project (LRMP) of the Survey Department (1984), are available in paper maps at 1:50,000 scale. These data are also available in digitized form. We obtained all these maps and digitized data covering the southern side of the Himalayas for this study.

The following paragraph, reproduced here from DOF(1973), describes the first major forest inventory. Areas covered by the survey in the eastern Nepal and the reported land-use data are reproduced in Figure IV-3.

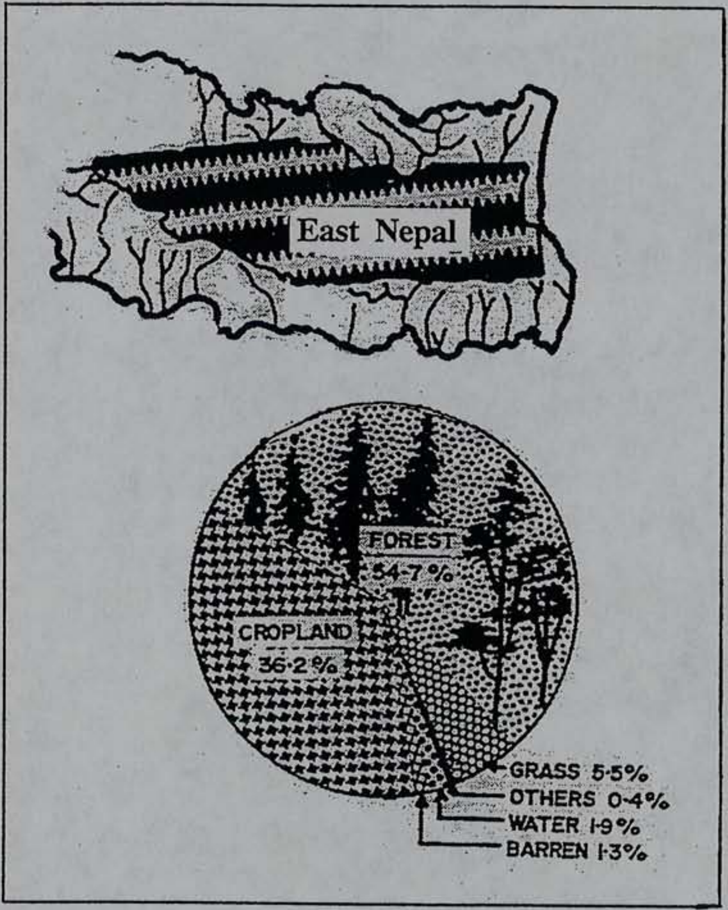


Figure IV-3. Land-use in the Mahabharat and middle hills and interior Himalayan areas of the eastern Nepal before 1965.

(Adapted from Department of Forestry, 1973, pp. 12)

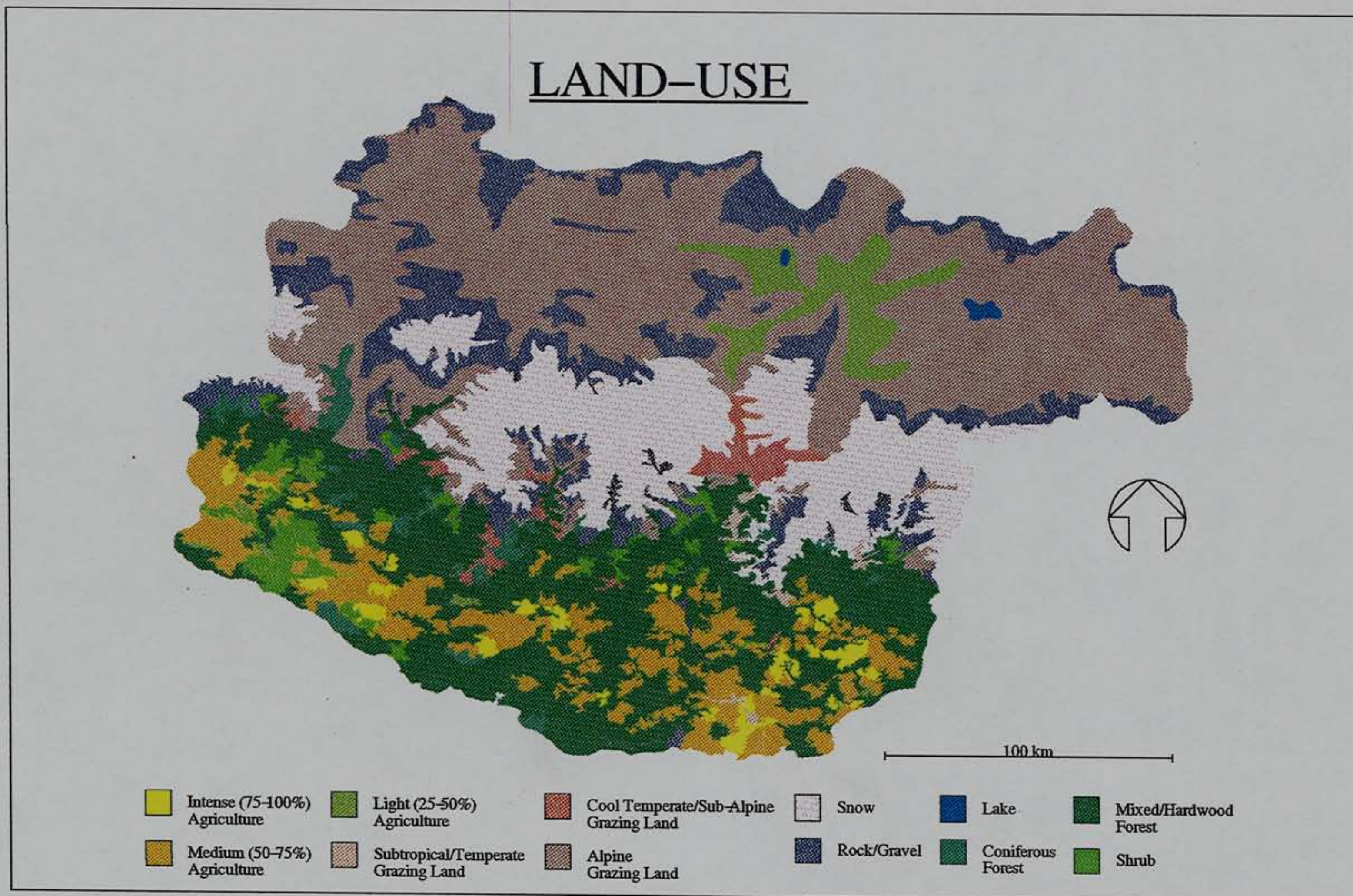


Figure IV–4. Major land–use in the Kosi basin in 1978–79.

> This information is obtained from the aerial photographs taken during 1953-58, 1962 and 1967. Wherever possible, the percentage of forest cover has been calculated for a unit of 15 minutes quadrangle. For most part of the hill area, it is based on photographs taken as many as twenty years back. The cover percentage shown on the map is, therefore, what it was at that time of photography. It is calculated by using the forest area unadjusted by strip photographs of 1964-1965. (p. 8)

The land-use, classified by the LRMP, consists of 75 classes within the Kosi basin. Use of these detailed classifications are not justified, primarily due to nonavailability of such data in the Tibetan part of the basin; hence, we reclassified the land uses into thirteen major classes. We used information available in maps (Population Map of China, 1988) and different other publications (Ekvall, 1968; Rongzu, 1989; Wenhua, 1993; Yanhua, 1992) for developing a land-use map for the Tibetan part of the Kosi basin. Figure IV-3 presents 13 major reclassified land-uses in the Kosi basin with added information on the Tibetan part.

As described in Chapter III, it is believed that rapid deforestation occurred from mid-1950s to 1960s. The two sets of available forest data (DOF, 1973; Survey Department, 1984), unfortunately, do not cover the period believed to be affected by the highest rate of deforestation.

Central Bureau of Statistics publications (CBS, 1987, 1993) are the additional source of land-use and anthropogenic data used in this study. CBS publishes different types of statistics regularly by dividing Nepal into political units, such as, development regions and districts. In addition, some data are published for the major physiographic divisions of Nepal: mountain, hill, and *Tarai.* The Kosi basin in Nepal shares its area with two major political divisions: Eastern Development Region and Central Development Region. Twelve districts that fall entirely in the Kosi basin include: Taplejung, Panchthar, Dhankuta, Terhathum, Sankhuwasabha, Bhojpur, Solukhumbu, Okhaldhunga, Khotang, Ramechhap, Dolakha, and Sindhupalchok. Almost 90 per cent of the Kavrepalanchok district lies in the Kosi basin while less than five per cent areas of the Sindhuli and Udaipur districts contribute to the Kosi. Nyalam, Tingri, Dinggye, and Gamba are the counties in Tibet that fall in the Kosi basin.

The history of population census in an organized manner in Nepal goes back to 1911. The first census of 1911 has been repeated every ten years (1920, 1930,1940, 1952-54, 1961, 1971, 1981, and 1991). The census taken in 1952-54 is recognized as the first scientific census conducted by an organization established for such task (CBS, 1987).

Digital Elevation Model

Digital Elevation Model (DEM) is core information; topography dominates almost all the land surface and atmospheric environment of the Himalayas. Besides, DEM is the only available data base that covers the whole basin with reasonable accuracy and satisfactory resolution. In conjunction with a GIS technology, we used a DEM for several hydrological computations including: watershed boundary of the basin and its gauged sub-basins, river network and basin characteristics. We also used DEM information for classification of vegetation in Tibetan plateau and for developing soil map of the Tamor River basin.

We obtained the digital elevation model for the Kosi basin from a 1-km elevation data base made available by Earth Resources Observation System (EROS) data center. We downloaded the data from the UNEP/GRID (1996), Sioux Falls internet site, for the region covering the Kosi basin. Primary source of the 1-km resolution elevation data base is the US Defense Mapping Agency Digital Terrain Elevation Data (DTED). Additional sources used to fill the gaps in DTED include: Digital Chart of the World (DCW, ESRI, 1992a) and ETOPO5 (Edwards, 1992). Since the primary source of 1-km data base is not available, it is difficult to assess the accuracy of the data for the Kosi basin. DCW data base contains significant gaps in the high elevation areas of the Kosi basin.

Comparison of the map obtained from 1-km elevation data base (Figure II-3) to the maps published in atlases indicates good agreement. We also used the data base to generate a river networking using Arc/Info (ESRI, 1992b). Comparison of the generated river network with the river network available in DCW also confirms good quality of the 1-km elevation data base. We faced only one problem in the generated river network at the southernmost part of the Sunkosi River. The program was not able to capture the north easterly flow of the Sunkosi River at its lower end. We rectified the error manually by editing few grids employing elevation data of the area.

Data Quality

Before the use of data in this research work, it was essential to evaluate its temporal and spatial accuracy and representativeness. Such evaluation is more important for the region such as the Kosi basin where poor logistic and technical support, rugged terrain, and inaccessibility directly affect establishment and maintenance of hydrological and meteorological networks. Despite this, the Kosi basin has the longest records of climatic data when compared with other major basins in Nepal. The following sections describe the factors that may affect the quality of hydrological and meteorological data in general.

Instrumentation and Measurements

WMO standard practices (WMO, 1981) are the major guidelines that are followed while selecting instruments and sites and while installing, maintaining, and observing climatological and hydrological variables. Observations are made at all the climatological and precipitation gauging stations every day at 0300 Universal Time that is 0845 Local Time (LT). The daily climatic values observed at 0300 are used to compute the monthly means used in this study. Unlike climatic observations, river gauges are not read at standard times. The daily values of the river gauge height are obtained by calculating the arithmetic mean of different observations made in a day. In general, river gauges are read three times a day at 0800 LT, 1200 LT, and 1700 LT with additional observations during floods at some stations. Hourly gauge heights are used to compute the daily mean values for stations equipped with automatic water level recorder. The average daily gauge heights are used to compute the average daily river discharges using stage-discharge relations. The stage-discharge relation for a site is updated every year with additional discharge measurements.

Daily precipitation amount is measured with a standard 203 mm cylindrical precipitation gauge without wind shield. Precipitation is measured with a measuring stick. Daily values of temperature are computed by using the maximum and minimum readings of the day. The maximum temperature thermometer is the mercury-in-glass type and the minimum temperature thermometer is the alcohol-in-glass type. Relative humidity is computed by using the dry-bulb and wet-bulb thermometers both of which are the mercury-in-glass type. Precipitation, maximum temperature, and minimum temperature are observed at all the climatological stations.

The instruments used for the measurement of evaporation, wind, and sunshine duration are Class A pan evaporimeter, vertical axis rotating cup anemometer with digital counter, and Campbell-Stokes sunshine recorder, respectively (WMO, 1971). Similarly, the river discharges and suspended sediment are measured by Price meter and depth integrated sediment sampler, respectively (WMO, 1981).

Despite the application of standard instruments and procedures, there are several shortcomings that may directly affect the quality of data. Some examples of such shortcomings are the inadequate discharge measurements for establishing and updating stage-discharge relations, and the use of current meters for several years without recalibration. Similarly, there is not enough information to trace the history of the stations to evaluate the changes in site conditions and relocation. Inadequate funds for regular field visits and inadequate training facilities for the technical personnel are other factors influencing the proper monitoring of hydrological and meteorological networks. Application of stage-discharge relation to the mean daily gauge heights, instead of individual gauge heights, to compute mean daily discharge is an example of procedural deficiency as the stage discharge relations are often nonlinear.

Network

Existing networks of precipitation gauges, thermometers, evaporimeters, stream gauging and sediment sampling stations in the Kosi basin are less than the ideal (100-250 km^2 per station) recommended by the World Meteorological Organization (1981). Although the existing precipitation network of about one station per 900 km^2 is within the limit of recommended network for difficult conditions, the density falls short in the Tibetan part of the basin (12,000 km^2 per station). This density is even less than the recommended limit (10,000 km^2) applicable for highly remote areas such as polar and arid regions.

Besides spatial inadequacy, the network also lacks representation of high elevation areas of the drainage. Six, out of eight, stations located above 3000 m on the southern side of the Himalayas have been closed. Both of the stations located at and above 4000 m were operational for less than seven years starting in 1948.

Poor precipitation gauge network density in the northern half of the basin is a major constraint toward establishing an accurate precipitation distribution pattern over the basin. We used measurements and estimates available for few locations in the Tibetan plateau near Nepal-China border (LIGG/WEC/NEA, 1988) to assess precipitation pattern in data sparse areas. Although such interpolation as well as extrapolation of records can be considered reasonably acceptable for average water balance computation, it is inadequate for modeling of temporally continuous hydrographs.

The stream gauging network density of about 100 km^2 per station below 500 m and 600 km^2 per station between 500 m and 1000 m meets the WMO(1981) recommendations of minimum network. The network of about 2000 km^2 per station in the elevation range of 1000 m and 2000 m meets the WMO recommended network criteria under difficult conditions. No regular hydrometric station exists above 2000 m that covers almost three quarters of the total basin area.

The class A pan evaporation network of about 11,000 km^2 per station is satisfactory for the basin; the WMO(1981) recommended minimum network being 50,000 km^2 per station. Notwithstanding, the information available for the high elevation areas of the basin is inadequate. The southern part of the basin is represented by the stations lying in lower elevation zones below 1800 m.

Missing Records

Although sixteen precipitation gauges were established in 1947 in the Kosi basin, only three stations (1303, 1316, and 1403) have almost complete data set from 1948 to 1993. The other stations have several missing records particularly before 1960. Twenty-one out of sixty-one precipitation stations contain almost complete record from 1960 to 1992. We estimated some of the missing records for these data sets using precipitation records at neighboring stations. Such estimates are made mainly for the dry months, so that the estimations do not significantly affect the annual amount. Appendix I contains the annual time series of the precipitation for these stations.

Temperature data are available for twenty-three locations within the basin; out of which seven stations were established in 1962. Only three stations have reasonably complete records. We have used average monthly values for estimating the values of few missing months of the time series. About four per cent of the total monthly data contains such estimates for these selected three stations. Appendix J gives the annual temperature time series for these three stations:1206, 1303, and 1405.

Out of the sixteen regular streams gauging stations over the Kosi basin, two stations have less than ten years and four stations have less than twenty years of discharge records. The records of the Kosi River extend from 1947 to 1994 with about nine missing months in 1980/1981. We have estimated the data for these missing months using flows in the nearest upstream tributaries. The other stations with long term discharge records include the Tamor at Tribeni/Mulghat (1948-1994) and the Sunkosi River at Kampughat (1948-1984). The other two stations, with complete data from 1968 to 1993, are the Balephikhola (Station No. 620) and the Dudhkosi (Station No. 670). Appendix K gives the time series of the annual discharge values for all the stations with longer than 25 years of records.

We used some estimated data, as described above, only for some stations with fairly complete and relatively long period of records. The remaining data are used without filling in missing records.

Homogeneity of Time Series

Evaluation of the homogeneity of time series data is a primary step for long term climatic trend studies (Mitchel et al., 1966) and for the validation of proper instrument, site, exposure, and data processing procedure. The evaluation of the homogeneity of data for the Kosi basin is particularly important as the hydrological and meteorological networks were established by CWC and IMD and upgraded by DHM. An example of the instrumental changes as a result of such transition is the different types of precipitation gauges used by different agencies. IMD uses 127 mm Symon's precipitation gauge as its standard for measurement of precipitation whereas DHM uses a standard 203 mm precipitation gauge. Similarly, some of the stations were relocated after the transfer of stations from IMD/CWC to DHM as described earlier.

We applied the following procedures for assessing the homogeneity of precipitation, temperature (Mitchell et al., 1966) and discharge (Linsley, Kohler & Paulhus, 1988) records.

- Assessment of the homogeneity of precipitation and discharge by plotting double-mass curves. Appendix L and appendix M presents double mass curves for selected stations with relatively long length of records.
- Objective assessment of the homogeneity of precipitation and temperature using statistical methods.

We used the following steps, as recommended by Mitchell et al. (1966), for testing the homogeneity of precipitation and temperature data series.

Test of Normality

We obtained the difference between the values of two stations in the case of temperature and ratio between the values of two stations in the case of precipitation. We then tested the normality of the series of the difference or ratio by using Kolmogorov-Smirnov statistics (Haan, 1977) given as:

$$D = Max_y|F_n(y) - F(y)| \tag{IV-1}$$

where $F(y)$ is the hypothesized cumulative distribution function (cdf) and $F_n(y)$ is the empirical distribution function of the sample computed as:

$$F_n(y) = \frac{1}{n}\sum_{i=1}^{n} I(y_i \leq y), \tag{IV-2}$$

where n is the number of observations and $I(y_i \leq y)$ is the indicator function in which:

$$I(y_i \leq y) = 1 \text{ if } y_i \leq y \tag{IV-3a}$$

$$= 0 \text{ if } y_i > y. \tag{IV-3b}$$

The null hypothesis of a normal distribution is rejected if the probability value for this hypothesis is significantly small. Application of this test to 22 ratio sets with relatively long term annual precipitation series indicated a lack of evidence against the null hypothesis in all cases at one per cent level of significance and all but six cases at five per cent level of significance.

Application of the test to the difference set obtained for the maximum and minimum temperature data of three stations with more than 30 years of records indicated normal distribution in all cases except one (minimum temperature for station 1303) at one per cent level of significance. The null hypothesis was, however, rejected for minimum temperature at five per cent level of significance for all the three stations. Hence, despite some limitations, particularly for minimum temperature, we considered annual precipitation as well as temperature data suitable for analysis using parametric statistics. Null hypothesis of normality was not rejected at one per cent level of significance for the discharge data (Appendix K) and at five per cent level of significance for all but one station (670).

Test of Randomness

We tested the difference or ratio series of the last step for nonrandom component using Bartlett's Kolmogorov-Smirnov statistics and Fisher's Kappa statistics to the spectrum of the data. The Kolmogorov-Smirnov statistic tests the critical value of maximum absolute difference between normalized periodogram and cumulative distribution function of a uniform random variable (SAS, 1993). Fisher's Kappa statistic, under the null hypothesis of normal white noise, tests the Kappa value given by the following relation against entries within a table (Fuller, 1976).

$$\zeta = \left[\frac{1}{m} \sum I_n(w_k) \right]^{-1}, \qquad \text{(IV-4)}$$

Where $m = (n-1)/2$ if n is odd

$= n/2$ if n is even

$I_n(w_k)$ = Periodogram ordinate

$w_k = (2\pi \kappa)/n$

n = Number of observation

$I_n(L)$ = Largest periodogram ordinate in a sample

If $\zeta > (Value)_{m,\ \alpha}$ then null hypothesis is rejected. $(Value)_{m,\ \alpha}$ is the value obtained from a table for a significance level of α.

Almost all the annual time series of precipitation indicated white noise when Fisher's Kappa statistics were applied. Data of only one station (Station No. 1403) showed statistically significant cycle of two to three years. Two to three year cycle was also found to be statistically significant by Kolmogorov-Smironov test but not by the Kappa test for the station 1104. The 73-year long precipitation record at Kathmandu also shows 2.5-year cycle at five per cent level of significance. The white noise test applied to the long term temperature data of three stations of the Kosi basin shows that the null hypothesis of white noise is not rejected in the case of two stations (1206 and 1405) but is rejected in the case of station 1303.

Analysis of discharge data for five stations (620, 670, 680, 690, and 695) indicates white noise for all the cases except one (620) which shows 15 year's cycle. Station No.

690 shows 11.5-year cycle under Kolmogorov-Simironov test, but none under the Kappa test.

Discussion

Regular monitoring of the Himalayas for land-use and climatic changes represents a significant challenge and the existing operational hydrological and meteorological techniques are not adequate for climatic monitoring in remote areas. Meteorological and hydrological information, although not long enough for historical climate change studies, covers the most important period. It covers the recent 30 to 50 years which is the period of major concern regarding high population growth rate in the region and the enhanced greenhouse warming. The processed and analyzed meteorological and hydrological data are consistent, homogeneous, and fairly regular for the majority of the stations. Due to strong seasonal influences, the monthly time series are not normally distributed; but the annual data or the data for particular months for most of the hydrological and meteorological elements are good for analysis using parametric statistics. Some time series data show significant periodicities; but the periodicities are not homogeneous. In summary, nonparametric statistics are better suited for the analysis of meteorological and hydrological time series while parametric statistics can be used for annual series of annual and monthly values with due caution.

DEM is the only information that does not need regular monitoring but is a major factor influencing the climate of the region. Application of DEM within a GIS is probably the best means available for modeling hydrology and other environmental aspects at present. Out of the available ten minute resolution DEM and 30 arc second resolution DEM, the first one is almost useless as it can not capture the drainage pattern correctly for the Himalayan topography while the later is adequate for meso-scale hydrological modeling.

Available land-use data are good for qualitative assessment of land-use changes for about 30 years from 1950 to 1980. Quantitative assessment based on this information should be considered approximate. There is no scope for statistical interpretation and analysis of land-use data. Decadal national censuses of Nepal provide a reliable time series of anthropogenic data for the Himalayan region in Nepal.

CHAPTER V

METHODOLOGY

As described in the earlier chapters, this study considers the following two major aspects for the assessment of climatic changes over the Kosi basin.

- Evaluation of existing meteorological and hydrological information using statistical tools, and
- Evaluation on the basis of hydrological principles.

The following sections describe the hypothesis, major approaches, and methods used in the study.

Statement of Hypothesis

Using the observed climatic and hydrologic records, we tested the hypothesis that observed climatic trends in the Himalayan basin reflect a stationary climate. An alternate hypothesis is that the observed trends in climatic records indicate significant change in climate.

The null hypothesis in the case of hydrological impacts due to changes in climate and land-use is that the hydrological variables do not show statistically significant trends. The alternate hypothesis, in this case, is that significant trends are evident in hydrological variables. Discharges of the main river and its major tributaries are the main hydrological variables used to test the hypothesis. We also used sediment records to supplement the tests obtained using discharge records.

Characteristics of Time Series

All the climatic and hydrologic data used in this study have a strong seasonal component due to the influence of monsoonal climate in the region. As a first attempt to assess the general long term characteristics of the time series, we used X-11 method (Kendall & Ord, 1990; SAS, 1993) to deseasonalize the data. The basic of the X-11 procedure is to separate time series into seasonal component, trend-cycle component, and random component. The additive model used in this procedure can be given as:

$$X = C + S + I, \qquad \text{(V-1)}$$

where X is the original time series, C is the trend cycle component, S is the seasonal component, and I is the irregular component. The trend cycle component obtained in this fashion gives a clearer picture of the long term progression along with the long term periodic characteristics of a time series.

A series of 12 month moving averages is the first approximation of trend-cycle component computed in the X-11 method. The program in this method subtracts this component from the original series to obtain the sum of irregular and seasonal components. The moving average of this combined seasonal plus irregular component gives the preliminary estimate of seasonal component. The irregular component is the residual after removal of the seasonal component from seasonal plus irregular component. As its second iteration, the program adjusts the original series using a moving standard deviation of irregular components. The program computes the final series of trend-cycle, seasonal, and irregular components in its third iteration. The details of the computation are given in SAS (1993).

Analysis of Trend

Common statistical methods used to test the hypothesis of the existence of a long term trend can be divided into two broad categories: parametric and nonparametric. Several methods are available in both of these categories (Helsel & Hirsch, 1992). The following sections describe the methods used to assess time series data and their trends from each of these two categories.

Parametric Method

A simple linear trend can be computed by using the linear equation:

$$y = a + b * T, \tag{V-2}$$

where y is the variable used to test the trend, T is the time variable of the time series, and a and b are the coefficients of the equation obtained by regression. The coefficient b, which is slope of the regression line, is an indicator of the trend. Null hypothesis (b=0) is tested using t statistics given as:

$$t = \left| \frac{\sqrt{N-2}}{r\sqrt{1-r^2}} \right| , \tag{V-3}$$

where N is the number of observations and r is the correlation coefficient. The null hypothesis is rejected if $t > t_{1-\alpha/2,\ \upsilon}$ where α is the significance level and υ is the degrees of freedom. The parametric method is considered a powerful method for testing trend (Helsel & Hirsch, 1992); however, we note that the normality of residuals is a basic requirement for the application of this method.

Nonparametric Method

The nonparametric method used in this study is the seasonal Kendall test (Smith, Hirsch, & Slack, 1982). The method, based on a modified form of Kendall's τ, computes statistics for different seasonal divisions independent of each other. Kendall's S statistics are computed for ith season by the following relation:

$$S_i = P_i - Q_i, \qquad \text{(V-4)}$$

where P_i is the number of positive values and Q_i is the number of negative values obtained by subtracting each value of the series to subsequent values. The Kendall's τ for a given month is computed by using the following equation:

$$\tau_i = \frac{2S_i}{n_i(n_i - 1)}, \qquad \text{(V-5)}$$

The significance of τ is assessed by evaluating the value of S_i against the p-values for Kendall's τ. For larger samples (>10), the Kendall's statistics are approximated by the normal distribution (Helsel & Hirsch, 1992). Standard normal deviates (Z-statistics) are then computed as (Smith, Hirsch, & Slack, 1982):

$$Z_i = \frac{S_i - 1}{\sqrt{Var(S_i)}}, \qquad \text{if } S_i > 0 \qquad \text{(V-6a)}$$

$$Z_i = 0, \qquad \text{if } S_i = 0 \qquad \text{(V-6b)}$$

$$Z_i = \frac{S_i + 1}{\sqrt{Var(S_i)}}, \qquad \text{if } S_i < 0 \qquad \text{(V-6c)}$$

$Var(S_i)$ is computed by using the following relation:

$$Var(S_i) = (\frac{n}{18})(n_i - 1)(2n_i + 5), \qquad \text{(V-7)}$$

where n_i is the number of data for i season. The Z_i values are then used to test the null hypothesis by using critical values of standard normal distribution. Equation (V-7) is changed to the following form if ties (zero difference between compared values) are present in the series.

$$Var(S_i) = \left[\frac{n_i(n_i - 1)(2n_i + 5) - \sum_{j=1}^{n} t_j(j)(j-1)(2j+5)}{18} \right], \qquad \text{(V-8)}$$

where t_j is the tie of extent j.

Overall trend of the whole series for a given station is obtained by the Kendall's S statistics adding all the seasonal S statistics.

$$S = \sum_{i=1}^{m} S_i \qquad \text{(V-9)}$$

where m is the number of seasons. The slope of the trend line, in this method, is obtained by computing median value of D_{ij} where D_{ij} is given as:

$$D_{ij} = \frac{x_i - x_j}{i - j}. \qquad \text{(V-10)}$$

where x_i and x_j are consecutive ith and jth values of the variable.

For obtaining the basinwide trend, we used the methods described by Belle and Hughes (1984). Global trends in these methods are assessed in terms of seasonal heterogeneity, site heterogeneity, and the combined site-season heterogeneity. The trends with m seasons and n stations are tested against χ^2 using the following formulation and degrees of freedom.

a) Total χ^2 with m*n degree of freedom is given as:

$$\sum_{i=1}^{m}\sum_{j=1}^{n} Z_{ij}^{\ 2}$$

b) Homogeneity with (m*n - 1) degree of freedom is given as:

$$\sum_{i=1}^{m}\sum_{j=1}^{n} (Z_{ij} - Z..)^2$$

c) Seasonal homogeneity with (m-1) degree of freedom is given as:

$$n\sum_{i=1}^{m} (Z_{i.} - Z..)^2$$

d) Site homogeneity with (n-1) degree of freedom is given as:

$$m\sum_{i=1}^{m} (Z_{.j} - Z..)^2$$

e) Site-season homogeneity with (m-1)(n-1) degree of freedom is given as:

$$\sum_{i=1}^{m}\sum_{j=1}^{n} (Z_{ij} - Z_{i.} - Z_{.j} + Z..)^2$$

f) Trend with one degree of freedom is given as:

$$mk(Z..)^2$$

The subscripts *i*, and *j*, in the above expressions given above, indicate season and station respectively. The subscript *i.* indicates average of all the stations in a basin obtained for each season. Similarly, *.j* indicates average of all seasons obtained for each station and .. indicates an overall average.

If the χ^2 for the given degrees of freedom is nonsignificant in all the cases of site, season, and site-season then the null hypothesis of homogeneous trend is not rejected. In such instances, we can test the overall trend for a basin using the expression (f).

Modeling

Watershed and regional scale modeling are widely used for assessing the impacts of land-use changes (Henderson-Sellers et al., 1993; Kite, 1993) and the impacts of climatic changes (Nikolaidis, Hu, Ecsedy, & Lin, 1993; Panagoulia, 1991; Rind, Rosenzweig & Goldberg, 1992) on hydrology. Such models are useful to simulate the effects of predicted changes on hydrology of a basin. We used the following two approaches to evaluate the expected hydrologic impact over the Kosi basin as a result of conceivable climatic changes and land-use changes.

Lumped Approach

Basinwide Water Balance. We used the methodology proposed by Wigley and Jones (1985) for assessing CO_2 induced global warming effect on runoff characteristics. The method, summarized by Dingman (1994) can be given as:

$$RO = P - ET, \qquad \text{(V - 11)}$$

where *RO, P,* and *ET* are runoff, precipitation and evapotranspiration respectively. Similarly, the long term average runoff can also be defined as:

$$RO = w^*P, \qquad \text{(V-12)}$$

where *w* is the runoff ratio obtained by dividing long term runoff by long term precipitation. The value of *w* depends on basin characteristics. The following expression can be obtained for change in runoff by solving the equations (VI-11) and (VI-12).

$$r = \frac{p-(1-w)e}{w}, \qquad \text{(V-13)}$$

where, e and p are the fraction of change in evaporation and precipitation respectively as a result of climatic changes as well as changes in CO_2 of the atmosphere.

For the evaluation of changes in runoff using equation (VI-13), we used the precipitation scenarios applicable for the south Asia in general and the Kosi basin in particular (Chapter X). Evaluation of e needs the assessment of evaporation changes due to: temperature change, land-use change and CO_2 change. The multiplicative effects of these three variables are used to compute e given as (Wigley & Jones, 1985).

$$e = e_1 * e_2 * e_3. \qquad \text{(V-14)}$$

where e_1, e_2, and e_3 are the factors affecting evapotranspiration due to temperature change, land-use change and CO_2 change, respectively.

We used Table VII-6 and Table VII-8 to compute change in evapotranspiration due to change in temperature (e_1). For the computation of e_2, the change in evapotranspiration due to change in forest cover, we used the semi-empirical Calder-Newson model (Calder & Newson, 1979) given as:

$$E = PET + f(a*P - b*PET), \qquad \text{(V-15)}$$

where E is the total water loss due to evapotranspiration including interception loss, PET is the potential evapotranspiration of the basin, f is the fraction of watershed with full canopy cover, a is the interception fraction, and b is the fraction of year canopy is wet.

Evapotranspiration from the plants is expected to be suppressed in a scenario of increased CO_2 due to progressive reduction in photorespiration and stomatal openings (Kimball, Mauney, Nakayama, & Idso, 1993; Kirschbaum, 1996; Mooney, Drake, Luxmoore, Oechel, & Pitelka, 1991; Nonhebel, 1996). We used the following approximate relationship for the computation of e_3 which is the CO_2 induced evapotranspiration factor (Wigley & Jones, 1985).

$$e_3 = 1 - 0.3 * d, \qquad \text{(V-16)}$$

where d is fraction of vegetated area of the watershed.

Statistical Approach. Regression analysis provides information on the strength of association between streamflow and basin characteristics including climatic variables. We used this approach to examine the role of vulnerable climatic variables and basin characteristics in influencing the flow regime of the basin. For instance, only the low laying areas and valleys of the basin are vulnerable to land-use changes whereas the climatic changes may influence snow cover and snowmelt in high elevation zones and evapotranspiration and precipitation throughout a basin. Hence, significant correlation of streamflow with low elevation areas may suggest the vulnerability of hydrology due to land-use change in a basin. Similarly, the strong correlation of high elevation areas with river discharge is likely to suggest vulnerabilities of land surface hydrology to possible changes in snow cover due to climatic changes.

Distributed Deterministic Model

We used the grid based deterministic Water Balance Model (WBM) to study the land-use as well as climate change impact on hydrology. The model (Vorosmarty et al., 1989; Vorosmarty & Moore, 1991; Vorosmarty et al., 1996) is based on explicit soil moisture accounting for each grid. It computes runoff as a residual of the water balance equation. The model uses monthly input information on precipitation, potential evapotranspiration, temperature, soil texture, vegetation cover and DEM to compute runoff and its components. Total runoff for an individual month is computed as 50 per cent of the detention storage of moisture in soil when precipitation and snowmelt do not meet soil moisture deficit. If the moisture input to the soil exceeds field capacity then the model uses the following equation (Equation V-17) to compute runoff.

$$RO_i = 0.5\,[D_i + p_i(P_i + SR_i - PET_i)], \quad \text{(V-17)}$$

where RO_i, D_i, P_i, SR_i, and PET_i are runoff, detention storage, precipitation, snowmelt, recharge, and potential evapotranspiration respectively for ith cell. The factor p_i is defined as:

$$p_i = \frac{P_i}{P_i + SR_i}, \quad \text{(V-18)}$$

The model accounts for snowmelt depending on the threshold air temperature of -1° C. Vegetative cover plays a role in the model by influencing the total porosity of soil for holding water. The water capacity, defined in the model as field capacity minus wilting point, is calculated using the soil texture and rooting depth information. The model considers the root depth for all types of vegetation in lithosol as 0.1 m. The root depth of forest varies from 0.1 m for lithosol to 2.5 m for sandy soil. Root depth for grassland varies from 0.1 m to 1.3 m, the latter being the root depth of grassland in silt loam. Water holding capacity varies from 14 per cent for lithosol to 48.5 per cent for clay (Vorosmarty et al., 1989).

CHAPTER VI

ANTHROPOGENIC CHANGES

Anthropogenic changes, including land-use alterations, are the likely sources of global climatic changes (Tolba, 1992). The land-use alterations are the direct impact of food, fuel, and construction needs of population. Although quantitative estimates of these population needs vary from author to author and from one region to another (Applegate & Gilmour, 1987; Mahat, 1987), these are the major factors blamed for deforestation in Nepal (Chapter I & Chapter III).

Population Pressure

Some recent and reasonable estimates of forest needs applicable to the Kosi basin (Applegate & Gilmour, 1987; Mahat, 1987; Rieger, 1981; Bajracharya, 1985) show that the per capita wood consumption exceeds one cubic meter in a year of which fuel wood approaches 90 per cent of the total consumption. Mahat (1987) calculates a ratio of about 1:4 between agriculture and forest land to meet the basic requirements of the forest products. Available information (Table VI-3 & Table VI-4) shows that the ratio between agricultural land and forest land is about 1:2 which indicates the deficiency of forest to meet basic requirements of the population.

Human Population

Figure VI-1 shows the trend of population in Nepal and in the Kosi basin obtained from CBS data. Similarly, Table VI-1 presents population density and population growth rates for different districts in the Kosi basin. The table includes three surveys of the recent past.

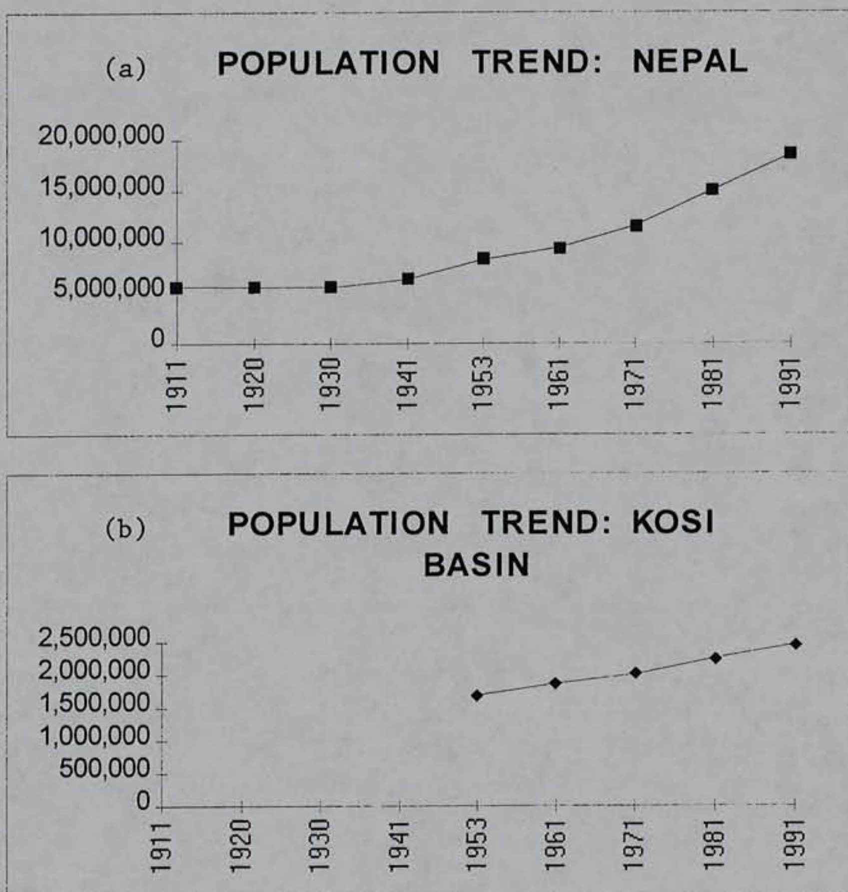


Figure VI-1. Population trend in (a) Nepal and (b) the Kosi basin.

Figure VI-1 shows that the population remained almost static up to 1952. Annual growth rate of population in Nepal started increasing rapidly exceeding two per cent per annum in the following years. Despite such increase, the population growth rate in the Kosi basin remained relatively low. National average increase of population in Nepal exceeded two per cent per annum in both the decades considered in Table VI-1; whereas, the compound growth rate was about one per cent per annum in the Kosi basin. A major reason behind the lower rate of population growth in the basin is believed to be the effect of migration of people towards *Tarai* (low laying plain areas outside the Kosi basin considered in this study) and cities. High population growth rates in *Tara*i indicate such large scale migration (Gurung, 1991; CBS, 1987).

Table VI-1. Area and population density in the districts of Nepal and the Tibet autonomous region of China that lie in the Kosi basin.

	Area (km^2)	*Pop. Density (Person/ km^2) 1971*	*Pop. Density (Person/ km^2) 1981*	*Pop. Density (Person/ km^2) 1991*	*Pop. 1971-81*	*Growth 1981-91*	*Rate 1971-91*
Taplejung	3646	23.2	33.1	32.9	3.63	-0.06	1.77
Panchthar	1241	117.5	123.9	141.2	0.53	1.32	0.92
Dhankuta	891	120.8	145.7	164.3	1.89	1.21	1.55
Terhathum	679	175.7	136.2	151.5	-2.52	1.07	-0.74
Sankhuwasabha	3480	32.8	37.2	40.8	1.26	0.93	1.09
Bhojpur	1507	129.1	127.9	131.9	-0.10	0.31	0.11
Solukhumbu	3312	31.8	26.6	29.3	-1.75	0.97	-0.40
Okhaldhunga	1074	114.4	128.2	129.8	1.14	0.13	0.64
Khotang	1591	102.6	133.6	135.7	2.68	0.16	1.41
Ramechhap	1546	101.8	104.4	121.6	0.26	1.54	0.89
Dolakha	2191	59.3	68.7	79.1	1.49	1.41	1.45
Sindhupalchowk	2542	81.2	91.4	102.7	1.19	1.17	1.18
Kavrepalanchowk*	1396	175.6	202.2	213.6	2.28	0.55	1.41
Tibet**	29500	2.1	2.5	2.9	1.76	1.32	1.54
Kosi Basin	54000	37.1	41.5	45.5	1.15	0.91	1.03
Nepal	147181	78.5	102.1	125.6	2.66	2.10	2.41

Data from CBS (1987, 1993) and The Population Atlas of China (1987)

* A small area of Kavrepalanchowk (less than 10 %) does not lie in the Kosi basin. The other two districts (Sindhuli and Udaipur), not listed in the table, contribute some (less than five per cent each) drainage to the Kosi basin.

** The population for the Tibetan part of the Kosi basin is available only for 1982. Estimates of population density for other years are based on the population growth rate of the Tibetan autonomous region.

The density of population as well as population growth rate varies widely within the basin (Table VI-1). The range of population density among districts lying in the Kosi basin in Nepal ranges from 29 persons/km^2 (Solukhumbu district) to 232 persons/km^2 (Kavrepalanchowk district). The density is only about 2 persons/km^2 to 3 persons/km^2 in more than 50 per cent of the basin lying in Tibet. Similarly, the population growth rate within the basin varies from negative rates (as low as -2.52 per cent per annum in Terhathum) in some of the districts to more than three per cent per annum (as high as 3.63 per cent per annum in Taplejung during 1971-81). Average compound growth rates for the basin for 1971-81 and 1981-91 are 1.15 and 0.91 respectively. These rates are the lowest when compared with the rates for similar regions in Nepal (Gurung, 1991).

Livestock Population

Livestock is a major component of agrarian socio-economy that dominates the Kosi basin. An estimate made by Shrestha (1989) in a *Haat* (weekly market) of a district head-quarter in the Kosi basin shows the product of animal origin exceeding quarter of the value of all products.

Land-use products are used by livestock in different forms. Plants and agriculture residue are used for fodder and grasslands are used for grazing. Livestock, hence, contributes to the depletion of forest and disturbance of soil surfaces resulting in the changes in surface and sediment characteristics (Lee, 1980). The livestock population becomes more important in high elevation areas due to significantly higher human:livestock ratio (Ekvall, 1968; Shrestha, 1989).

Unlike human population, information on livestock population is severely lacking. Not much historical information of livestock in Kosi basin is available. A recent survey (1981-82) shows the following statistics (Table VI-2) of livestock in different political division of the Kosi basin

Table VI-2. Livestock population in the districts of Nepal and the Tibet autonomous region of China that lie in the Kosi basin.

Districts	*Cattle*	*Yak*	*Buffaloes*	*Goats and sheep*	*Total*	*Ratio Livestock:human:*
Taplejung	82723	1382	22784	67080	173969	1.44
Panchthar	70069		25151	86334	181554	1.18
Dhankuta	56260		10600	76269	143129	1.10
Terhathum	48166		14939	65379	128484	1.39
Sankhuwasabha	115357	934	22708	83028	222027	1.72
Bhojpur	118969		39895	96103	254967	1.32
Solukhumbu	33307	8515	11445	18272	71539	0.81
Okhaldhunga	64666		41746	61938	168350	1.22
Khotang	134093		66961	93611	294665	1.39
Ramechhap	66300		34276	91437	192013	1.19
Dolakha	77960	17628	36909	129808	262305	1.74
Sindhupalchowk	111816	2777	61378	124123	300094	1.29
Kavrepalanchowk	124467		62992	132811	320270	1.13
Kosi in Nepal	1104153	31236	451784	1126193	2713366	1.29
Kosi Basin	1104153		451784			
Nepal	6501577	55499	2379723	4320762	5071209	0.88

Data from CBS(1993)

Table VI-2 shows that the population of livestock exceeds human population in almost all the mountainous districts of the Kosi basin. The only district with lesser livestock than human population is Solukhumbu where the economy is strongly influenced by tourism and mountaineering. The table also shows that the livestock:human ratio is higher in the high mountain districts (Taplejung, Sankhuwasabha, Dolakha) than in the middle mountain districts. Although no information is available for the Tibetan part of the basin, studies in similar part of Tibet indicate the livestock:human ratio as high as 6:1 (Rongzu, 1989). The ratios of Table VI-2 can be used for an approximate estimate of the historical trend of livestock changes over the districts; since similar trends can be expected in the region as long as the socio-economy pattern does not change.

Land-Use Changes

Lack of information on forest cover before the 1960s and the debate on the pattern of land use change in mountainous areas of Nepal in the last four decades have already been discussed in Chapter III. Considering these discussions, including our evaluation of data sources, and an assessment of physiographic conditions of the basin, we derived some conclusive facts as described in the following paragraphs.

Considering anthropogenic influence on land-use over the basin, the Kosi basin can be divided into the following two major parts.

Higher Elevation Zone

Higher elevation zones, considered here, are the areas lying 4000 m above sea level. As almost all the areas in this zone are inaccessible; there are negligible agriculture and other human activities except in a small section of the Himalayas explored for tourism, such as, Sagarmatha National Park. This zone can be considered as an area free from land use change for meso-scale hydrological and climatic modeling. About 55 per cent of the basin lies in this elevation zone (Figure II-3).

Lower Elevation Zone

Being a zone of agriculture, grazing, and timber harvesting, significant anthropogenic influence on land-use pattern can be expected in this region. Lower elevation zone, lying below 4000 m elevation occupies about forty-five per cent of the total basin area. Except for a small corridor of the Arun valley in Tibet, almost all the areas of the basin below 4,000 m lie in the southern part of the Himalayas in Nepal

The two major surveys carried out in the 1960s and 1970s in Nepal provide land-use data on nationwide basis. The data from the first forest survey published in 1973

(Department of Forest [DOF], 1973) indicate forest cover areas of 54.7% and grassland of 5.5%. Although the areas covered by the survey do not include all the study area, the statistics can be assumed fairly representative for the hill areas and mountainous areas of the Kosi basin. The map, presented in a DOF (1973, p. 9) publication, shows the forest cover areas ranging from less than 25 per cent in eastern part of the basin to more than 75 per cent in some areas of the Mahabharat range. Most of the surveyed areas fall in the class of 50 per cent to 75 per cent forest cover.

The forest cover data, developed for the Kosi basin using recent survey (Survey Department, 1984) in Nepal and published literature on land use in Tibet (Chapter III), are presented in Figure IV-4. Table VI-3 presents the accumulated land use in different classes. Table VI-4 presents the table of accumulated areas for the region below 4000 m.

Table VI-3. Land-use in the Kosi basin in the late 1970s.

Classification	*Area (km^2)*	*Per cent*
Intense Agriculture (75 to 100 %)	948	1.7
Medium Agriculture (50 to 75 %)	4520	8.2
Light Agriculture (25 to 50%)	1740	3.2
Subtropical/Temperature grazing land	217	0.4
Cool temperature/Sub-alpine grazing land	849	1.5
Alpine	17800	32.3
Rock/boulder	7170	14.8
Ice/snow	8180	13.0
Lake	90	0.2
Shrub	1320	2.4
Hardwood/mixed forest	11400	20.7
Coniferous forest	947	1.7
Total	55200	100

Data obtained from the reclassified map (Figure IV-4). Cell size used to derive the data is 111 m.

Table VI-4. Land-use in the Kosi basin below 4000 m in the late 1970s.

Classification	*Area (km^2)*	*Per cent*
Intense Agriculture (75 to 100 %)	956	4.5
Medium Agriculture (50 to 75 %)	4490	21
Light Agriculture (25 to 50%)	174	0.8
Subtropical/Temperature grazing land	213	1
Cool temperature/Sub-alpine grazing land	661	3.1
Alpine	350	1.6
Rock/Boulder	576	2.7
Ice/Snow	677	3.2
Lake	0	0.0
Shrub	1260	5.9
Hardwood/Mixed forest	11200	52.4
Coniferous forest	822	3.8
Total	21400	100

The data are based on the reclassified land-use map (Figure IV-4) overlaid over the topography map (Figure II-3). Cell size of the grid used to derive the data is 1331 m.

Although Table VI-3 presents data for the whole basin, only the data presented in Table VI-4 can be compared to the forest data of the basin prior to 1965. Even if the areas considered are not exactly the same in these two cases, data presented in percentage terms can be compared with enough confidence for the Mahabharat and the middle mountain areas of Nepal. The following table (Table VI-5) presents the comparison of forest and grassland estimates of the two major surveys.

Table VI-5. Comparison of forest cover in the Mahabharat and the middle mountain region of the Kosi basin during 1964-65 and 1978-79.

	Percentages of Forest cover 1964-65	*Percentage of Forest Cover 1979-80*
Forest Cover	54.7	56.2
Shrub		5.9
Grassland	5.5	4.1
Total	60.2	66.1

Table VI-5 indicates slightly higher forest area in recent period compared to the past survey; nevertheless the quantity and quality of data are not enough to make conclusive remarks. Several limitations are likely to play their role in proper assessment of land-use changes. The factors such as, differences in survey methods, data analyses procedure, and presentation techniques may influence the outcomes besides some difference in areas covered during the two surveys. Since the percentage data presented in the table above (Table VI-5) are not much different, the information cannot be considered sufficient to reject the null hypothesis (no change in land-use). Lack of information about the changes in forest density and inadequacy of data for statistical time series modeling constrains the scope of our conclusions.

Discussion

Eradication of fatal diseases, such as malaria, and improvement in health sector in Nepal resulted in a dramatic rise in population during the last 50 years. Since the population remained almost static in the earlier half of this century, the population explosion can be considered a recent phenomenon. The average annual population growth rate of about 2.1 per cent, observed in Nepal during 1981-91, is almost equal to the average of less developed countries during 1985-90 (Bulatao, Bos, Stephens, & Vu, 1990). Considering the fragile mountain environment of Nepal, the rate of population growth has been a major concern among planners because of considerable link between natural resources and population factors.

Average population growth rate of about one per cent per annum in the Kosi basin during the last two decades, indicates a modest population pressure. The rate is close to the rate of population growth in the USA for the same period. Since the computation is not based on birth rates and death rates, the actual population growth rate can be expected to be higher than one per cent as a significant migration trend exists in the region. Although the population growths indicate a modest rise, the pressure of livestock to forest and grazing land is increasing at a rate higher than the pressure of human population due to high livestock:human ratio.

A general assessment of the available information suggests that the population pressure in Nepal, reflected by high population growth rates, is generating more impacts in foothills, plain areas, and cities than in the mountainous region. For instance, the records of the Ramechhap district, in the central part of the Kosi basin, indicate the population growth rate of 0.53 per cent per annum during 1971- 81 (Table VI-l). Population growth rate for the same period in an inner *Tarai* (Sub-Himalaya) district of Sindhuli, south of Ramechhap, remained 2.2 per cent. The growth rate for that period was 8.2 per cent per annum in Sarlahi, a *Tarai* (plain) district south of Sindhuli (CBS, 1987). During the similar period, the plain areas of Nepal lost almost 24 per cent of forest areas to agriculture lands (Gilmour, 1991).

The distribution of *Tarai* and mountain population in Nepal was 35 per cent and 65 per cent, respectively in 1952/54. This proportion of population has changed to almost 50 per cent in recent years. Economical opportunities and increasing communication facilities in *Tarai* have encouraged the downward migration of mountain and hill people. Such migration trends are likely to continue and the existing trends of human and livestock populations are likely to remain similar in the Kosi basin for several years to come. Under the assumption of existing population growth rate, the present population of the Kosi basin is likely to double in seventy to seventy-five years.

A general evaluation of the requirement of land-use for the rising population and livestock clearly shows pressure on forest and land resources which is less than sustainable in a business as usual scenario. On the other hand, the land-use data based on two extensive surveys of fifties and seventies do not show distinct trends in forest depletion. Although the land-use data suffer from several sources of uncertainties with respect to survey techniques, data processing techniques and the differences in areas covered, the statistics clearly indicate that the deforestation rate in the mountainous areas of the Kosi basin is not alarming. Some depletion of forest areas can be predicted for the future on the basis of population needs and the supply capacity of forest. Such predictions are, nonetheless, subject to several uncertainties as the rate of deforestation is highly dependent on political factors, community afforestation programs, and public awareness besides other natural processes.

CHAPTER VII

HYDRO-CLIMATIC CHANGES

This chapter describes the statistical analyses of meteorological and hydrological data carried out to examine hydro-climatic trends over the Kosi basin. Along with the available data within the Kosi basin, we also analyzed the meteorological records of Kathmandu. Kathmandu provides the longest meteorological time series in the area nearest to the region considered in this study.

Temperature Changes

Temperature Trends in Kathmandu

Although Kathmandu does not lie in the study area, it is the closest location of the Kosi basin with long term climatological data. Station No. 1014, located at the Indian Embassy in Kathmandu, is the only station with a 50 plus years regular temperature records in Nepal. The temperature records for this station are available from 1921 through 1975. DHM discontinued the publication of climatologic records for this station from 1975. We used the data available from the aeronautical meteorological station located at Kathmandu airport to supplement these records. Figure VII-1(a) and Figure VII-1(b) present the monthly time series of average maximum temperature for Station No. 1014 and Station No. 1030 respectively by separating the series into trend-cycle component, seasonal component and irregular component using X-11 method. Similarly, Figure VII-1(f) and Figure VII-1(g) present these time series components of minimum temperature for the same stations. Out of these figures, only the maximum temperature records at Station No. 1030 show a distinctly rising trend of temperature since the start of its records in 1968.

Application of Student's t statistics on the long term means of temperature data recorded at Station No. 1014 and at Station No. 1030 in Kathmandu show that the two data series cannot be considered as belonging to the same population. Hence, the temperature records collected from these two stations are treated separately for statistical analysis.

Figure VII-2 shows the temperature anomaly of two stations in Kathmandu valley. The period of reference mean is 1951 to 1975 which is the period considered by Vinikov, Groisman, and Lugina (1994) for the computation of global climatic trend. The reference mean period for Kathmandu airport is from 1968 to 1975.

Comparison of the anomalies between the two stations during overlapping period from 1968 to 1975 shows a similar pattern (Figure VII- 4). Hence, despite the significant difference in long term mean, we combined the records of these two stations to obtain the long term series of temperature anomaly covering the period from 1921 through 1992.

A combined picture of the anomalies of the two stations (Figure VII-2) shows that Kathmandu experienced a long term decreasing trend of temperature from 1921 to mid-1960s followed by an increasing trend until only recently. The patterns of trends, however, are not the same between maximum and minimum temperature. Statistical analyses of the trend of maximum and minimum temperature for these two stations are presented in Table VII-1.

Table VII-1. Statistical significance of maximum temperature trend in Kathmandu at two locations during two different periods.

	Station:	*1014*	*Station:*	*1030*
	Year :	*1921-1975*	*Year:*	*1968-92*
	Parametric	Nonparametric	Parametric	Nonparametric
Jan	ns	ns	+1%	+1%
Feb	ns	ns	+1%	+1%
mar	ns	-5%	ns	ns
Apr	ns	ns	ns	ns
May	ns	ns	ns	ns
Jun	-5%	-5%	+1%	+1%
Jul	-1%	-1%	+5%	+5%
Aug	-1%	-1%	+1%	+1%
Sep	-5%	-1%	+1%	+1%
Oct	ns	ns	+1%	+1%
Nov	ns	ns	+1%	+1%
Dec	+5%	+5%	+1%	+1%
Ann	-5%	-1%	+1%	+1%

Table VII-2: Statistical significance of minimum temperature trend in Kathmandu at two locations during two different periods.

	Station:	*1014*	*Station:*	*1030*
	Year:	*1921-75*	*Year:*	*1968 -92*
	Parametric	Nonparametric	Parametric	Nonparametric
Jan	ns	ns	ns	ns
Feb	-1%	-1%	ns	ns
Mar	ns	ns	ns	ns
Apr	ns	ns	ns	ns
May	ns	-5%	ns	ns
Jun	ns	ns	ns	ns
Jul	-1%	-1%	ns	ns
Aug	-1%	-1%	ns	ns
Sep	-5%	-5%	ns	ns
Oct	ns	ns	ns	ns
Nov	ns	ns	ns	ns
Dec	-1%	-1%	ns	ns
Ann	-1%	-1%	ns	ns

Assessment of temperature anomaly (Figure VII-2) and statistics of trend (Table VII-1 and Table VII-2), leads to the following observations:

- Overall decreasing trend of temperature from 1921 to 1967.
- Overall increasing trend of temperature from 1968 to near-present.

- The increasing trend of average temperature from 1968 to 1992 is primarily due to the increasing trend of maximum temperature as there is no increasing trend of minimum temperature in this period. This observation is not similar to the observation prior to 1968 when both the maximum and minimum temperatures show a decreasing trend.

The highest maximum temperature anomaly recorded so far is 2.2 °C above reference temperature, recorded in 1989. The average temperature anomaly for the same year is 0.90 ^{0}C above reference temperature. The average temperature anomaly of 1989, however, is not much different from the anomalies observed in 1928 (0.81 °C), 1931 (0.75 °C), and 1932 (0.86 °C).

Since Kathmandu is a city of rapidly increasing urbanization, the increasing trend of maximum temperature may be attributed to the heat island effect (Dingman, 1994). Since the minimum temperature does not confirm the rising trend of temperature, the null hypothesis of insignificant trend of temperature change cannot be rejected.

Temperature Trend in the Kosi Basin

Out of ten climatological stations in the Kosi basin, only three stations, located at Okhaldhunga, Chainpur and Taplejung, maintained fairly regular climatological records for period exceeding 30 years. Figure VII-1(c to e) presents the trend-cycle component, seasonal component and irregular component of maximum temperature for stations located at Okhaldhunga, Chainpur, and Taplejung (1206, 1303, and 1405) respectively. Similarly, Figure VII-1(h to j) presents these components for minimum temperature for the same stations: 1206, 1303 and 1405 respectively. Figure VII-3 illustrates the temperature anomalies whereas Table VII-3 and Table VII-4 present the statistics of the significance of trends for monthly and annual values for these three stations.

Table VII-3. Statistical significance of maximum temperature in three selected locations in the Kosi basin. Period of record is from 1962 through 1993 for stations 1206 and 1303. The period of record for Station No. 1405 is from 1962 through 1992.

	Station:	*1206*	*Station:*	*1303*	*Station:*	*1405*
	Parametric	Nonparametric	Parametric	Nonparametric	Parametric	Nonparametric
Jan	ns	ns	ns	ns	ns	ns
Feb	ns	ns	ns	ns	ns	ns
Mar	ns	ns	ns	ns	ns	ns
Apr	ns	ns	ns	ns	ns	ns
May	ns	ns	ns	ns	ns	ns
Jun	ns	ns	ns	ns	ns	ns
Jul	-5%	ns	ns	ns	ns	ns
Aug	-5%	ns	+5%	ns	ns	ns
Sep	-5%	-5%	+1%	+5%	ns	ns
Oct	ns	ns	+5%	+5%	ns	ns
Nov	ns	ns	+5%	+5%	ns	ns
Dec	ns	ns	+5%	+5%	ns	ns
Ann	ns	-1%	+5%	+1%	ns	ns

Table VII-4. Statistical significance of minimum temperature trend in three selected locations in the Kosi basin. Period of record is from 1962 through 1993 for stations 1206 and 1303. The period of record is 1962 through 1992 for station 1405.

	Station:	*1206*	*Station:*	*1303*	*Station:*	*1405*
	Parametric	Nonparametric	Parametric	Nonparametric	Parametric	Nonparametric
Jan	+1%	+1%	ns	ns	ns	ns
Feb	+5%	ns	ns	ns	ns	ns
Mar	ns	ns	ns	ns	ns	ns
Apr	ns	ns	ns	ns	ns	ns
May	ns	ns	ns	ns	ns	ns
Jun	+1%	+1%	ns	ns	ns	ns
Jul	+1%	+1%	ns	ns	ns	ns
Aug	+1%	+1%	ns	ns	ns	ns
Sep	+1%	+1%	ns	ns	ns	ns
Oct	+1%	+5%	ns	ns	ns	ns
Nov	+1%	+1%	ns	ns	ns	ns
Dec	+1%	+1%	ns	ns	ns	ns
Ann	+1%	+1%	ns	ns	ns	ns

The plot of temperature anomalies (Figure VII-3) indicates a consistent pattern for all the three stations from 1962 to the early 1970s and from late 1980s to the early 1990s. The earlier period does not show a trend. A slight increasing trend exists during mid-1980s to late-1980s. The records of recent years (early 1990s) show some decrease. Although the positive trend of maximum temperature at Station No. 1303 and the positive trend of minimum temperature at Station No. 1206 are statistically significant at 5% and 1% level of significance (Table VII-3 and Table VII-4), tests for an overall trend for the whole basin were not conclusive.

Figure VII-4 compares the average temperature anomaly for the Kosi basin and eastern Nepal with the global average (Vinikov et al., 1994). The average for the Kosi basin is the average of stations 1206, 1303, and 1405 while average for the eastern Nepal is computed by including the stations 1014 and 1030 in the above list. The pattern is similar, especially, in the period after 1960 compared to the pattern of earlier periods. Although the global average temperature anomaly during the period from 1920 to 1960 shows a slightly increasing trend, the records of Nepal indicate a decreasing trend for the same period.

Table VII-5, below, presents the overall trends of average temperature obtained by nonparametric method for major climatological stations over the basin. The table also includes the trend of annual temperature obtained by parametric method for comparison for the stations with relatively long record lengths.

Table VII-5. Statistical significance of the trend of average temperature in the Kosi basin for selected stations.

Station No.	*Period*	*Parametric*	*Nonparametric*
1036	1978 - 92		ns
1103	1971 - 92		+ 1%
1206	1963 - 93	+5%	ns
1209	1962 - 75		ns
1220	1971 - 93		+ 1%
1303	1962 - 93	ns	+ 1%
1304	1976 - 93		+ 1%
1307	1973 - 93	+ 1%	+ 5%
1310	1962 - 76	+ 5%	+ 1%
1318	1971 - 84		+ 5%
1405	1962 - 76	ns	+ 5%

Figure VII-5 and Figure VII-6 present parametric and nonparametric trend of the maximum temperature for each month. Similarly, the trends of minimum temperature are given in Figure VII-7 and Figure VII-8. A general review of these figures and Table VII-5 reveal the following nature of trends.

- As expected both the parametric and nonparametric methods lead to similar results in most of the cases.
- Most of the stations do not show a significant trend.
- In contrast to the result of monthly trend indicated by monthly data, more stations show positive overall trend (Figure VII-17) when nonparametric statistics are used.

Although the application of parametric statistics in the analyses revealed several characteristics of trends in different locations of the basin, we used nonparametric statistics to obtain overall trend for the whole basin. Computation of overall trend is based on assessment of the homogeneity of trend with respect to season and site as described in

Chapter V. The choice of nonparametric statistics against parametric statistics is based on the following criteria:

- Although most of the data used in parametric statistics are normally distributed, some data deviate from normal distribution.
- Time series records of only few stations extend to more than thirty years. Most of the available regular records are available for less than 15 years.
- Time series of several stations suffer from missing records. Nonparametric statistics are less sensitive to missing values (Hirsch & Slack, 1984).

Table VII-6 shows the results of the homogeneity assessment of trend applying Z-statistics. Appendix N gives the details of the computed Z-statistics for each month and for all the stations used to compute the heterogeneity.

Table VII-6. Statistical significance: heterogeneity of basinwide nonparametric maximum temperature, minimum temperature, and average temperature trend in the Kosi basin.

			Maximum Temperature		Minimum Temperature		Average Temperature	
Type	*Expression for* χ^2	*df*	χ^2	α	χ^2	α	χ^2	α
Season	$n\sum_{i=1}^{m}(Z_{i.} - Z_{..})^2$	11	25	p<0.01	11	ns	15	ns
Site	$m\sum_{i=1}^{m}(Z_{.j} - Z_{..})^2$	12	110	p<0.005	191	p<0.005	31	p<0.005
Site-Season	$\sum_{i=1}^{m}\sum_{j=1}^{n}(Z_{ij} - Z_{i.} - Z_{.j} + Z_{..})^2$	132	233	p<0.005	118	ns	111	ns

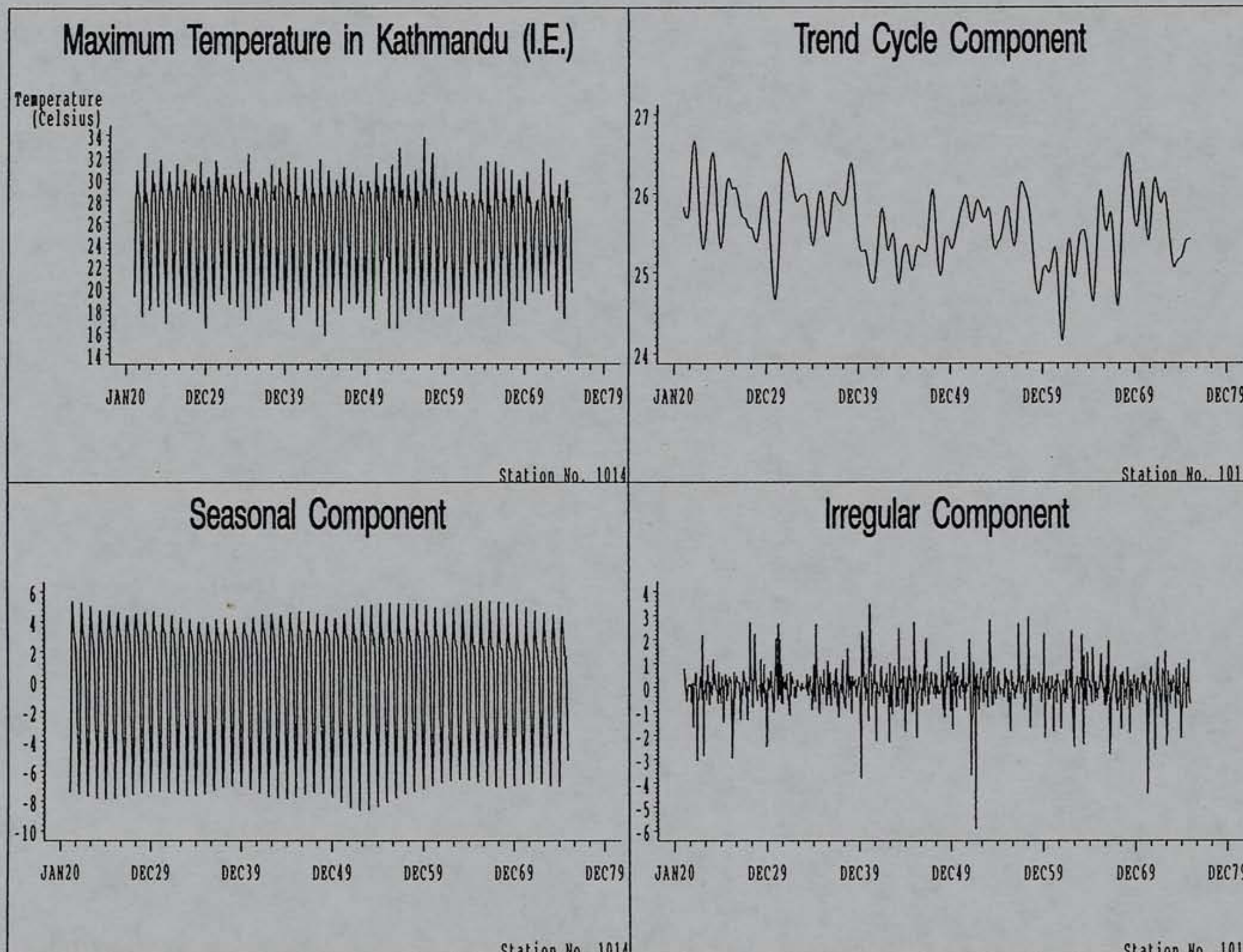
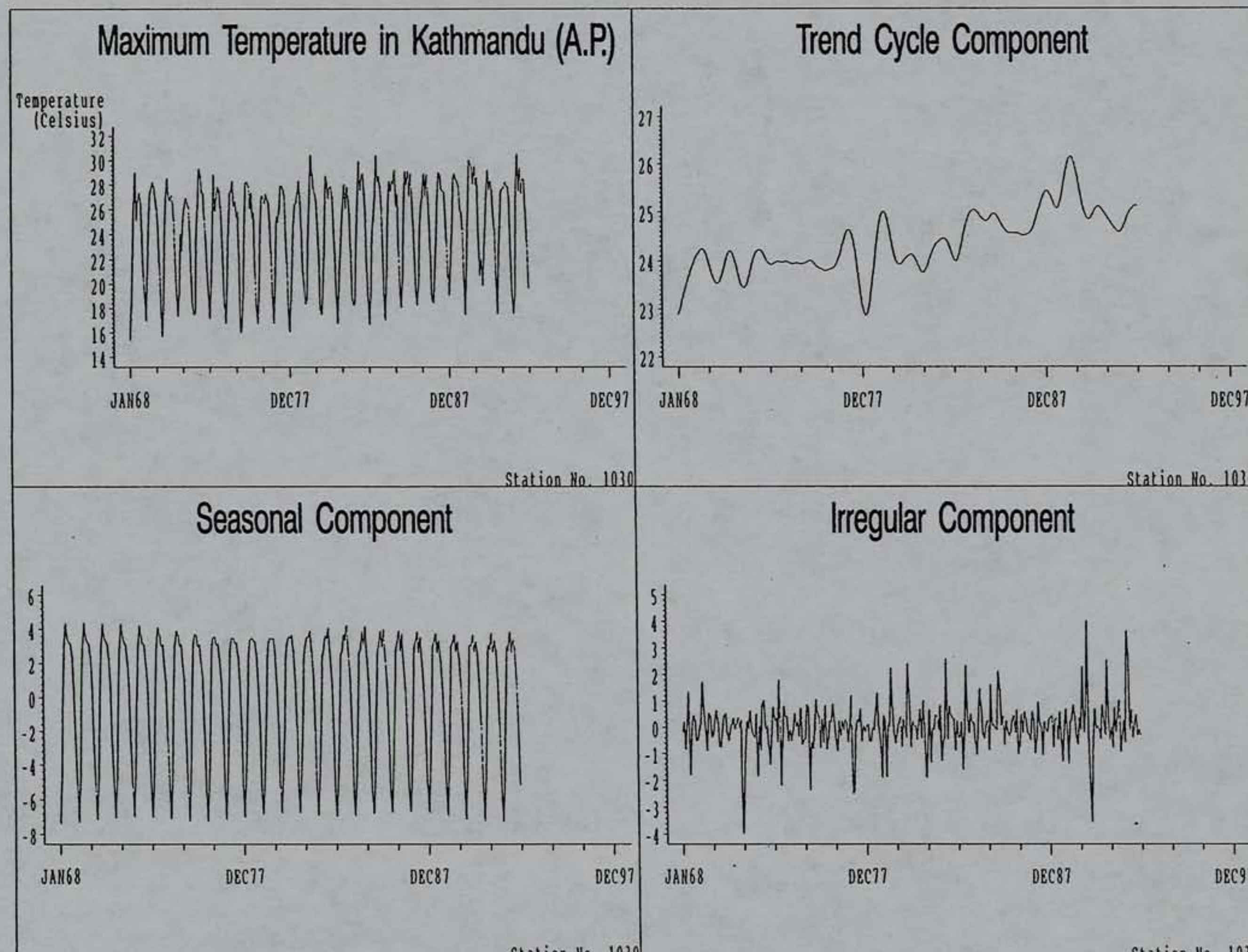
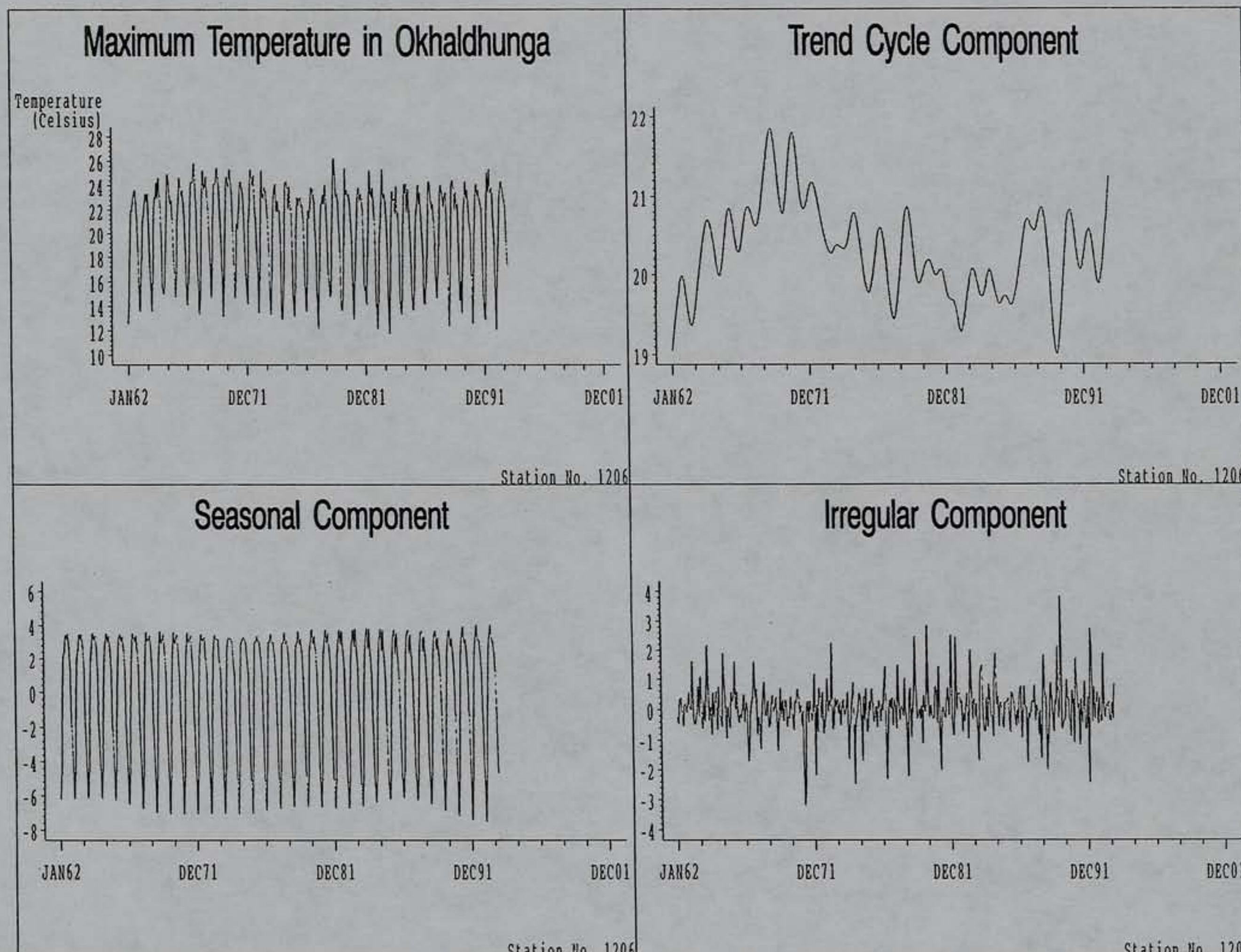


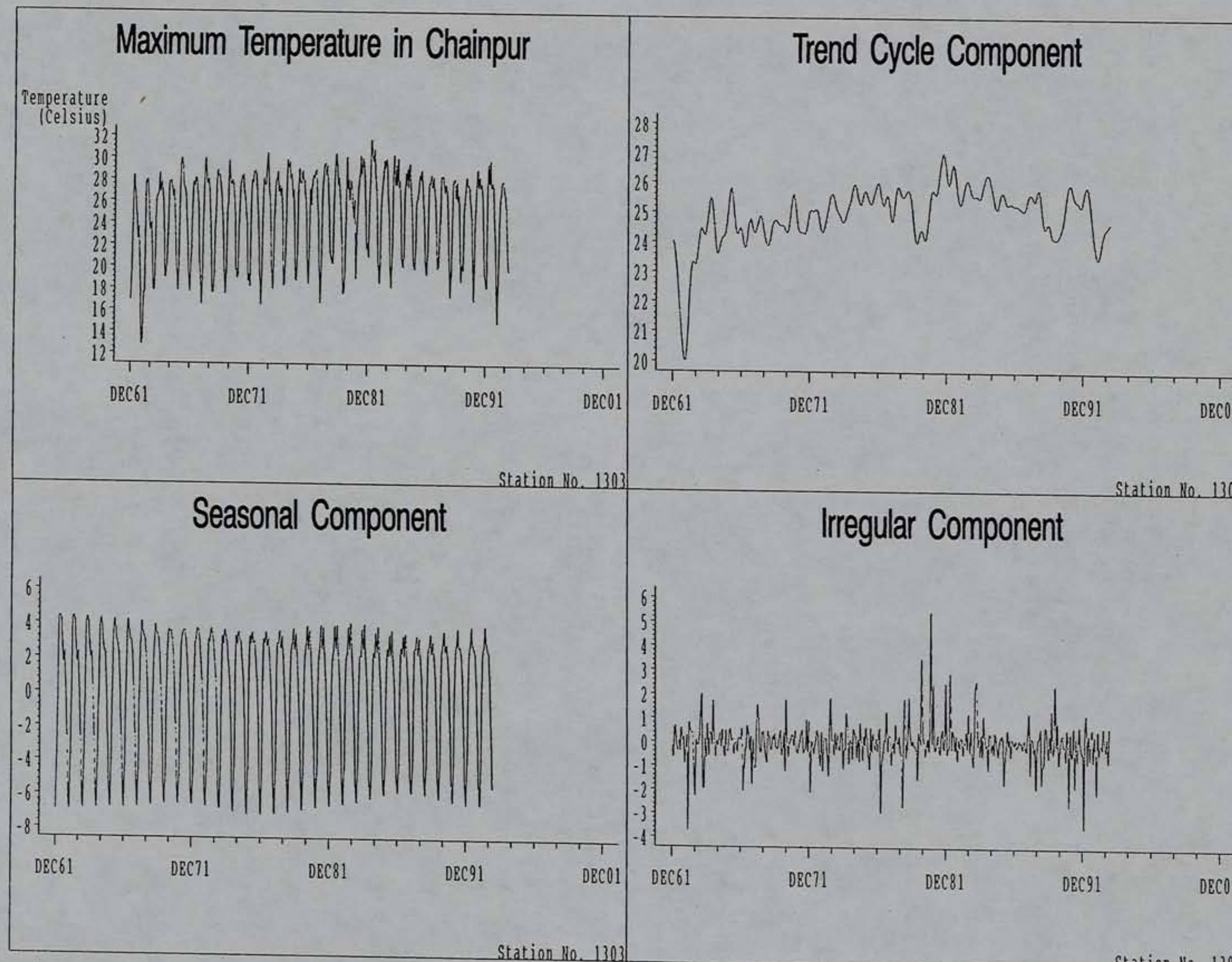
Figure VII-1. Original time series of monthly maximum and minimum temperature and their seasonal, trend cycle, and irregular components.
(a) Maximum temperature in Kathmandu (Indian Embassy, Station No. 1014)



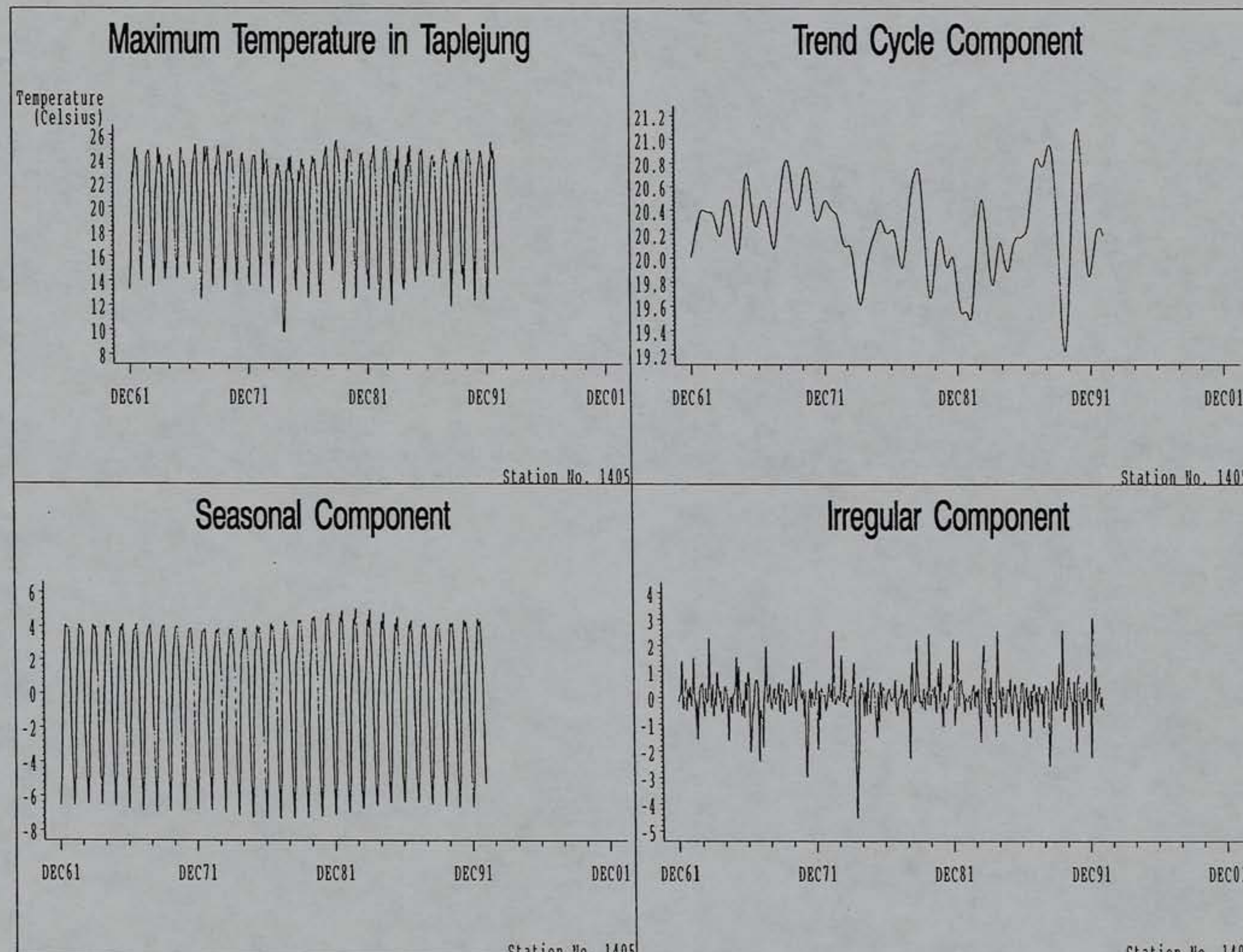
(b) Maximum temperature in Kathmandu (Airport, Station No. 1030)



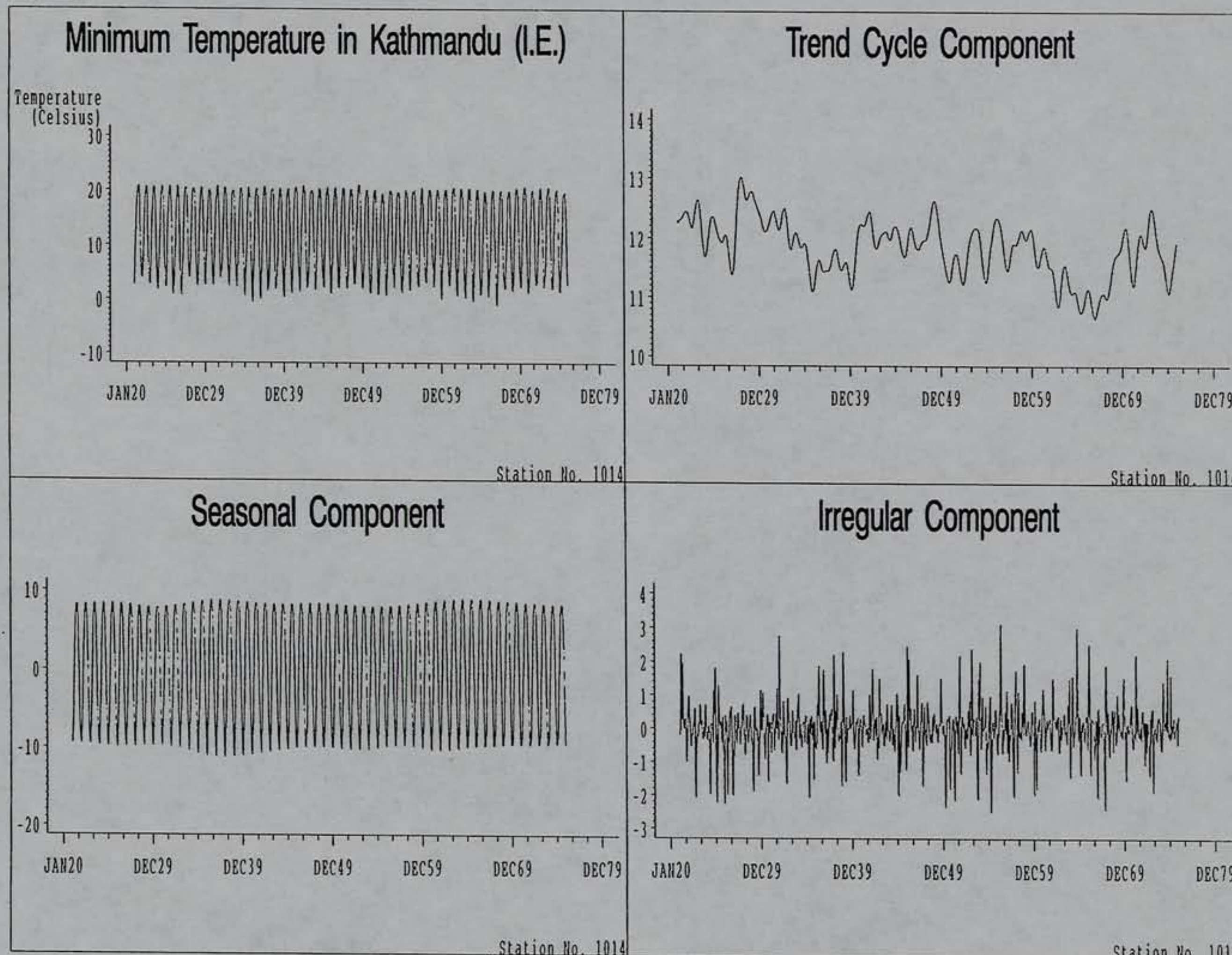
(c) Maximum temperature in Okhaldhunga (Station No. 1206)



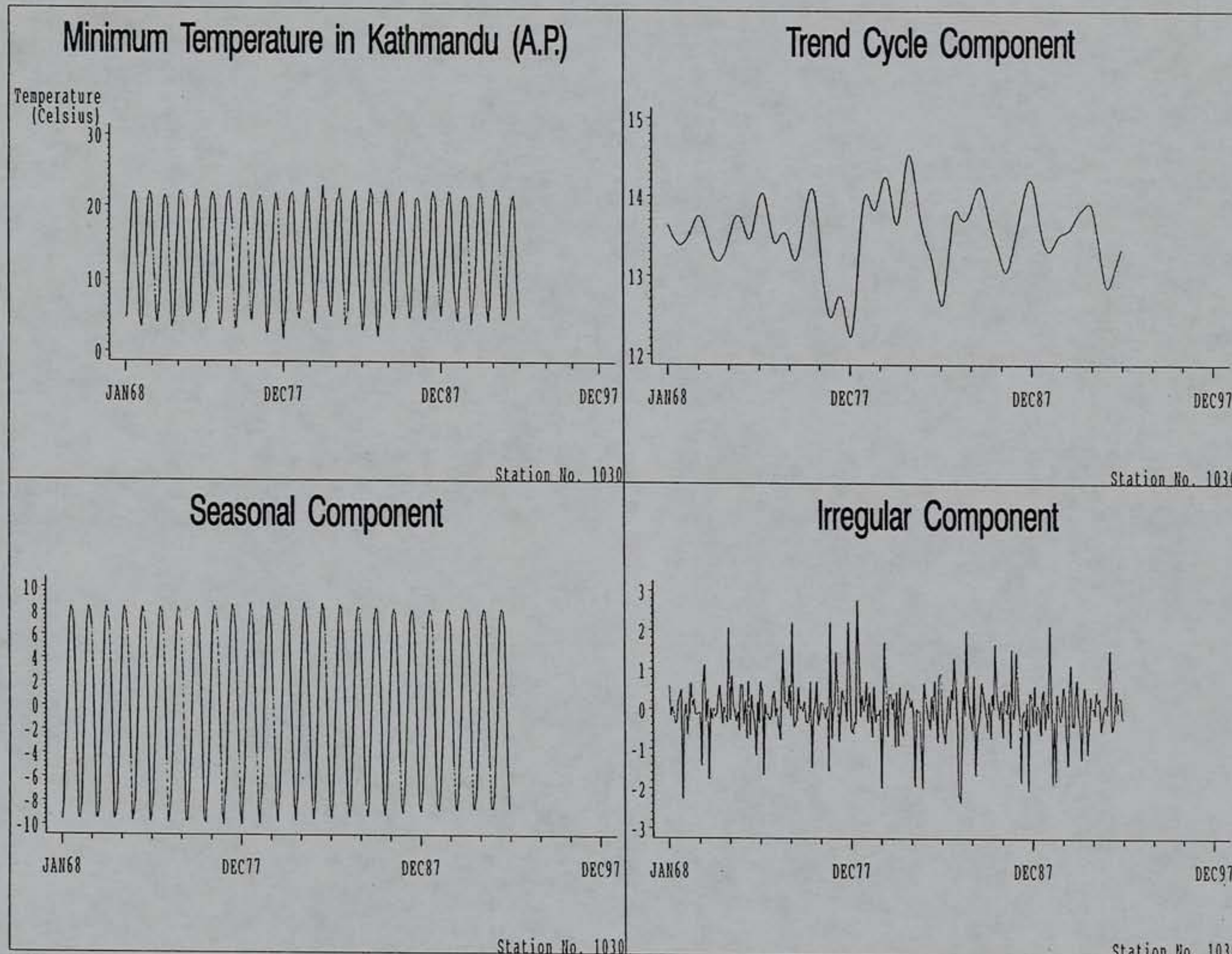
(d) Maximum temperature in Chainpur (Station No. 1303)



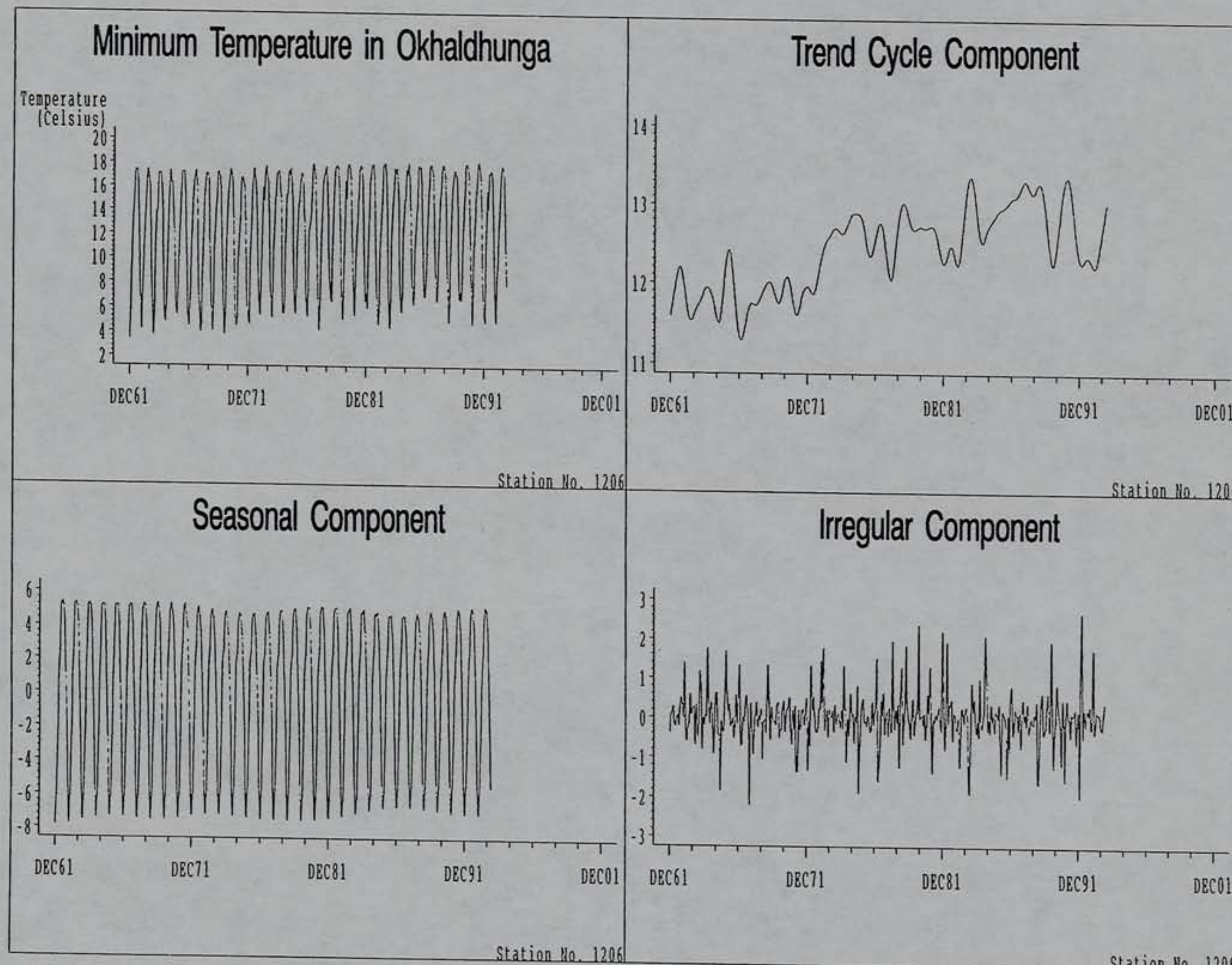
(e) Maximum temperature in Taplejung (Station No. 1405)



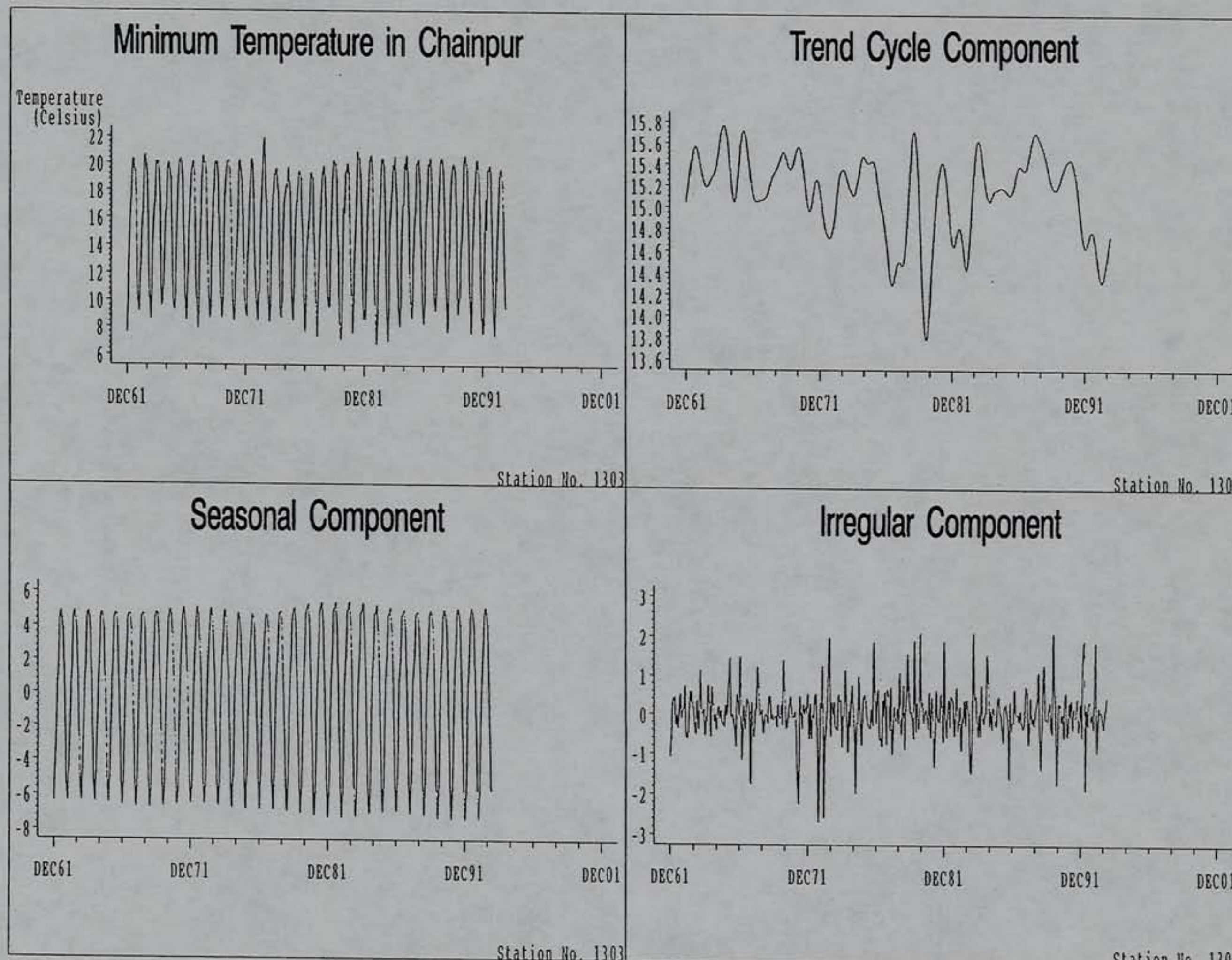
(f) Minimum temperature in Kathmandu (Indian Embassy, Station No. 1014)



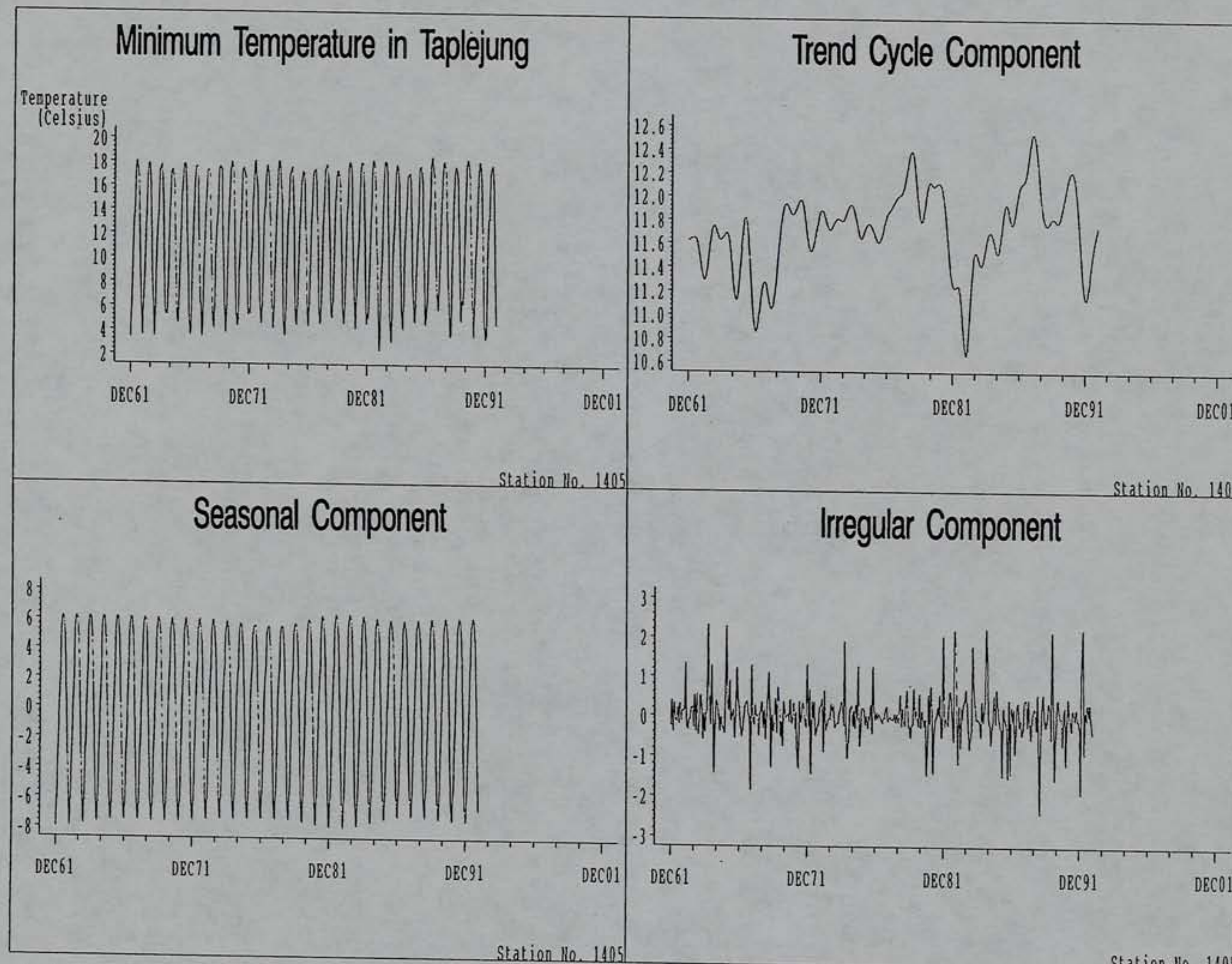
(g) Minimum temperature in Kathmandu (Airport, Station No. 1030)



(h) Minimum temperature in Okhaldhunga (Station No. 1206)



(i) Minimum temperature in Chainpur (Station No. 1303)



(j) Minimum temperature in Taplejung (Station No. 1405)

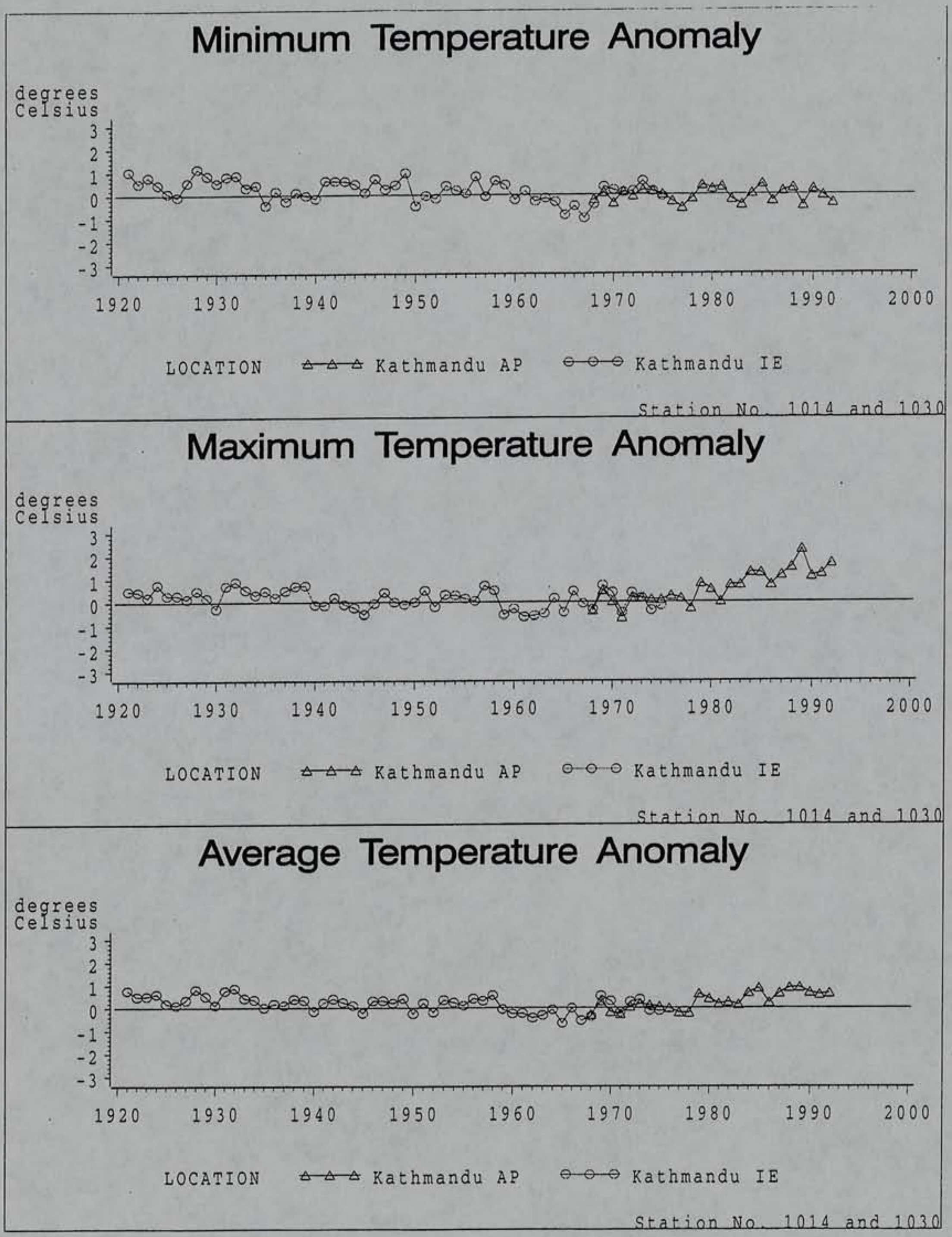


Figure VII-2. Minimum, maximum, and average temperature anomaly in Kathmandu.

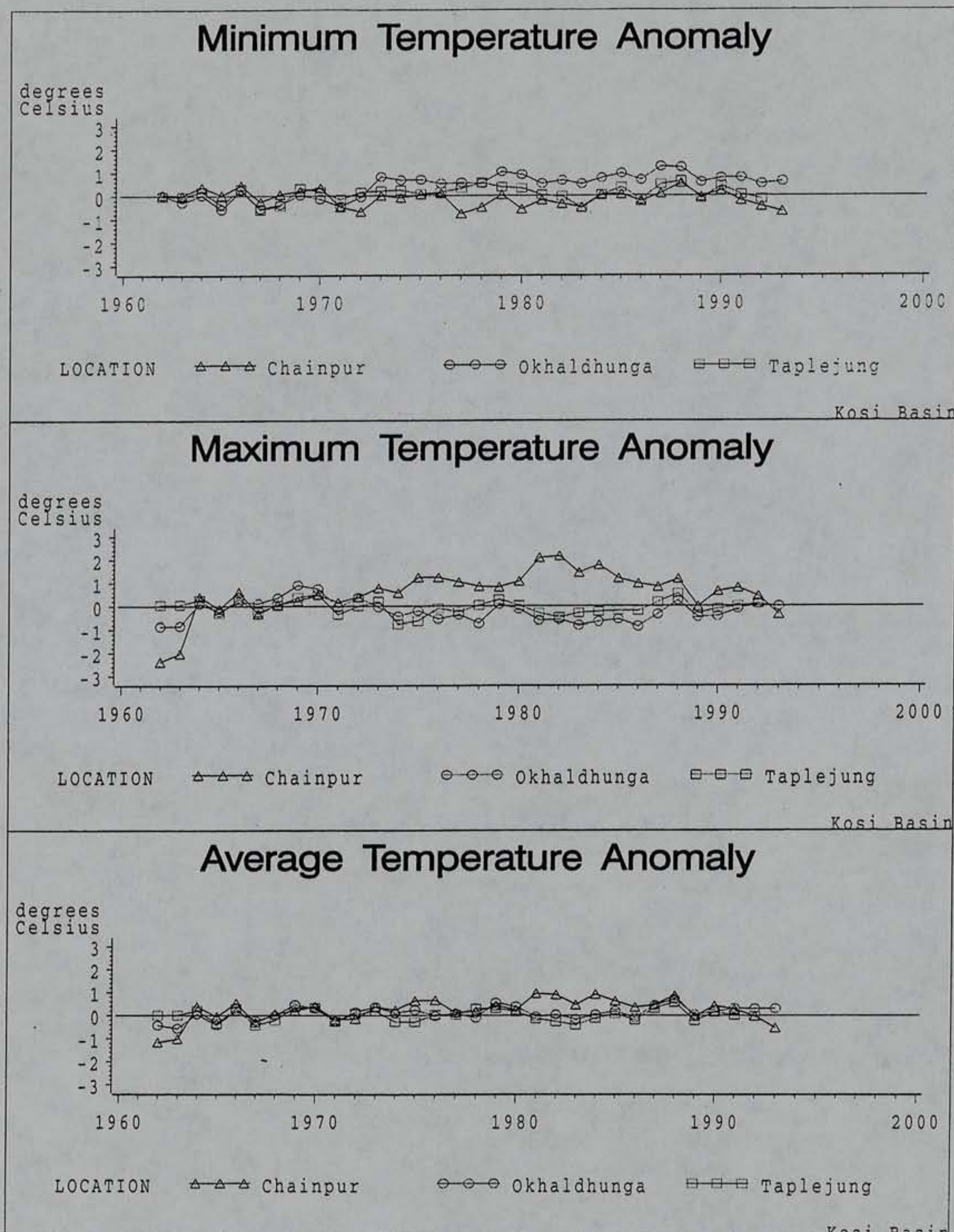


Figure VII-3. Comparision of minimum, maximum, and average temperature anomalies for Chainpur, Okhaldhunga, and Taplejung.

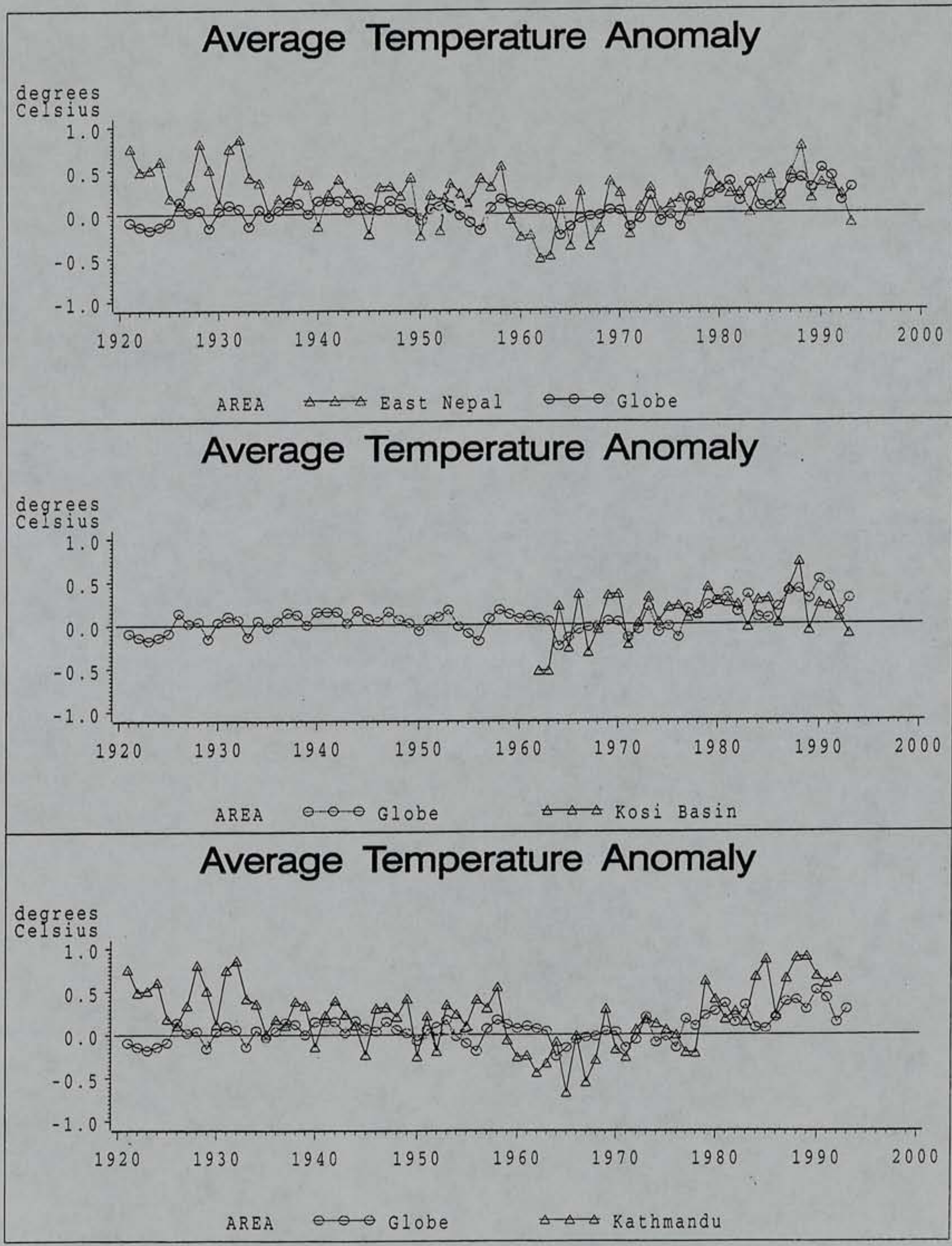


Figure VII-4. Comparision of average temperature anomaly of Kathmandu, the eastern Nepal, the Kosi basin, and the globe.

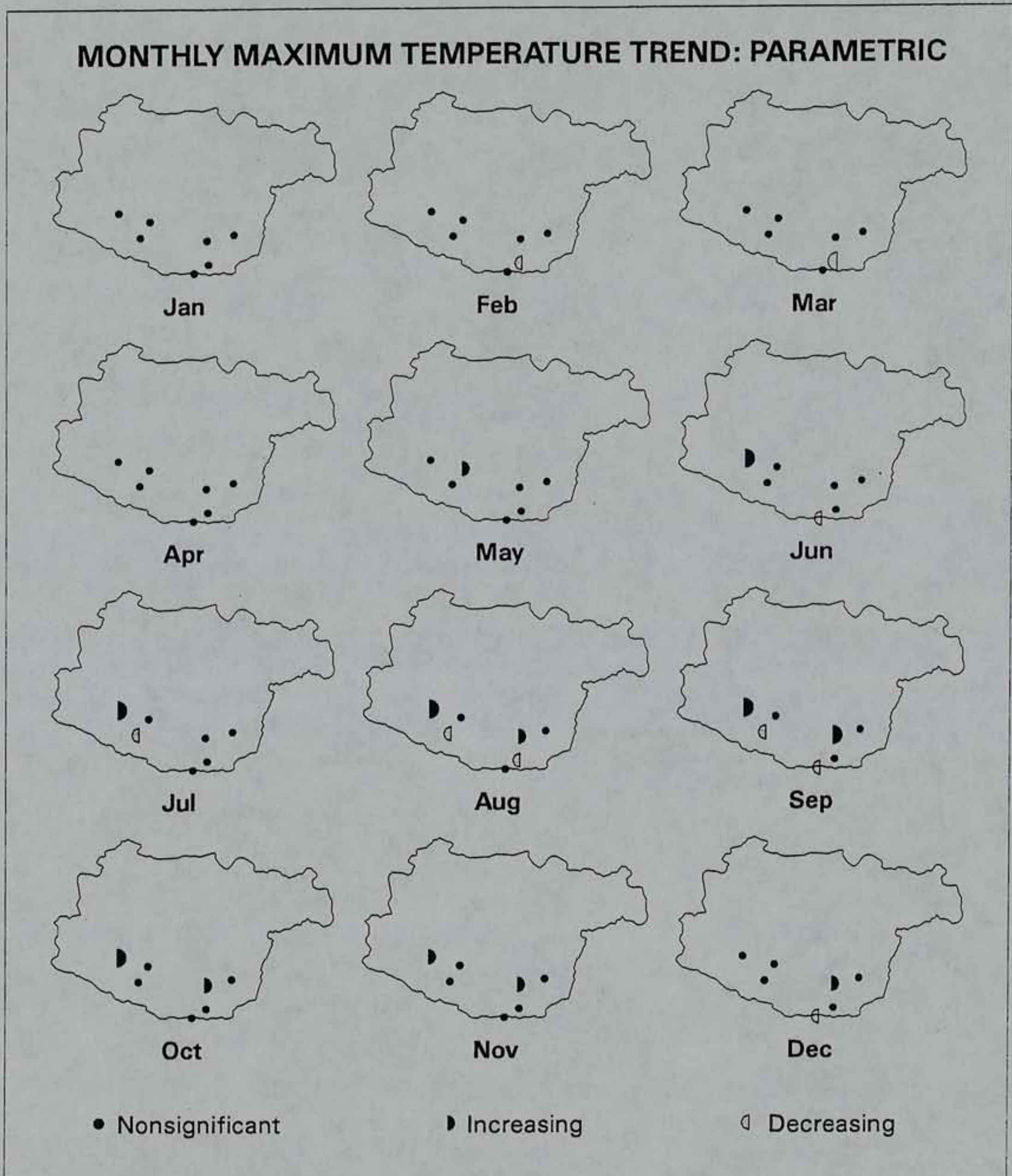


Figure VII-5. Trend of monthly maximum temperature in the Kosi basin computed using parametric method.

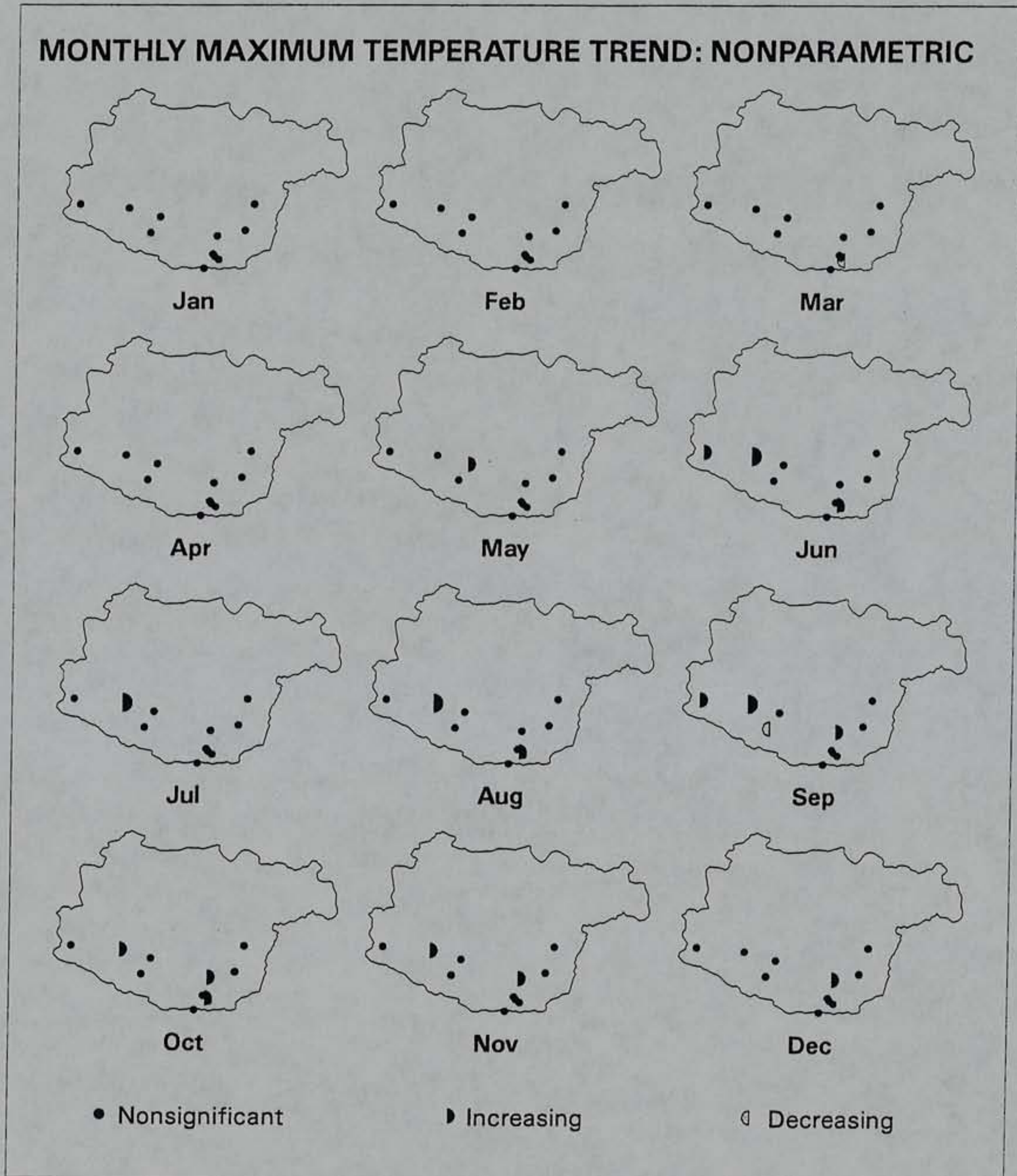


Figure VII-6. Trend of monthly maximum temperature in the Kosi basin computed using nonparametric method.

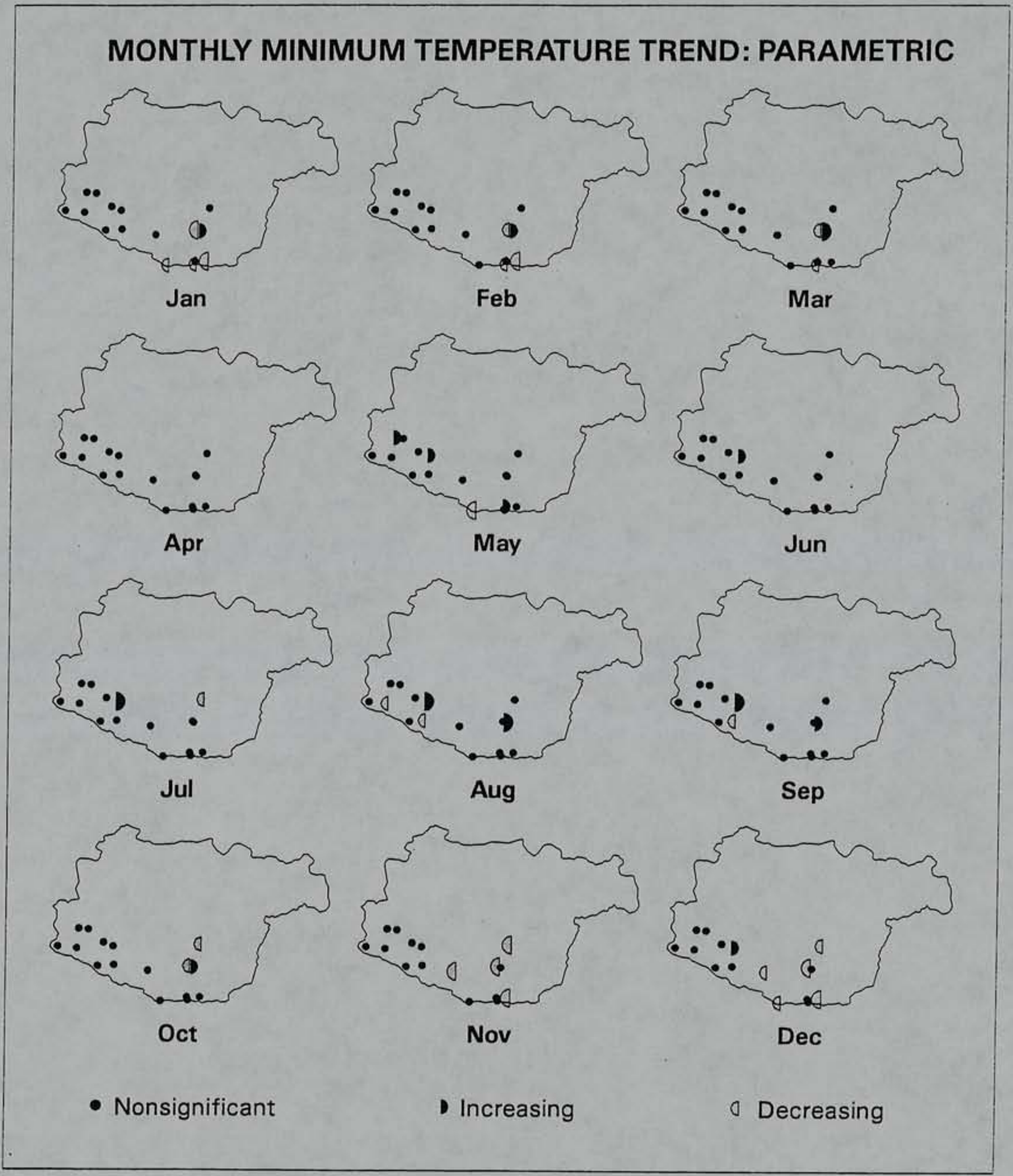


Figure VII-7. Trend of monthly minimum temperature in the Kosi basin computed using parametric method.

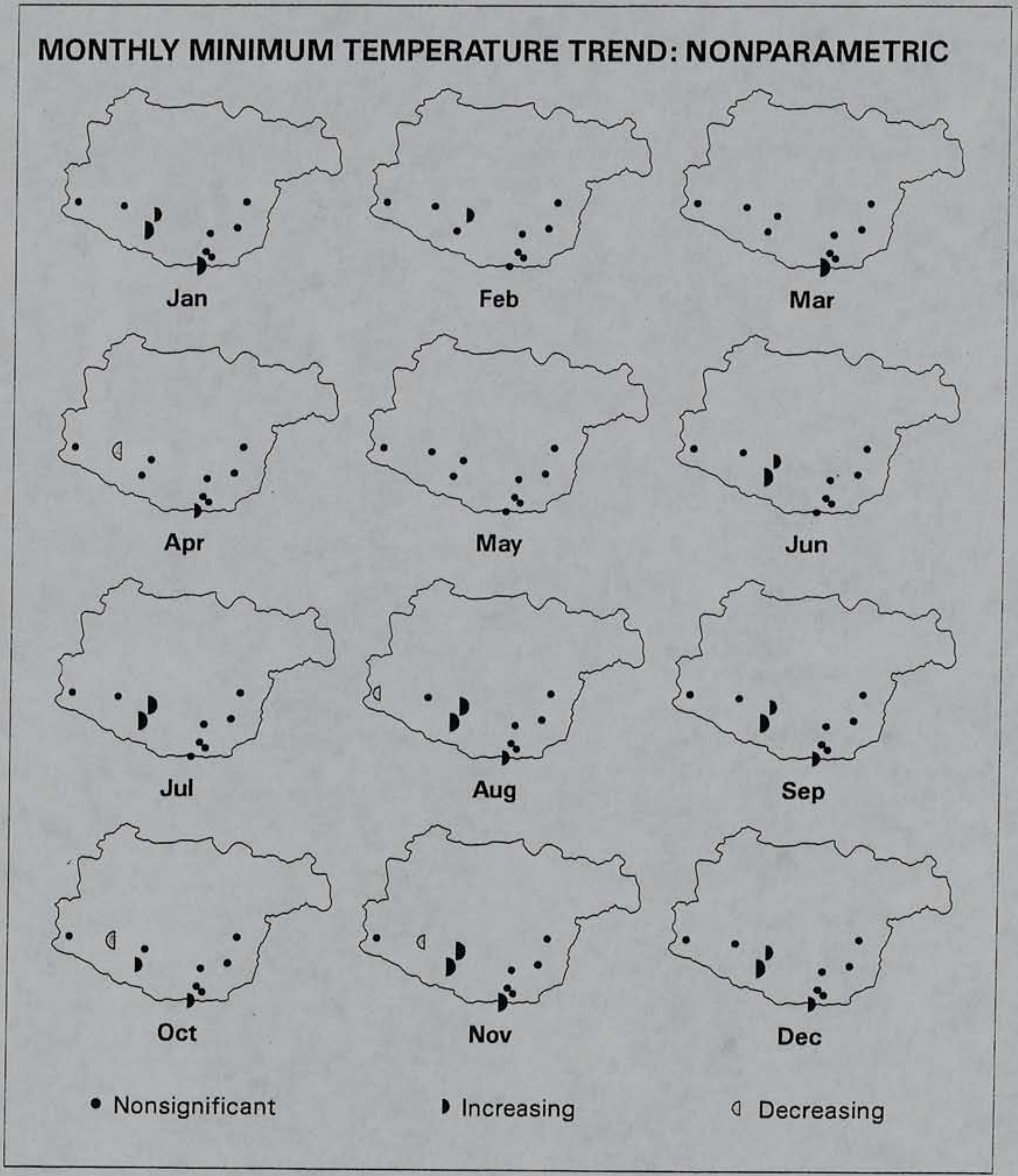


Figure VII-8. Trend of monthly minimum temperature in the Kosi basin using nonparametric method.

Table VII-6 shows that the basinwide increasing trend of average temperature is homogeneous with respect to season but nonhomogenous with respect to sites. The results, hence, do not indicate the existence of a statistically significant homogeneous trend in temperature over the basin. Furthermore, the tendency of increasing temperature is less homogeneous in the case of maximum temperature. Although statistically insignificant, the Table VII-6 shows the higher increasing tendency of basinwide minimum temperature, a similar pattern observed in the global climatic data (Karl et al., 1995).

Precipitation Changes

Changes in precipitation can be expected as a result of climatic changes and land use changes. Analyses of precipitation trend are, hence, useful not only to evaluate the characteristics of long term precipitation pattern over the basin but also to assess the climatic changes. Basic advantage in analysis of precipitation over temperature is that the precipitation data usually covers a wider area with denser network, longer time period and fairly complete records (fewer missing values). The density of the precipitation network in the Kosi basin is more than three times the density of the temperature network. There are 21 precipitation stations in the Kosi basin with record lengths exceeding thirty years which represent a number seven times greater than the number of temperature stations in the basin with 30 years of records.

Precipitation Trend in Kathmandu

The precipitation station located at Indian Embassy (Station No. 1014) in Kathmandu is the only station with the significantly long precipitation records available in an area closest to the Kosi basin. Since the publication of the records for this station was discontinued in 1975, we combined the data recorded at Station No. 1030 to make a precipitation series from 1921 through 1992. Before combining the records, we applied the Student's t test to the long term average of these two stations and confirmed that the averages were not significantly different from each other. Figure VII-9 exhibits the original series along with its seasonal, trend cycle and irregular components.

Since monthly precipitation data are not normally distributed, we only used the nonparametric method to test the trend for individual months. We used the parametric method by combining the monthly data into dry (October to May) and wet (June to September) seasons. Statistics of most of the annual and seasonal data confirmed a normal distribution.

Application of student's t test to the trend of seasonal data indicates nonsignificant trend. We obtained the same result when the test was applied to annual data.

<u>Precipitation Trend in the Kosi basin</u>

Figure VII-10 (a to t) illustrates the trend cycle components of the long term precipitation data for stations with relatively long period of records. The parametric trend of annual precipitation and the overall nonparametric trend based on monthly values for these stations are given in Table VII-7.

Table VII-7. Statistical significance of the trend of precipitation in the Kosi basin at stations with relatively long record length.

Station no.	*Period*	*Parametric*	*nonparametric*
1006	1947- 93	+ 1%	ns
1008	1959- 93	ns	ns
1023	1947- 93	ns	+ 5%
1102	1959- 93	- 5%	- 5%
1104	1959- 93	ns	ns
1202	1949- 94	ns	+ 5%
1203	1948- 94	ns	ns

Table VII-7 continued

Station no.	*Period*	*Parametric*	*nonparametric*
1204	1948- 94	ns	ns
1206	1948- 93	ns	ns
1211	1959- 93	ns	ns
1301	1959- 93	ns	+ 5%
1303	1947- 93	ns	+ 1%
1306	1947- 93	ns	ns
1307	1947- 92	ns	+ 1%
1308	1947- 93	ns	+ 1%
1309	1948- 93	ns	ns
1316	1948- 93	ns	ns
1325	1949- 93	ns	ns
1403	1947- 93	ns	+ 1%
1404	1947- 93	+ 1%	ns

As in the last section, statistical analyses of monthly data for all the stations in the basin indicated that precipitation data are not normally distributed in most of the cases. The data are positively skewed with high values of skewness and kurtosis. We analyzed the precipitation trend combining monthly values into seasonal data by dividing a year into dry (October to May) and wet (June to September) seasons. Figure VII-11 shows the trend of dry season and wet season precipitation at different stations over the basin. Only five stations, out of 57 stations, show statistically significant increasing trend of precipitation whereas only one station shows decreasing trend of precipitation during the wet season (summer monsoon). Only three stations show positive trend of dry season precipitation. The parametric statistics hence indicate a lack of statistically significant trend in both seasons in more than 85 per cent of the cases. The analysis of annual data also shows a similar result (Figure VII-16).

We also used nonparametric statistics for the analysis of monthly and overall trend based on monthly precipitation data. The results of the analysis for different months are presented in Figure VII-12 and the overall precipitation trends for each station are presented in Figure VII-17.

The nonparametric method indicates an increasing trend of precipitation in many more stations compared to the parametric method. Nonetheless, the number of stations showing nonsignificant trend far exceeds the number of stations showing statistically significant precipitation trend. Only a few stations show a negative trend of precipitation in the monsoon and post monsoon period (Figure VII-12) with only one station showing an overall decreasing trend of precipitation (Figure VII-17).

As in the case of temperature, we used the procedure described by Belle and Hughes (1984) to obtain homogeneity of trend over the basin and season. Table VII-8 presents the result of the analysis. Appendix N gives the details of the computed Z-statistics for each month and for all the stations used to compute the heterogeneity.

Table VII-8. Statistical significance: heterogeneity of basinwide nonparametric precipitation trend in the Kosi basin.

Type	Expression for χ^2	χ^2	df	Significance
Seasonal	$n\sum_{i=1}^{m}(Z_{i.} - Z_{..})^2$	220	11	< 0.005
Site	$m\sum_{i=1}^{m}(Z_{.j} - Z_{..})^2$	168	54	< 0.005
Site-season	$\sum_{i=1}^{m}\sum_{j=1}^{n}(Z_{ij} - Z_{i.} - Z_{.j} + Z_{..})^2$	558	594	ns

The above table and computation show that the trend is neither homogeneous in terms of season nor in terms of sites. Consequently, the hypothesis of homogeneous precipitation trend over the basin cannot be established.

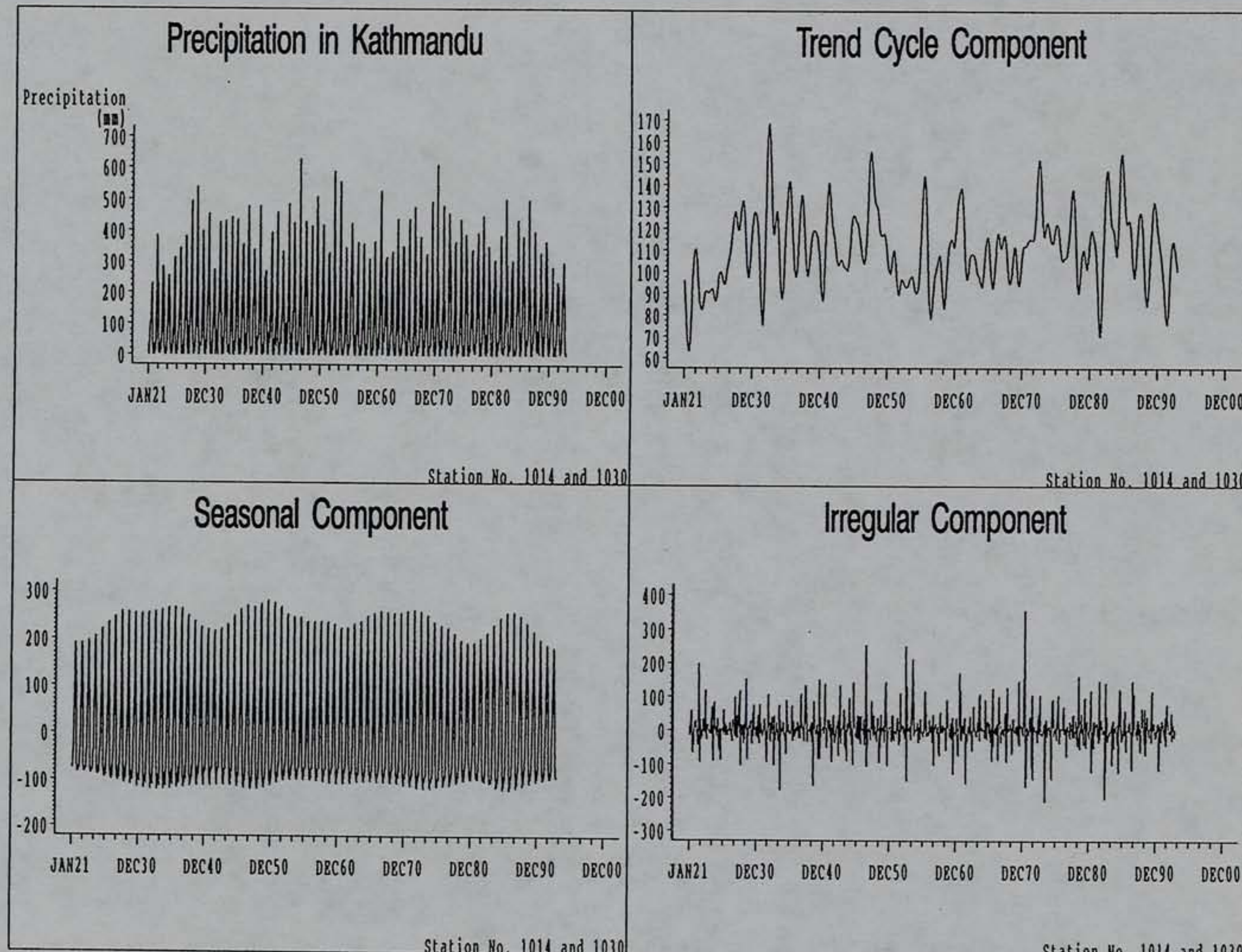


Figure VII-9. Original time series of precipitation in Kathmandu and its seasonal, trend cycle, and irregular components.

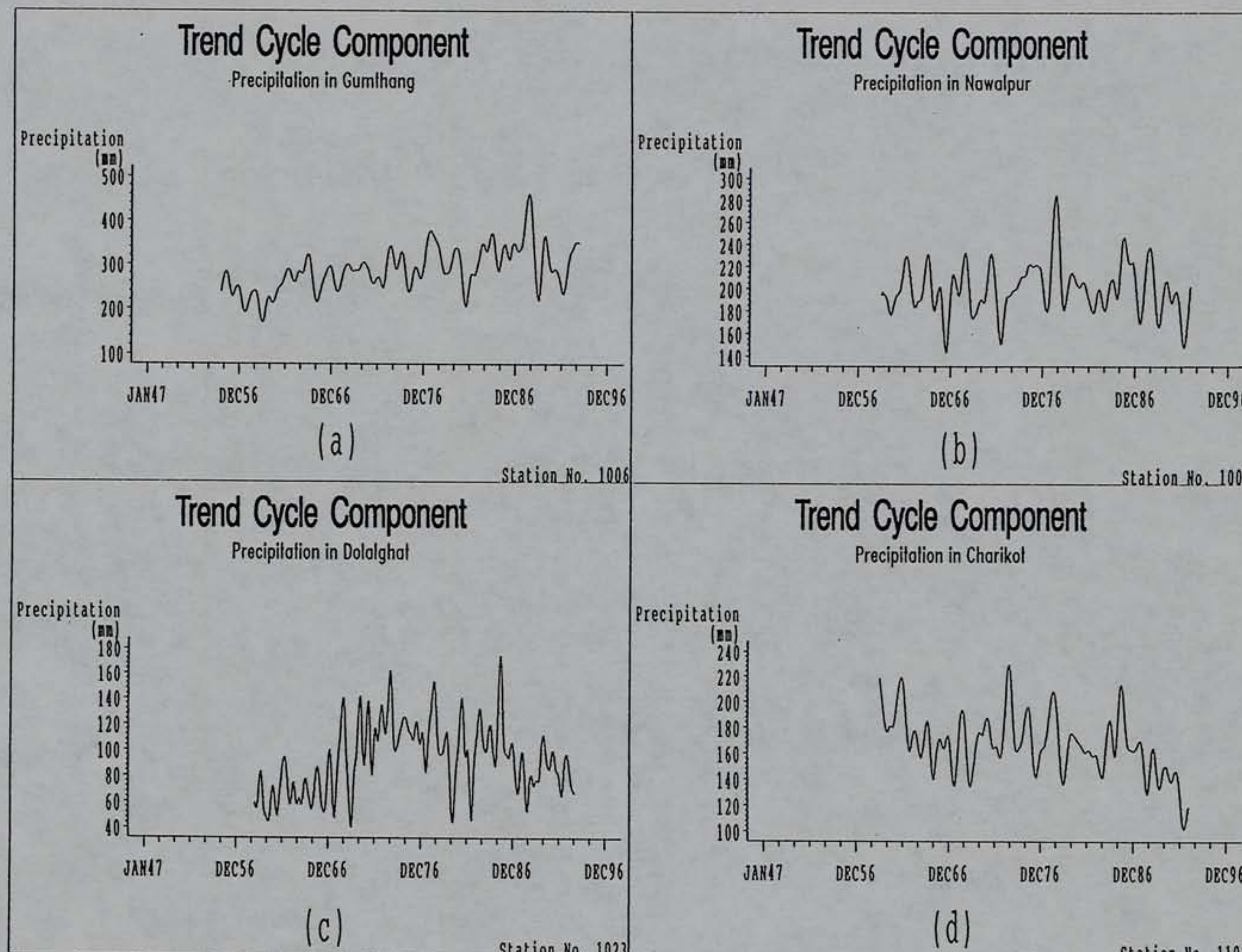
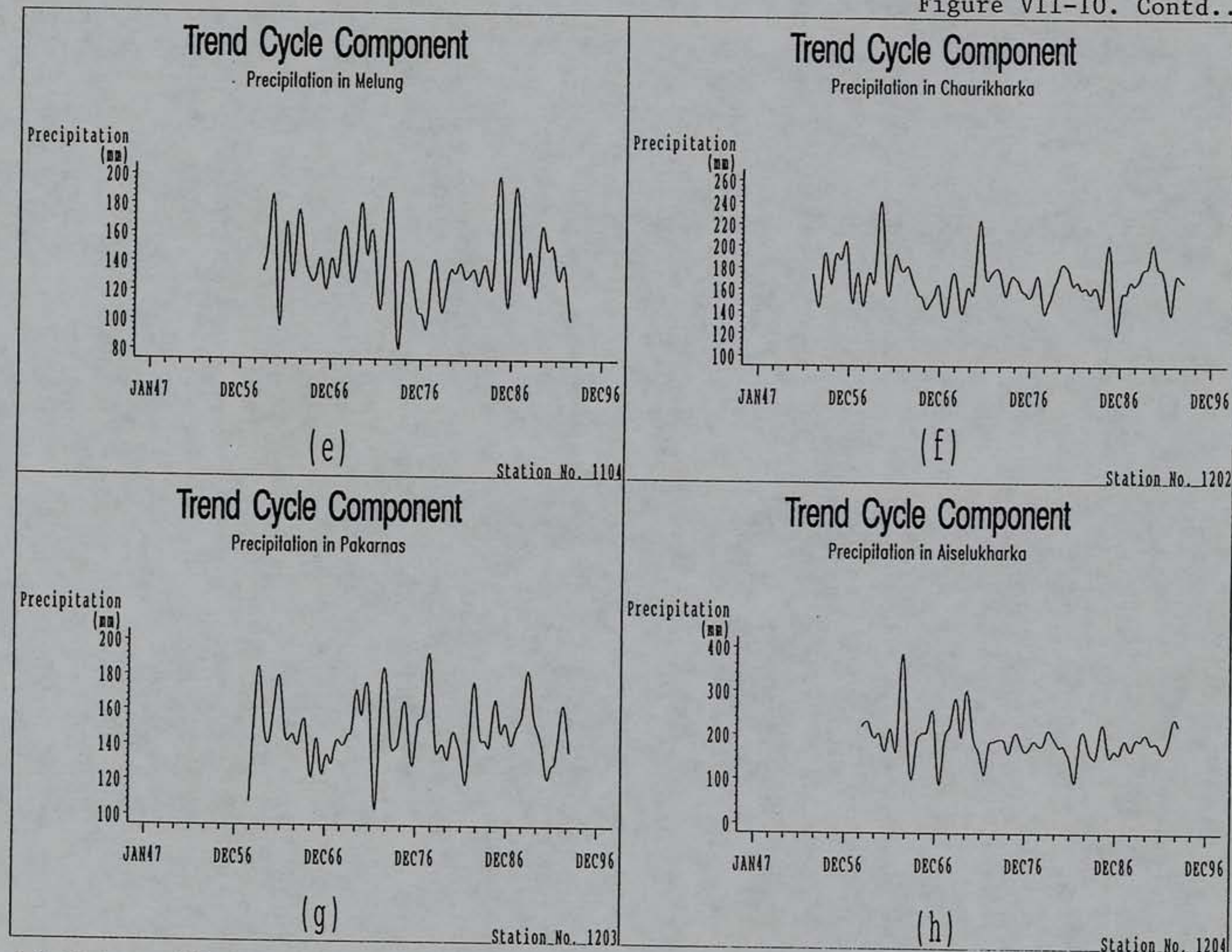


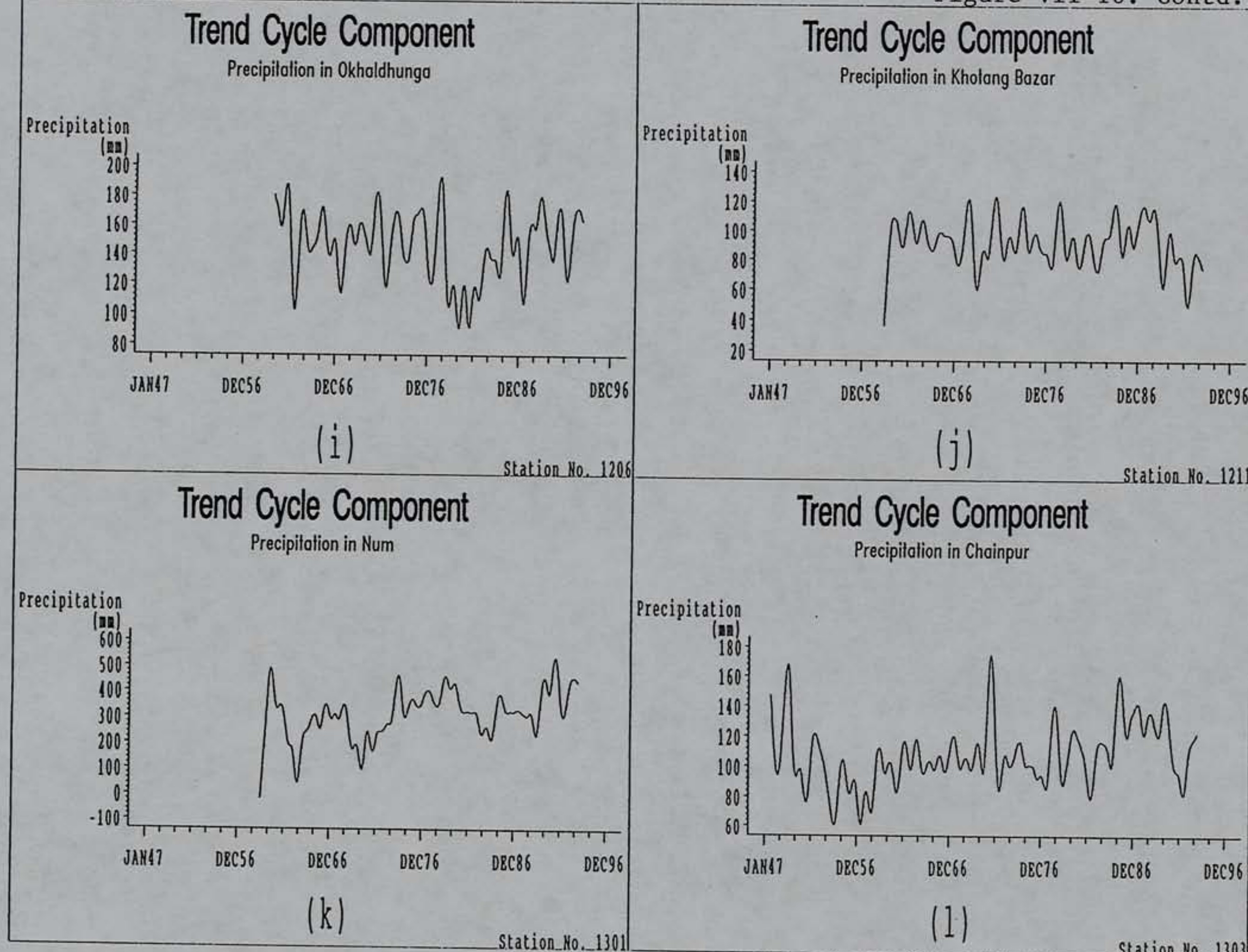
Figure VII-10. Trend cycle component of monthly precipitation: (a) Gumthang (b) Nawalpur (c) Dolalghat (d) Charikot

Figure VII-10. Contd..



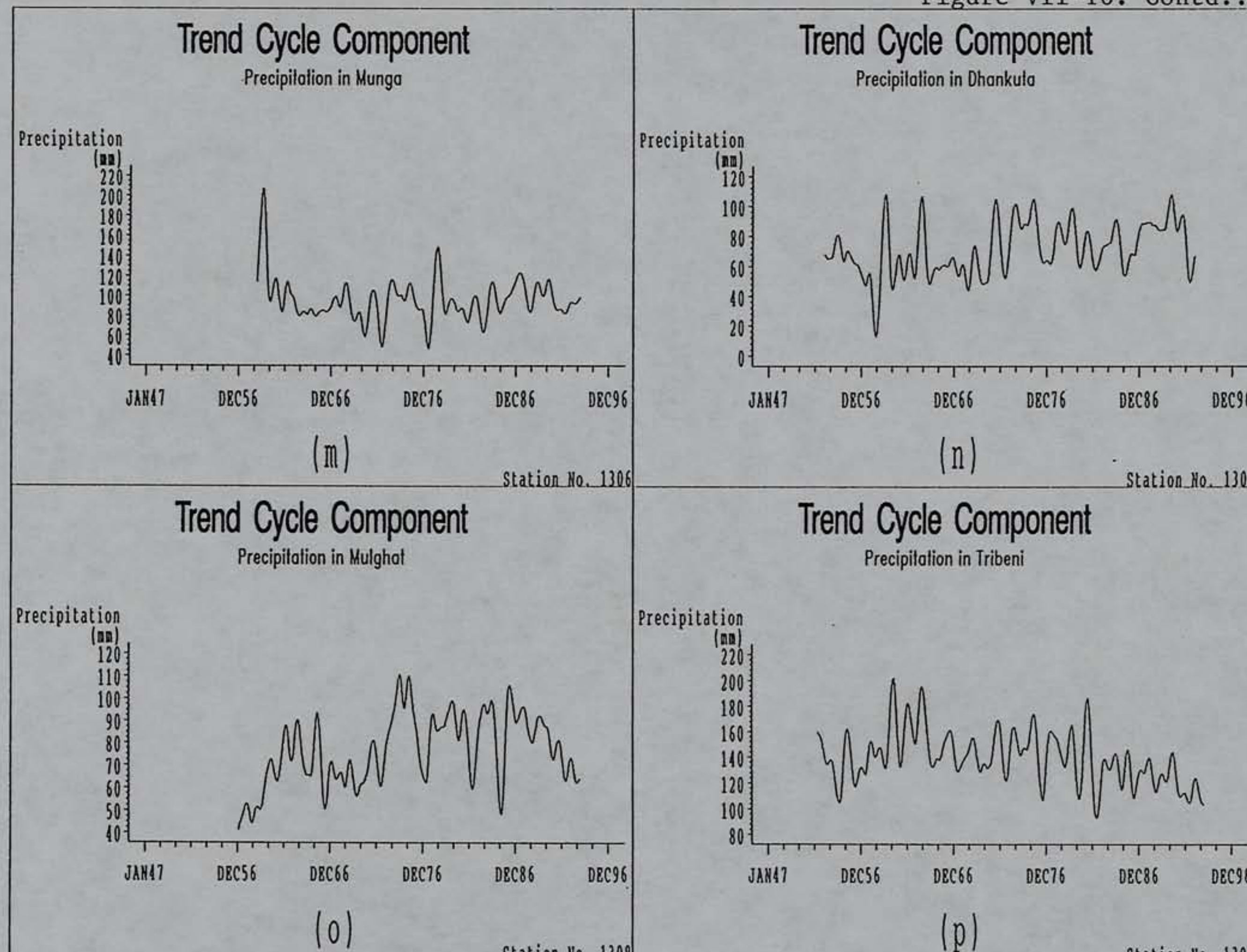
(e) Melung (f) Chaurikharka (g) Pakarnas (h) Aiselukharka

Figure VII-10. Contd..



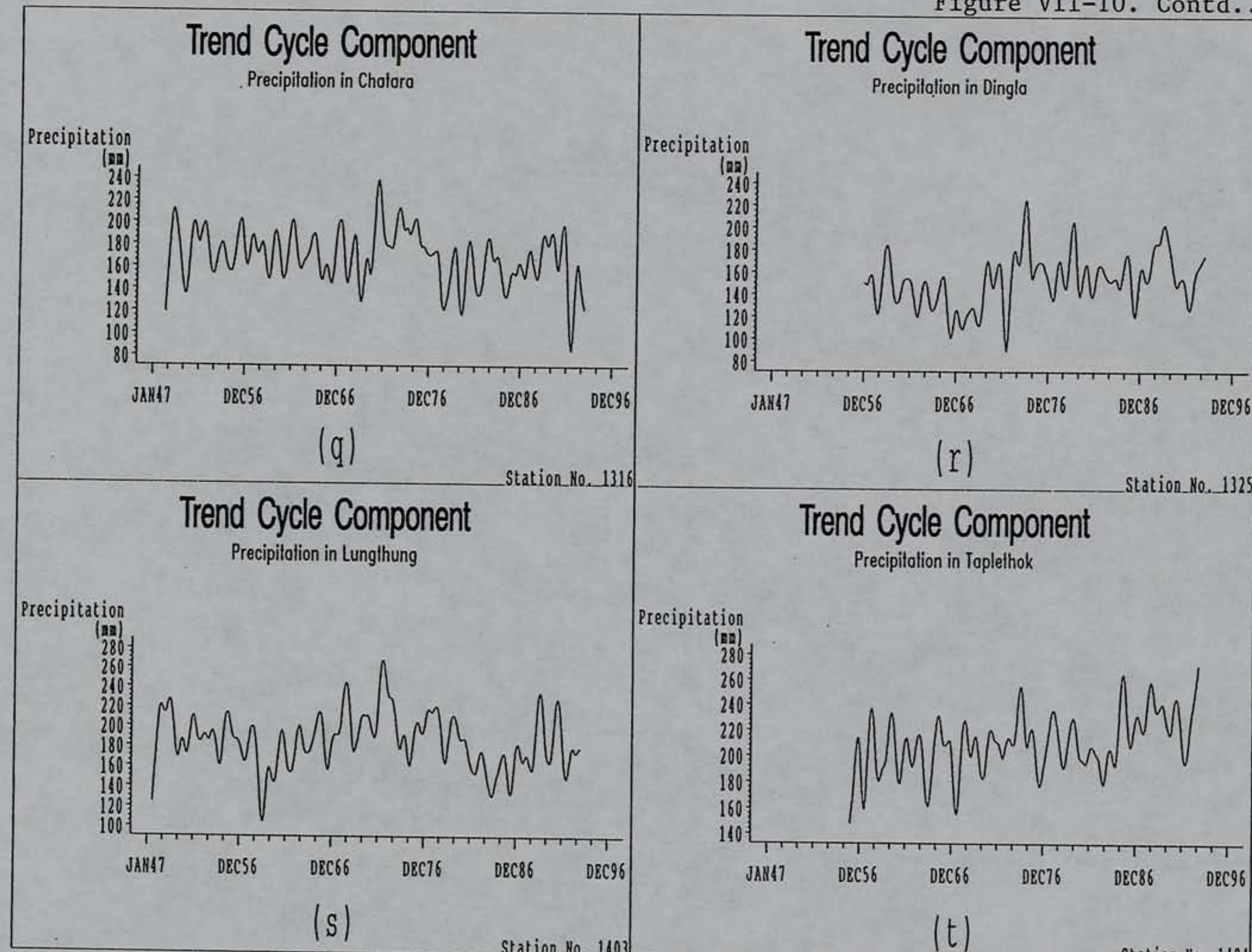
(i) Okhaldhunga (j) Khotang Bazar (k) Num (l) Chainpur

Figure VII-10. Contd..



(m) Munga (n) Dhankuta (o) Mulghat (p) Tribeni

Figure VII-10. Contd..



(q) Chatara (r) Dingla (s) Lungthung (t) Taplethok

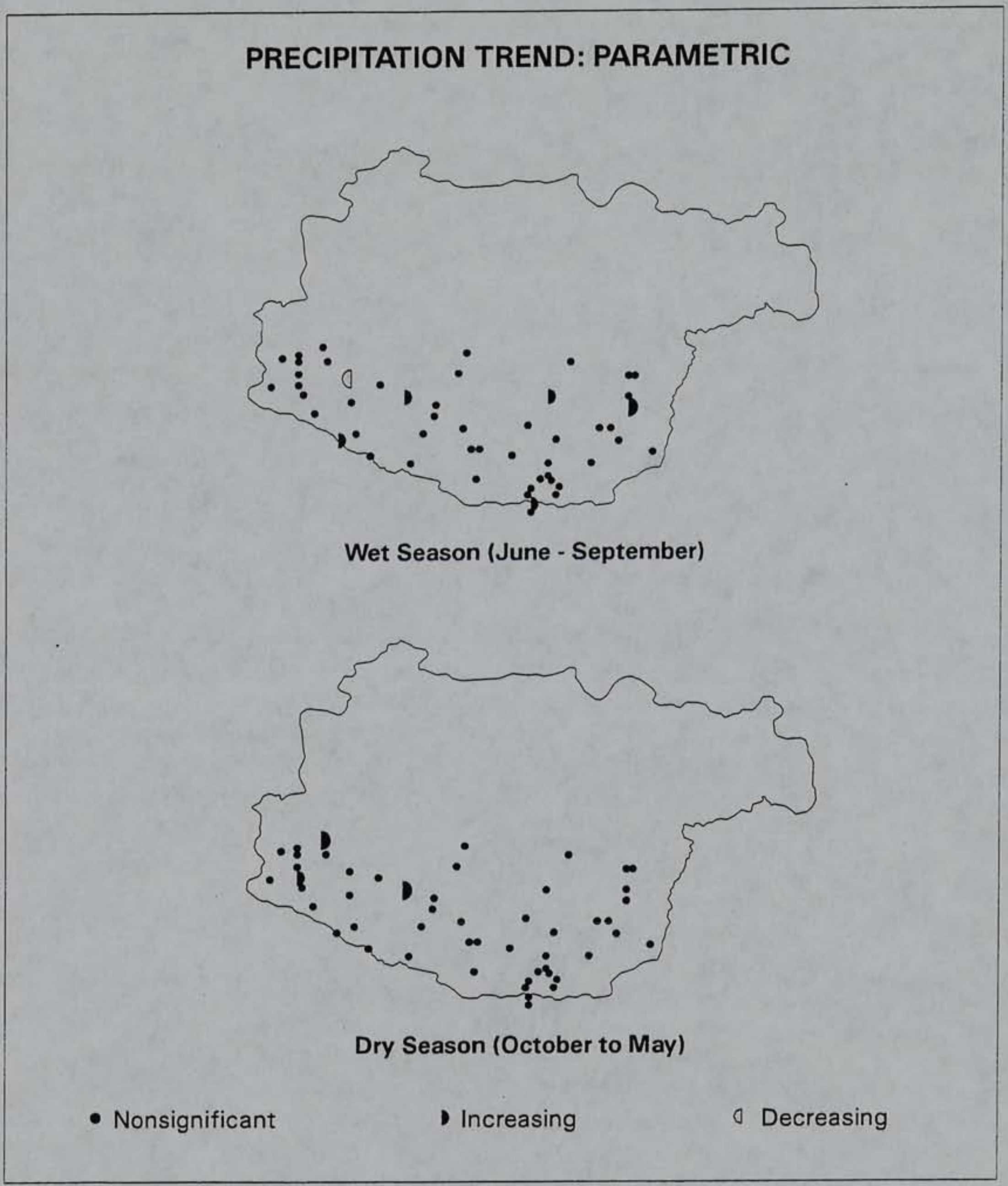


Figure VII-11. Trend of seasonal precipitation in the Kosi basin computed using parametric method.

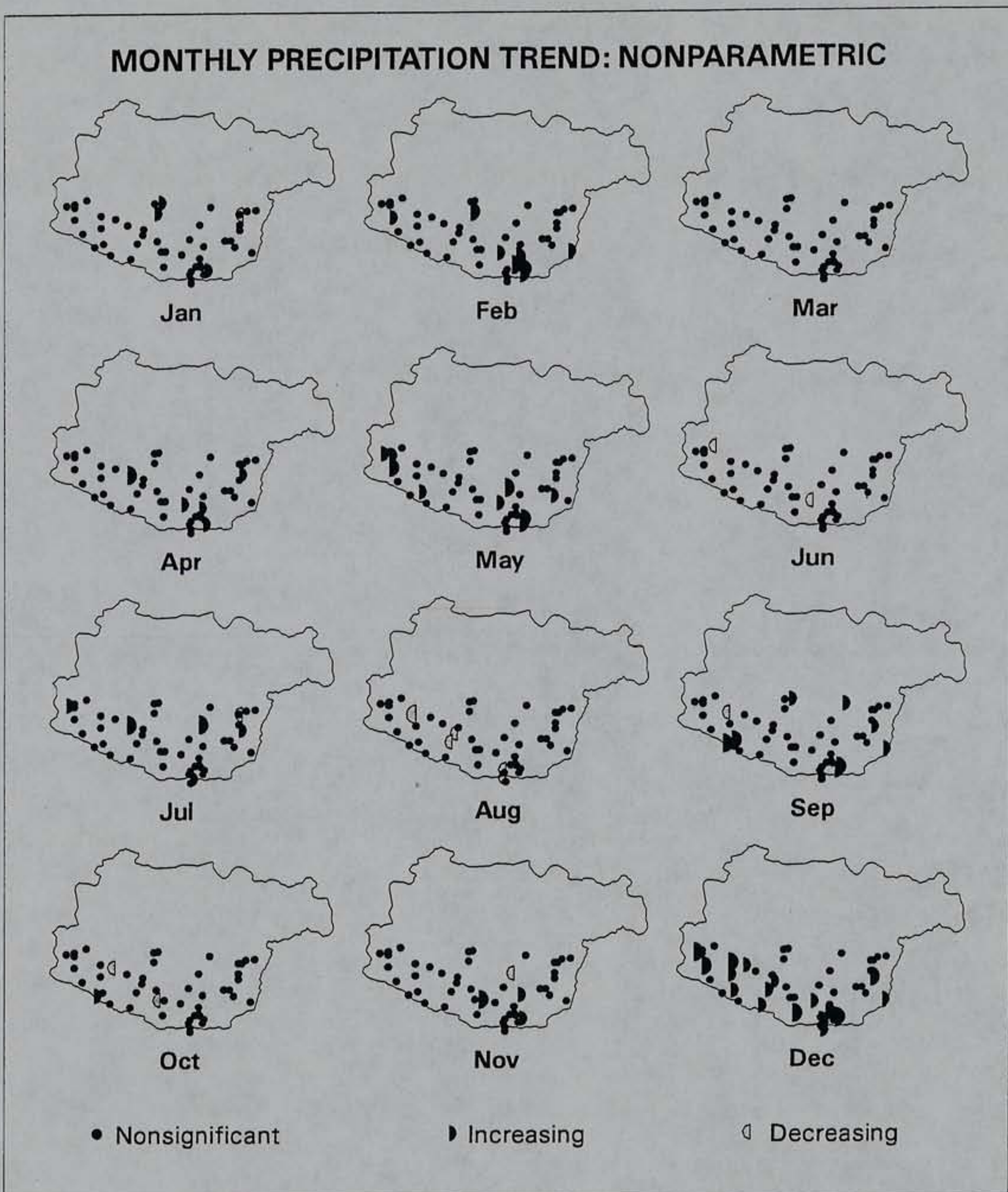


Figure VII-12. Trend of monthly precipitation in the Kosi basin computed using nonparametric method.

River Discharge Changes

River discharge is an important integrated measure of climate, land cover, and human activities that influence the hydrologic cycle over a drainage basin. The station (Station No. 695) located on the mainstem of the Kosi River at Chatara provides the longest discharge records available in Nepal. Discharge records for Stations 695 and Station No. 690 are available from 1947 and 1948 respectively. Figure VII-13 (a to e) illustrates the trend-cycle component, seasonal component and irregular component of discharge time series for hydrometric stations with relatively long time series. Table VII-9 below presents the results of the parametric and nonparametric statistics applied to the monthly discharge time series data for the stations 690 and 695.

Table VII-9. Statistical significance of trend for discharge recorded on the Kosi River and the Tamor River.

	Parametric		Nonparametric	
	Station 695	*Station 690*	*Station 695*	*Station 690*
Jan	- 5%	- 1%	- 5%	- 1%
Feb	- 5%	- 1%	- 5%	- 1%
Mar	ns	ns	- 5%	ns
Apr	ns	ns	ns	ns
May	ns	ns	ns	ns
Jun	ns	ns	ns	ns
Jul	ns	ns	ns	ns
Aug	ns	ns	ns	ns
Sep	ns	ns	ns	ns
Oct	ns	ns	ns	ns
Nov	ns	- 1%	ns	-1%
Dec	ns	- 1%	ns	-1%
Ann	ns	ns	ns	- 1%

Figure VII-14 illustrates the trend for all the stream gauging stations in the Kosi basin analyzed by parametric statistics using monthly data. The results of the analysis by nonparametric method using monthly data are presented in Figure VII-15. The parametric and nonparametric trends of annual discharge are illustrated in Figure VII-16 and Figure VII-17 respectively. Examinations of these figures indicate decreasing trend of discharge on mainstem and major tributaries particularly during low-flow season. The analysis of overall river discharge trends for their heterogeneity over the basin in terms of site, season and their combinations is given in Table VII-10. Appendix N gives the details of the computed Z-statistics for each month and for all the stations used to compute the heterogeneity.

Table VII-10. Statistical significance: heterogeneity of basinwide nonparametric discharge trend in the Kosi basin.

Type	Expression for χ^2	χ^2	df	Significance
Seasonal	$n\sum_{i=1}^{m}(Z_{i.} - Z..)^2$	10.4	11	ns
Site	$m\sum_{i=1}^{m}(Z_{.j} - Z..)^2$	217	12	$p< 0.005$
Site-season	$\sum_{i=1}^{m}\sum_{j=1}^{n}(Z_{ij} - Z_{i.} - Z_{.j} + Z..)^2$	122	132	ns

The above table (Table VII-10) shows that the trend is homogeneous in terms of season but not in terms of sites. For that reason, we cannot substantiate a basinwide discharge trend in the Kosi basin.

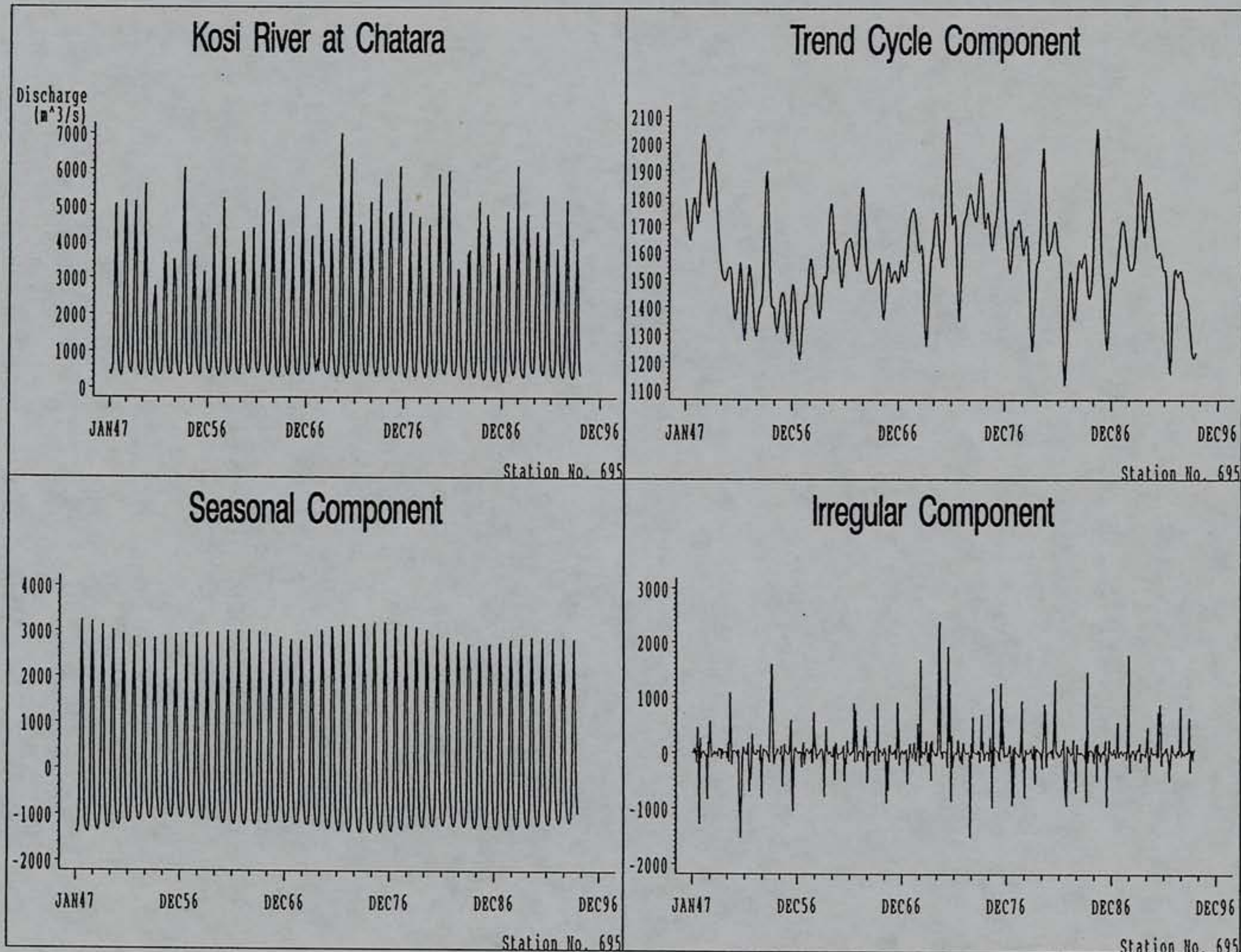
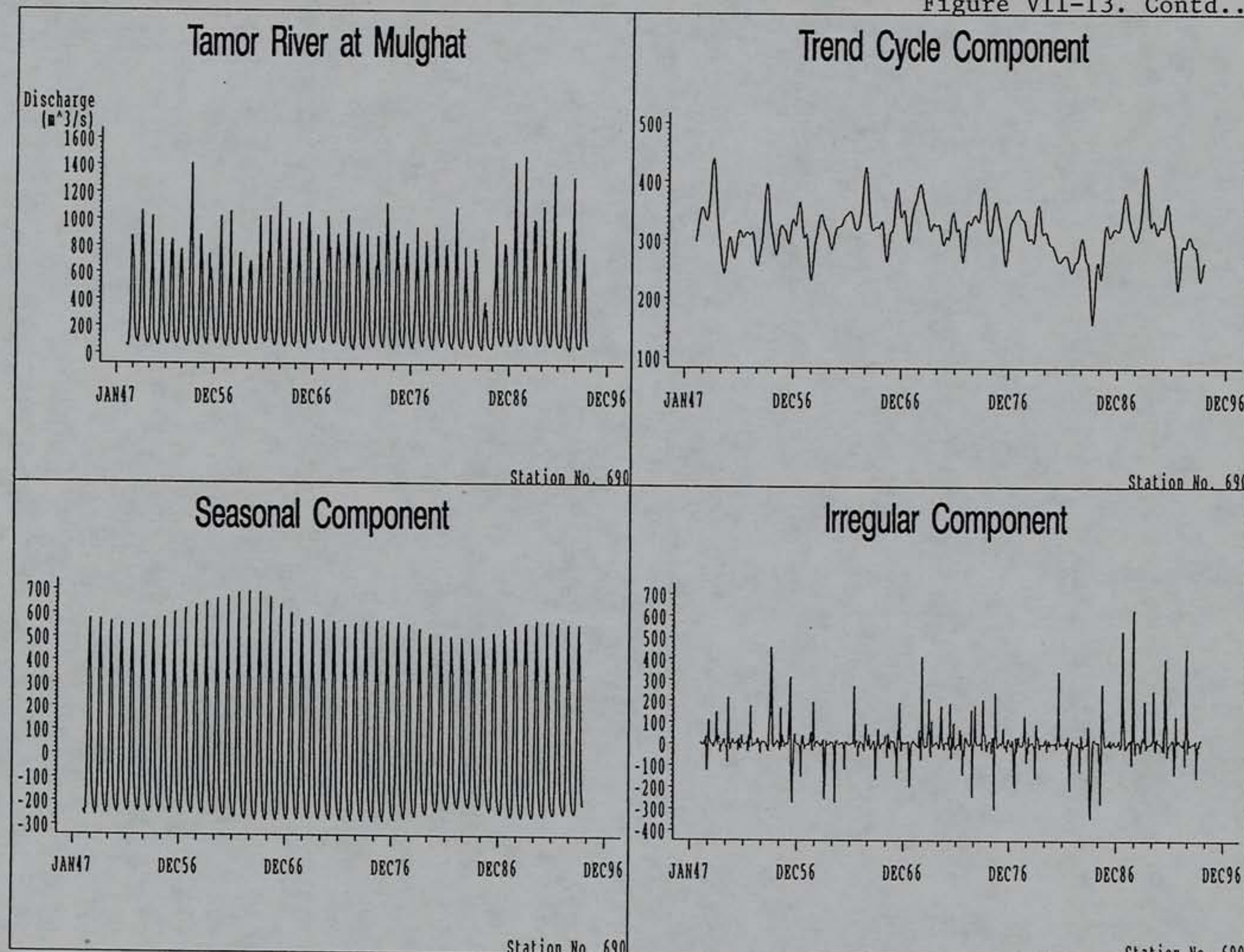


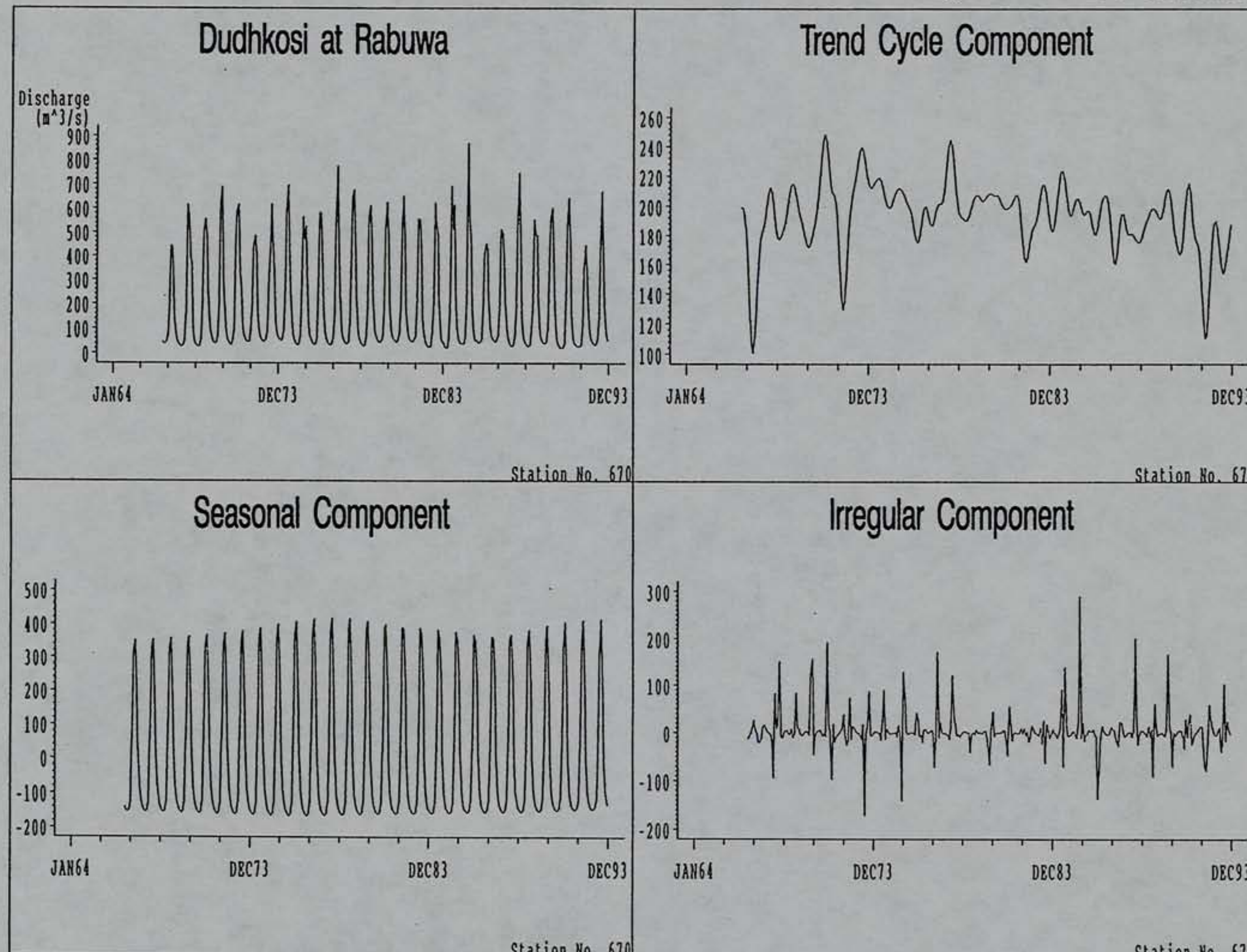
Figure VII-13. Original time series of discharge and its seasonal, trend cycle, and irregular components: (a) Kosi river at Chatara

Figure VII-13. Contd..



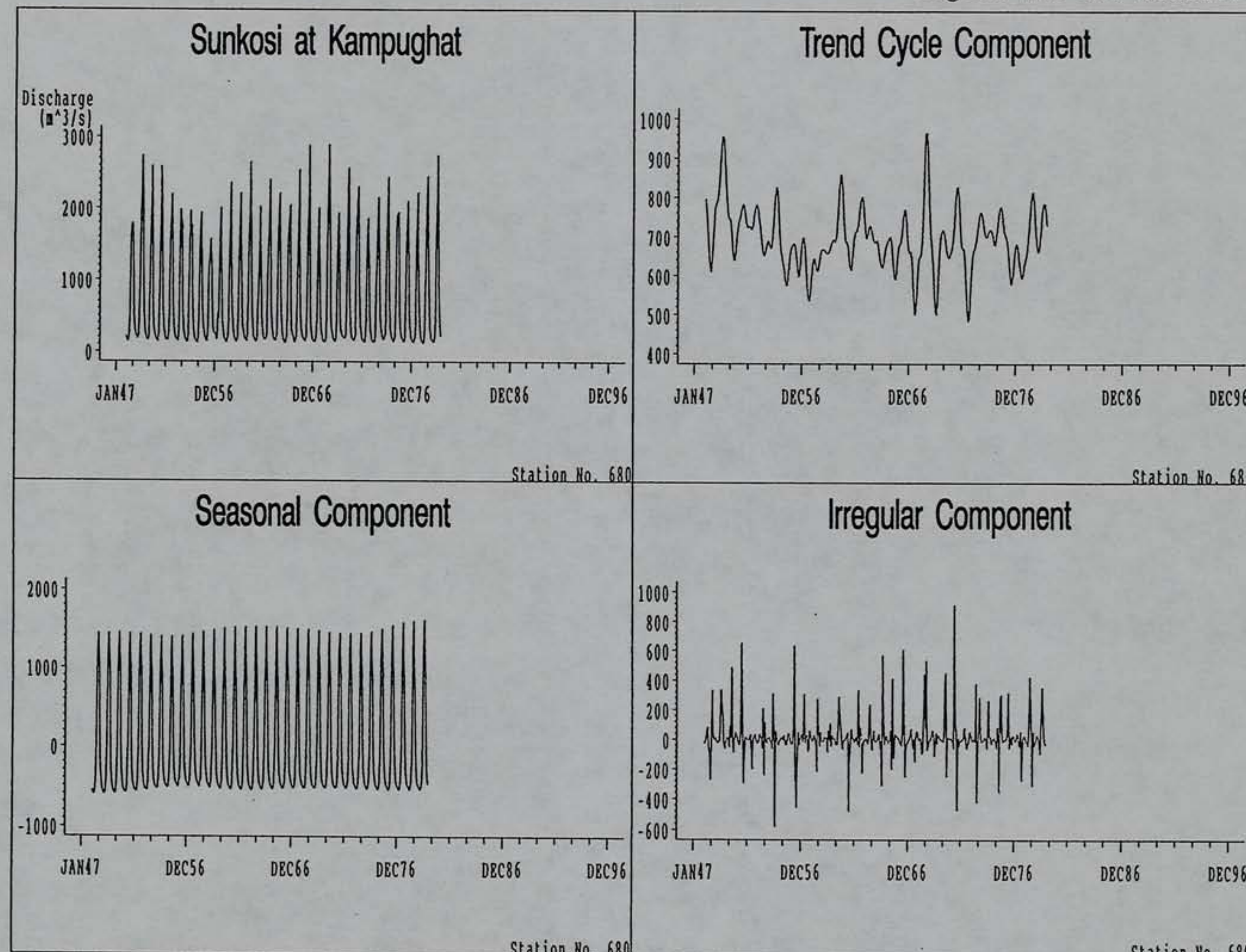
(b) Tamor river at Mulghat

Figure VII-13. Contd..



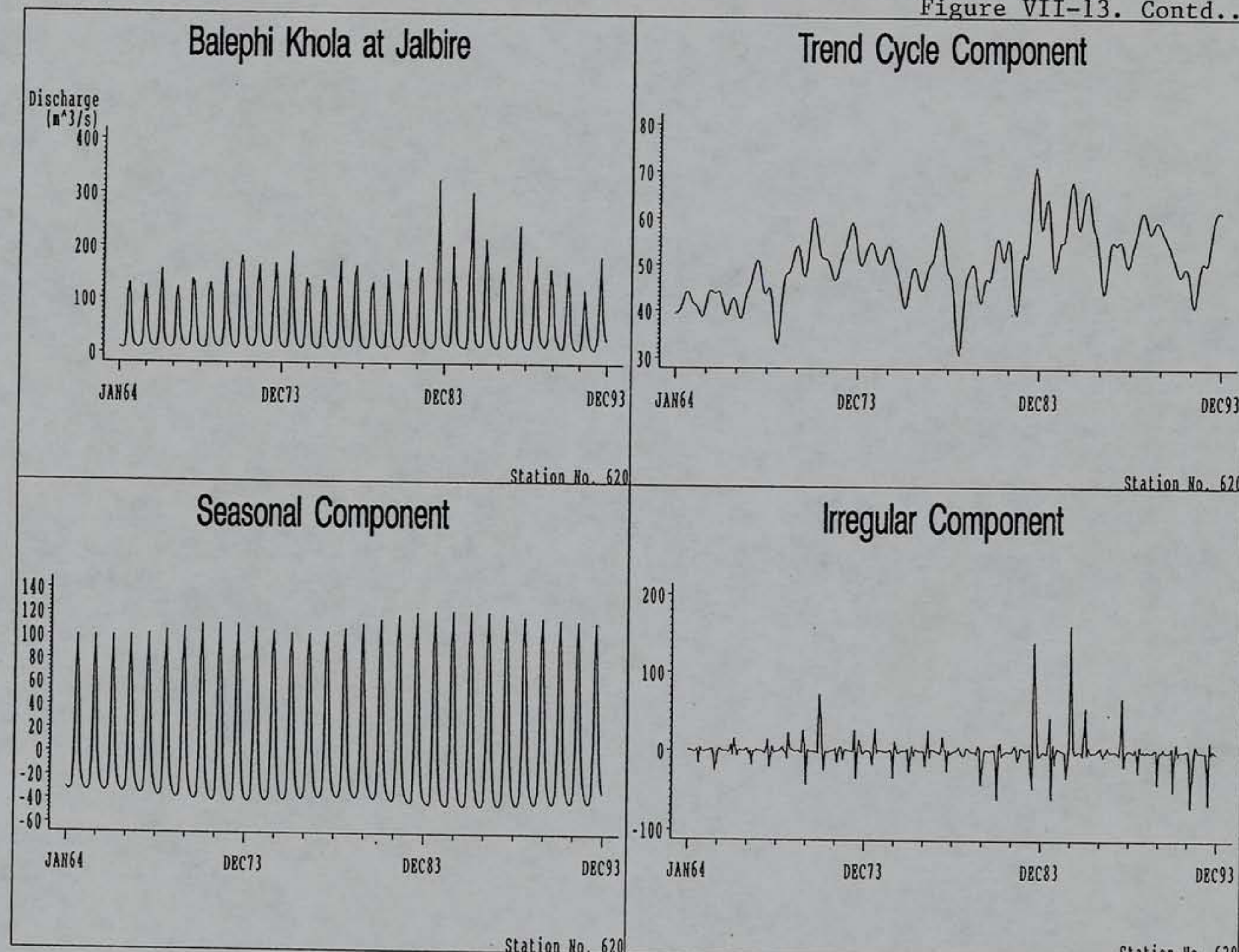
(c) Dudhkosi at Rabuwa

Figure VII-13. Contd..



(d) Sunkosi at Kampughat

Figure VII-13. Contd..



(e) Balephi Khola at Jalbire

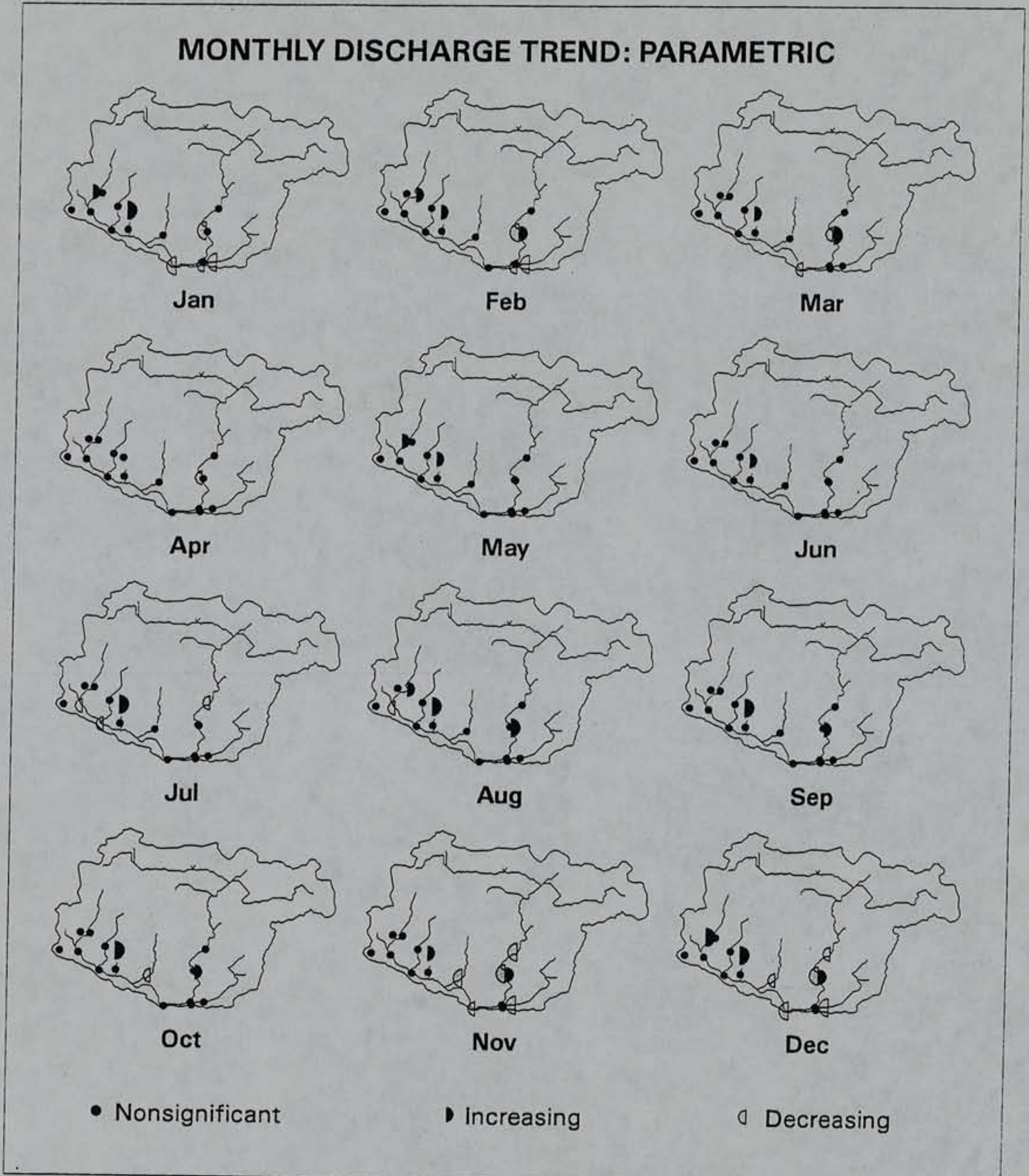


Figure VII-14. Trend of monthly discharge in the Kosi basin computed using parametric method.

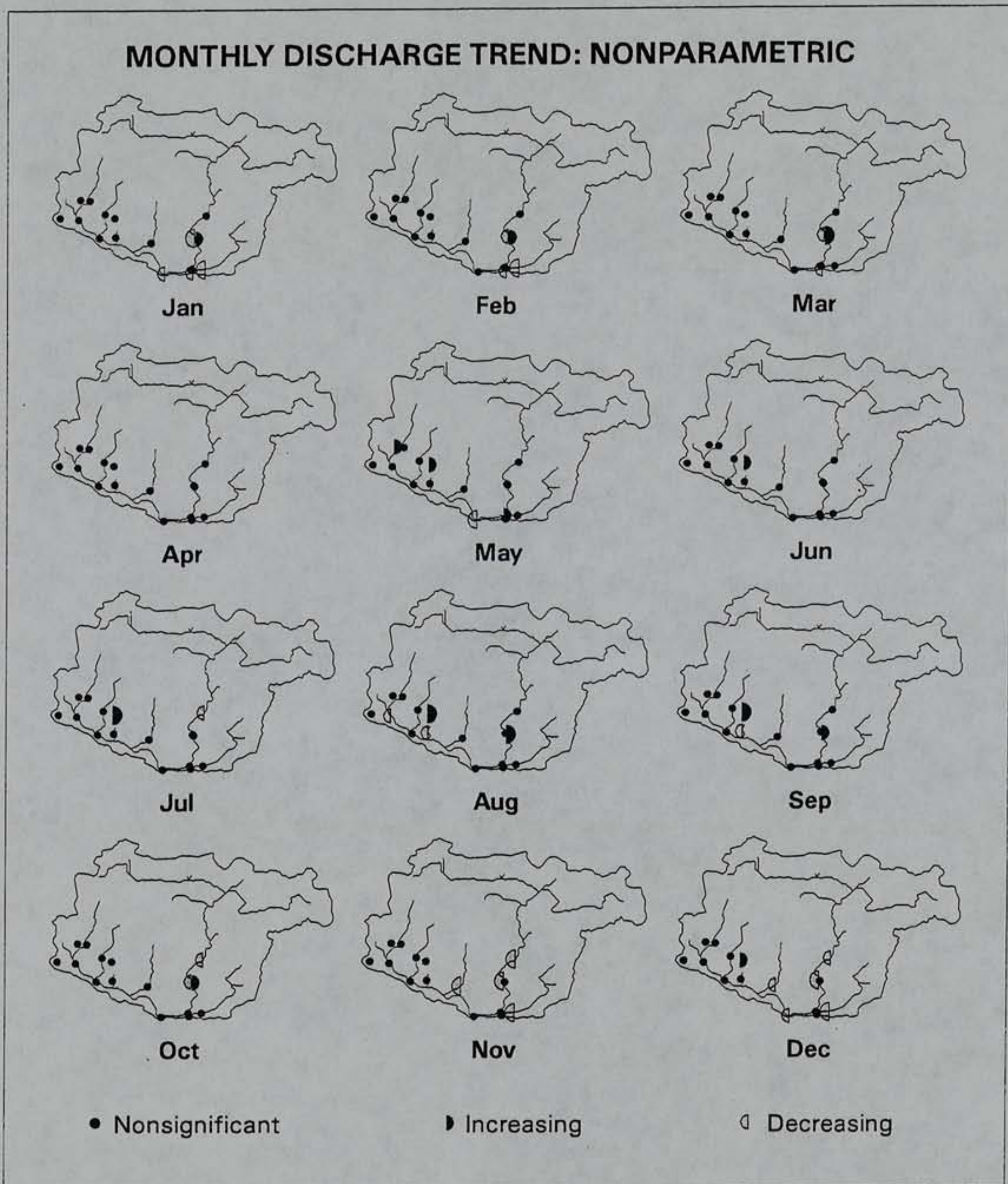


Figure VII-15. Trend of monthly discharge in the Kosi basin computed using nonparametric method.

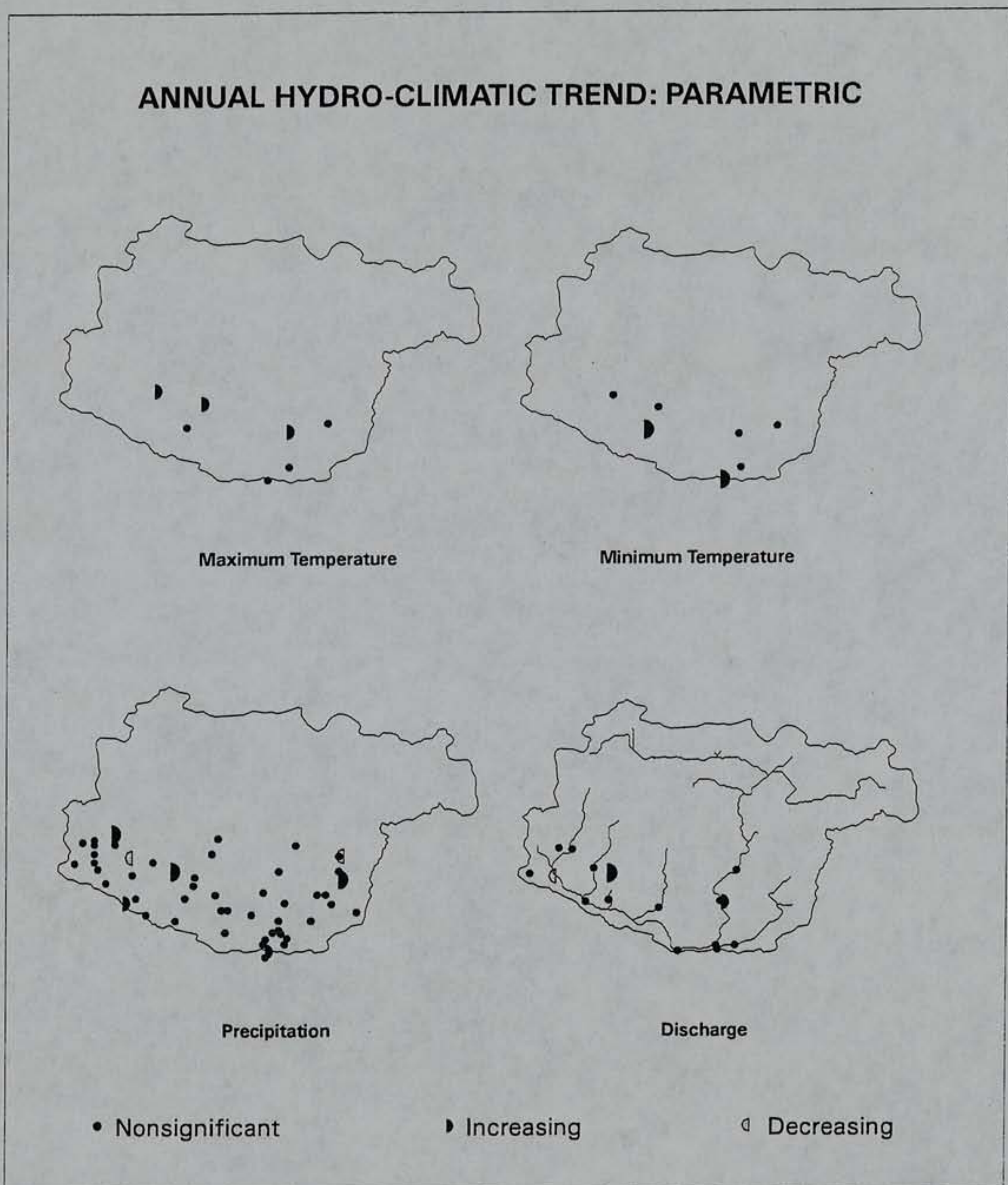


Figure VII-16. Trend of annual temperature, annual precipitation, and annual discharge in the Kosi basin computed using parametric method.

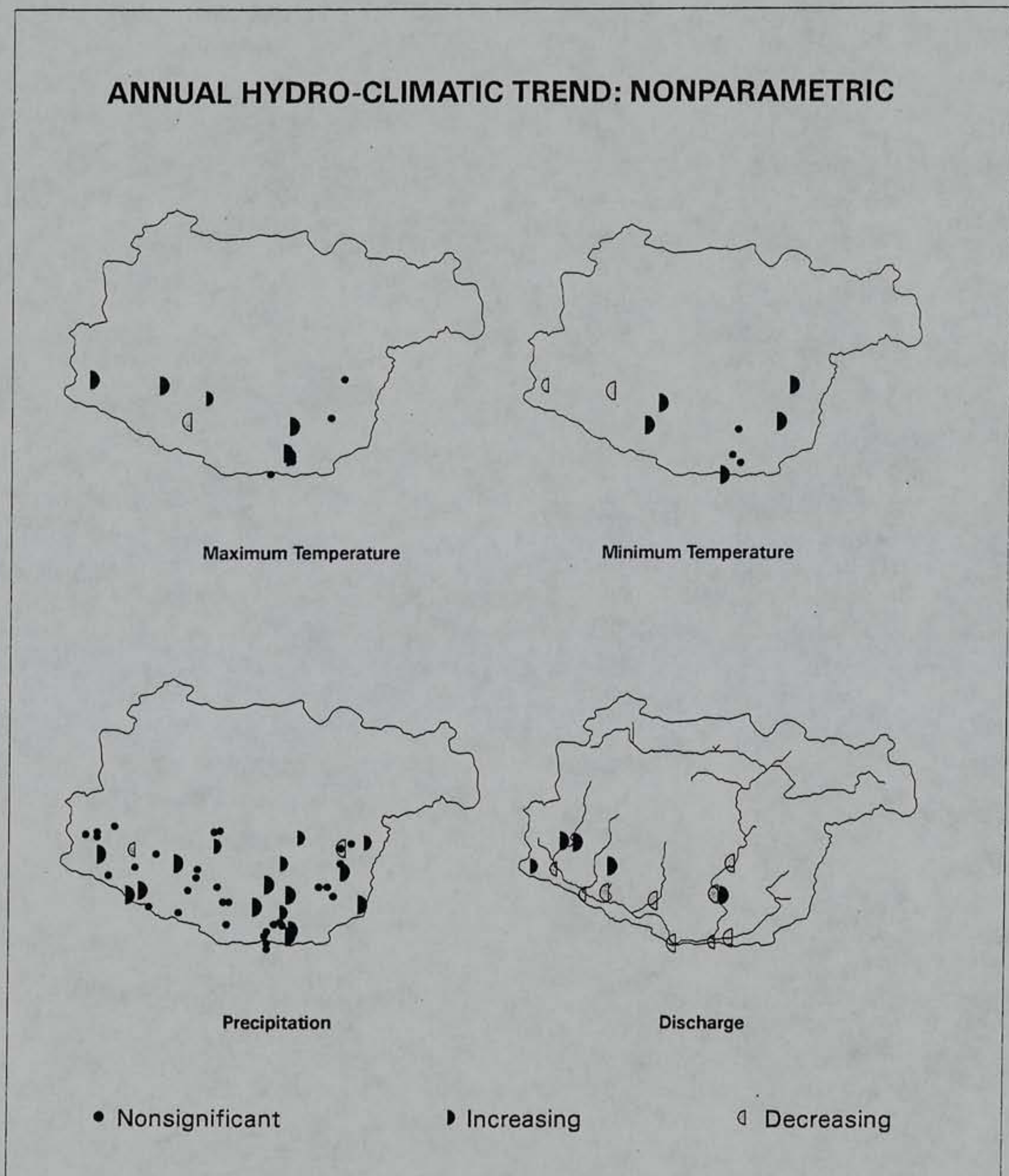


Figure VII-17. Overall trend of temperature, precipitation, and discharge in the Kosi basin computed using nonparametric method.

Discussion

Analysis of climatic changes in the Kosi basin reveals significantly increasing temperature and precipitation in some areas within the basin; yet most of the stations do not show any trend resulting in nonsignificant basinwide trend. The higher number of stations showing increasing temperature and precipitation trends as compared to fewer stations showing decreasing trends indicate that we need to pay special attention towards careful monitoring of climatic variables in future.

Contrary to the findings of more stations showing increasing trend of precipitation, more streamflow stations show decreasing trend of discharge. Significant negative trend shown by most of the snow fed rivers against positive trend shown by few gauged rainfed rivers indicate the role of snow covered high elevation areas. A plausible explanation to such observation could be the depleting snow cover areas and receding Himalayan glaciers as reported by some researchers (Chapter III). Although nonsignificant at basin scale, a general tendency of increasing temperature also justifies the higher evapotranspiration loss from the basin leading to overall decreasing tendency of the river discharges. Although the discharge trends are found to be homogeneous in terms of seasons, it is still nonsignificant in terms of sites indicating lack of basinwide trend.

Although few climatic stations have records extending to thirty years, most of the records used in the nonparametric statistical analysis have shorter lengths varying from 10 years to 30 years. Longer lengths of records provide not only long term climatic trend but also reduce the influence of irregular components and errors. To increase the confidence in the results of the statistical analysis, the hydrometeorological services of the region should give emphasis to the existing network for a long period of time with minimal loss of information. This recommendation is equally valid for temperature, precipitation, and river discharge. Chapter XII deals with the aspects related to river sediment discharges in more details.

CHAPTER VIII

MODELING HYDROMETEOROLOGIC CHARACTERISTICS

Understanding the spatial variation of major hydrological variables has been a major component of recent water balance and hydrological modeling experiments (Grayson, Moore, & McMahon, 1992; Vorosmarty et al., 1996). This chapter gives an analysis of major hydrometeorological variables: precipitation, temperature, and evapotranspiration operating in the Kosi basin. The purpose of this chapter is to examine the individual components of the hydrological cycle for modeling hydrological responses in the Kosi basin to different scenarios of climatic and land-use changes (Chapter IX & Chapter X). We put more effort on establishing the relationships between these variables and topographical variation as topography is a dominating characteristic of the Himalayan basins.

Modeling Precipitation

Precipitation is the major forcing function of any hydrologic system. Understanding its temporal as well as spatial distribution over a basin is the key to the success of any hydrological modeling exercise. Modeling precipitation distribution over a basin is required for water balance computations, and for modeling other hydrological variables, such as, evapotranspiration and runoff.

All the major hydrological regimes of the world are influenced by the variability of precipitation. The variability is extreme in heterogeneous areas, such as, the Himalayas where there is the influence of both high topographic variation and monsoon climate. The role of Himalayan topography is not only limited to local scale variations but also to regional scale precipitation distribution. For instance, the Himalayan region receives some of the heaviest precipitation of the world although the region lies in a geographical belt where general atmospheric circulation supports persistent subsidence (Black, 1991).

Influence of topography on precipitation and, notably, the general trend of increasing precipitation pattern with respect to increasing elevation has been recognized for many years. Such facts have been demonstrated with mathematical formulations (Donley & Mitchell, 1939) or graphical relationships (Barrows, 1933). Some of the notable studies, considering additional topographic factors other than elevation, include the work of Spreen (1947). The study shows that the inclusion of topographical factors, such as, slope, orientation, and aspect, besides elevation, bring significant improvements in the estimation of precipitation.

Figure VIII-1 illustrates an example of the variation of precipitation observed along a longitudinal transect of the Kosi basin. The cross-section covers part of the southern plain, the Mahabharat mountain, the Tamor valley and the southern section of a middle mountain. Although several large scale factors and local factors influence the precipitation, the figure shows that the topographical variations play crucial role in the Himalayan environment.

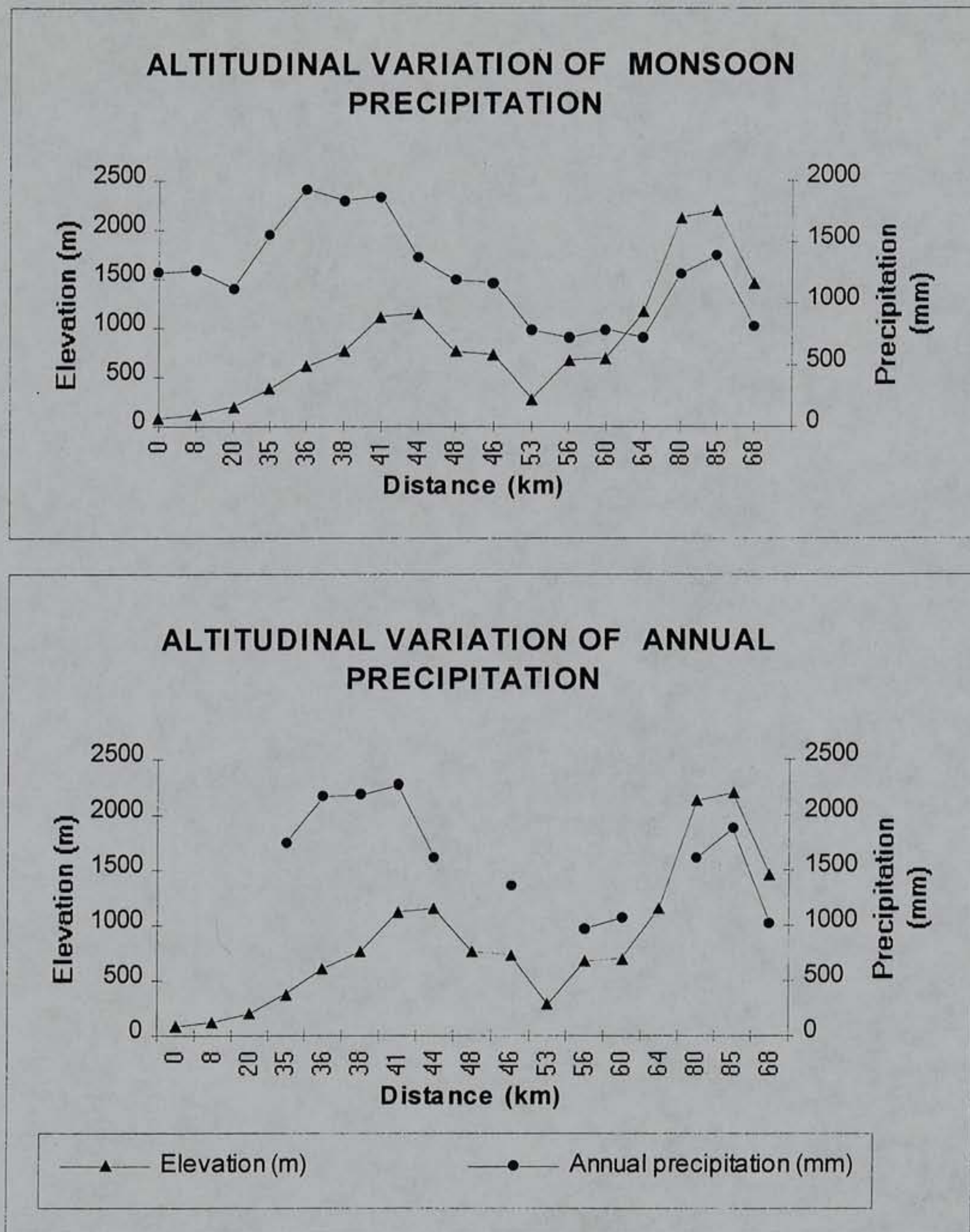


Figure VIII-1. Longitudinal profile of precipitation (monsoon and annual) and elevation in north-south direction in the southern part of the Kosi basin (Biratnagar to Basantapur). The area considered in this figure extends beyond 45 km to the South from the study area.

Modeling precipitation over the Himalayas is one of the most challenging aspects of hydrological modeling over the basin. Several factors such as physiographic heterogeneity, climatic heterogeneity and inadequacy of the precipitation gauging network influence the analysis of precipitation pattern. We used a statistical approach to analyze the role of several locational and topographical variables that influence the spatial distribution of precipitation in the basin. Univariate statistics of locational predictors selected for this purpose are given in Table VIII-1. We used monthly precipitation data (Sharma, 1996) for deriving correlation coefficients and their level of significance (p-value). Appendix C contains the monthly precipitation data used in this exercise.

Table VIII-1. Univariate statistics of locational and topographical variables used in multivariate regression with precipitation.

Variable	*Symbol*	*Mean*	*Std. Deviation*	*Minimum*	*Maximum*
Latitude (DD)	LAT	27.46	0.33	26.87	28.43
Longitude (DD)	LON	86.75	0.77	85.50	87.98
Elevation (m)	ELV	1816	1043	143	4340
Grid Elevation (m)	GELV	1767	1097	183	4878
Slope-Area Index (-)	SAINDX	99	39	0	177
Slope (degree)	SLOPE	9	5	1	26
Aspect (degree)	ASPECT	187	90	9	358

Table VIII-2 presents the coefficients of determination and p-values for selected potential predictor variables (Table VIII-1) and the mean monthly precipitation over the basin. The table also includes average annual precipitation amount and seasonal precipitation amount for the summer and winter monsoon months.

Examination of the Table VIII-2 and plots of the average annual and monthly precipitation values (Figure VIII-2 & Figure VIII-3) indicates the differential control of topographical influences for the winter and summer monsoon seasons. Table VIII-2 indicates insignificant influence of topographical variables on precipitation during summer months when all the precipitation data are used in a multiple regression. We further examined the correlation by dividing the samples into two groups. The division is based on the visual assessment of Figure VIII-2 and Figure VIII-3. The first group includes precipitation values for observation stations located below 2800 m and the other group includes stations located above 2800 m. Table VIII-3 presents the coefficients of determination and p-values for the stations included in the first group.

Table VIII-2. Coefficient of determination and p-values for potential predictors (applied individually), and mean monthly and seasonal precipitation over the Kosi basin

		GELV	*ASPECT*	*SLOPE*	*SAINDX*	*ELV*	*LAT*	*LON*
Jan	R^2	0.38	-0.08	0.39	0.3	0.48	0.47	-0.01
	p	0.003	0.53	0.002	0.02	0.0001	0.0002	0.92
Feb	R^2	0.54	-0.07	0.4	0.28	0.55	0.61	0.15
	p	0.0001	0.58	0.002	0.03	0.0001	0.0001	0.25
Mar	R^2	0.39	-0.05	0.47	0.37	0.4	0.44	0.29
	p	0.002	0.68	0.0002	0.004	0.002	0.0004	0.03
Apr	R^2	-0.07	0.09	0.25	0.27	-0.1	0.05	0.36
	p	0.61	0.47	0.06	0.03	0.43	0.71	0.004
May	R^2	-0.28	0.08	0.19	0.24	-0.28	-0.09	0.22
	p	0.03	0.56	0.14	0.06	0.03	0.5	0.09
Jun	R^2	-0.08	-0.12	0.15	0.15	-0.07	0.25	0.23
	p	0.56	0.37	0.26	0.26	0.62	0.06	0.08
Jul	R^2	-0.03	-0.17	0.14	0.11	-0.02	0.33	-0.4
	p	0.82	0.19	0.28	0.4	0.88	0.009	0.001
Aug	R^2	0.046	-0.2	0.11	0.07	0.06	0.45	-0.43
	p	0.73	0.12	0.39	0.57	0.67	0.0003	0.0006
Sep	R^2	-0.04	-0.25	0.19	0.16	-0.04	0.31	-0.27
	p	0.77	0.06	0.15	0.21	0.78	0.02	0.04
Oct	R^2	0.004	-0.13	0.2	0.21	-0.013	0.13	0.01
	p	0.97	0.31	0.12	0.11	0.93	0.31	0.92
Nov	R^2	0.33	0.01	0.28	0.27	0.38	0.37	0.31
	p	0.009	0.92	0.03	0.04	0.003	0.004	0.015
Dec	R^2	0.38	0.04	0.16	0.13	0.43	0.53	-0.16
	p	0.003	0.78	0.23	0.33	0.0006	0.0001	0.23
Summer	R^2	-0.02	-0.19	0.15	0.12	-0.008	0.36	-0.36
Monsoon	p	0.89	0.15	0.27	0.36	0.95	0.005	0.005
Winter	R^2	0.03	0.004	0.32	0.32	0.02	0.18	0.23
Monsoon	p	0.84	0.98	0.01	0.01	0.85	0.16	0.07
Annual	R^2	-0.01	-0.16	0.19	0.17	-0.002	0.35	-0.27
	p	0.94	0.21	0.14	0.2	0.99	0.006	0.04

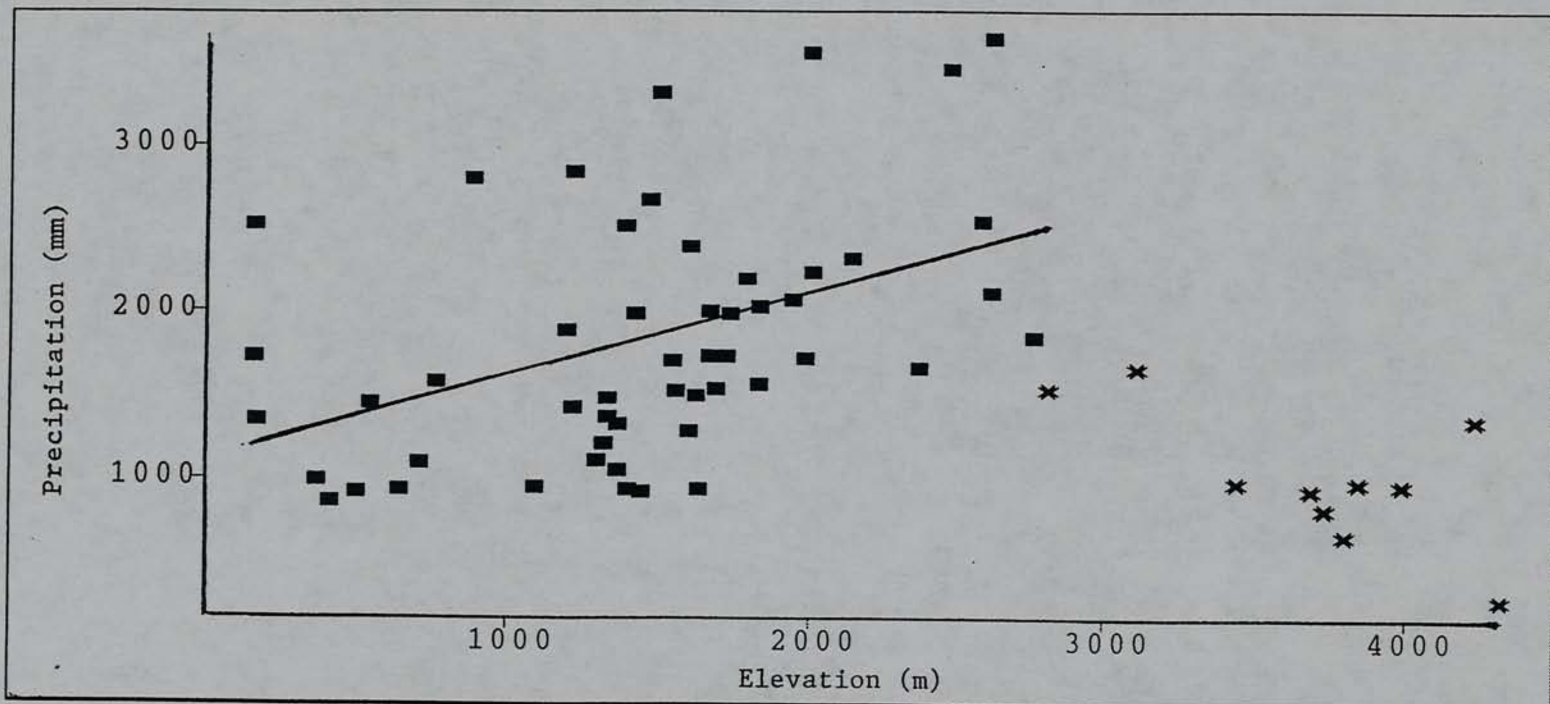


Figure VIII-2. Relation between annual precipitation and elevation in the Kosi basin. The cross symbols indicate the values excluded in computation.

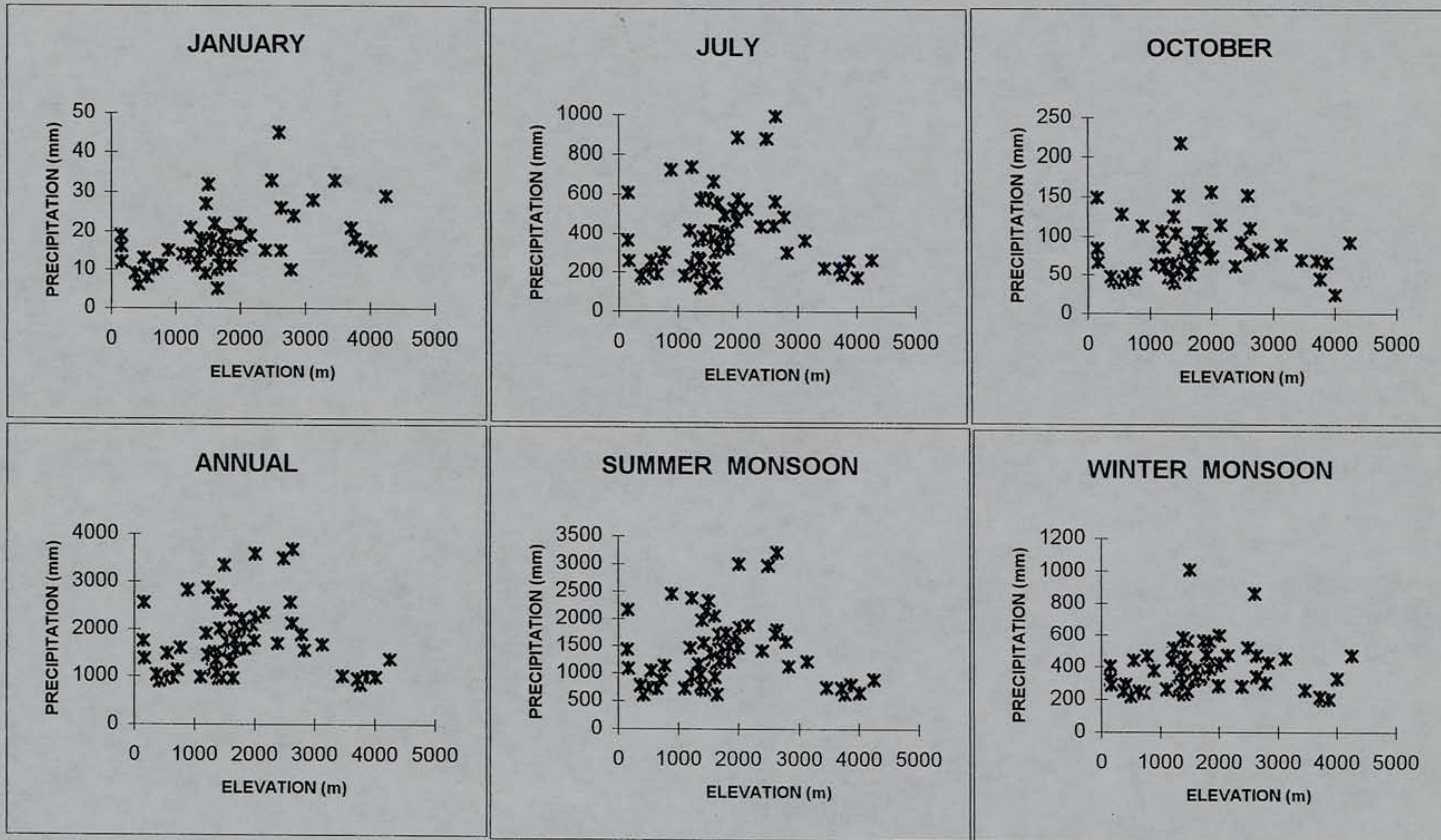


Figure VIII-3. Variation of monthly (selected months), annual, and seasonal precipitation in the Kosi basin with respect to elevation.

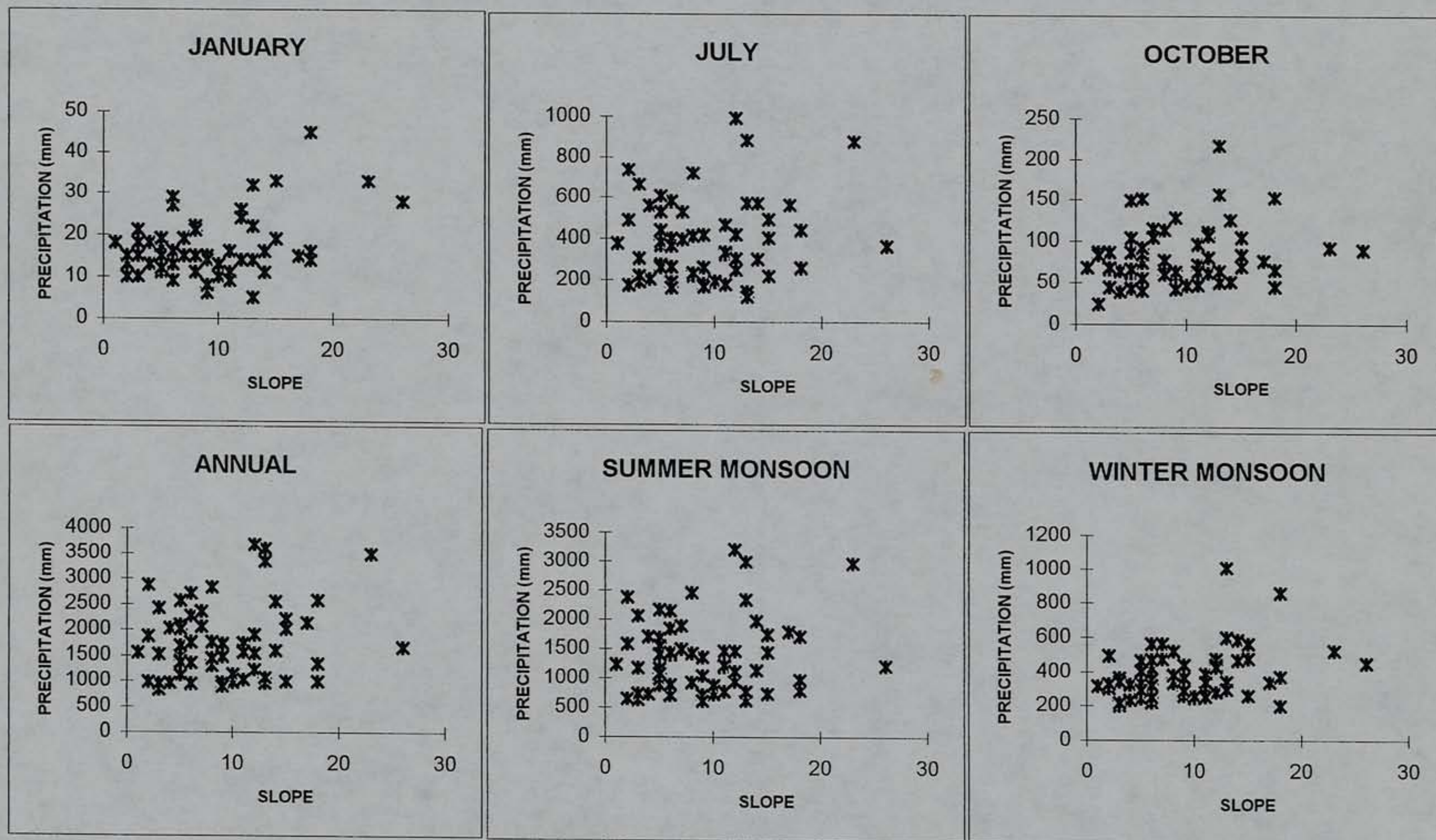


Figure VIII-4. Variation of monthly (selected months), annual, and seasonal precipitation in the Kosi basin with respect to slope.

Table VIII-3. Coefficient of determination and p-values for potential predictors (applied individually), and mean monthly and seasonal precipitation over the Kosi basin for observation stations lying below 2800 m.

		GRDELV	*ASPECT*	*SLOPE*	*SAINDX*	*ELV*	*LAT*	*LON*
Jan	R^2	0.29	0.02	0.26	0.15	0.38	0.34	-0.16
	p	0.04	0.89	0.07	0.29	0.007	0.02	0.26
Feb	R^2	0.39	0.08	0.34	0.23	0.44	0.62	-0.14
	p	0.007	0.57	0.02	0.119	0.002	0.0001	0.35
Mar	R^2	0.4	0.09	0.47	0.38	0.45	0.5	0.08
	p	0.004	0.55	0.0008	0.007	0.001	0.0003	0.6
Apr	R^2	0.17	0.12	0.33	0.31	0.22	0.22	0.39
	p	0.26	0.4	0.02	0.03	0.13	0.13	0.006
May	R^2	0.06	0.1	0.27	0.26	0.18	0.16	0.32
	p	0.7	0.48	0.06	0.07	0.22	0.29	0.03
Jun	R^2	0.21	-0.09	0.15	0.08	0.33	0.44	-0.19
	p	0.14	0.54	0.32	0.6	0.02	0.002	0.2
Jul	R^2	0.27	-0.15	0.14	0.02	0.38	0.53	-0.38
	p	0.06	0.29	0.34	0.92	0.008	0.0001	0.008
Aug	R^2	0.31	-0.17	0.07	-0.05	0.4	0.64	-0.42
	p	0.04	0.24	0.64	0.76	0.004	0.0001	0.003
Sep	R^2	0.22	-0.23	0.17	0.07	0.3	0.49	-0.23
	p	0.13	0.12	0.25	0.64	0.04	0.0005	0.12
Oct	R^2	0.11	-0.13	0.13	0.11	0.14	0.18	0.03
	p	0.47	0.39	0.39	0.48	0.35	0.22	0.85
Nov	R^2	0.25	0.15	0.22	0.23	0.35	0.3	0.21
	p	0.09	0.32	0.14	0.12	0.015	0.04	0.16
Dec	R^2	0.49	0.15	0.27	0.19	0.53	0.59	-0.33
	p	0.0004	0.32	0.06	0.19	0.0001	0.0001	0.02
Summer	R^2	0.27	-0.17	0.13	0.02	0.37	0.55	-0.33
Monsoon	p	0.07	0.26	0.38	0.9	0.009	0.0001	0.02
Winter	R^2	0.19	0.06	0.31	0.28	0.28	0.3	0.21
Monsoon	p	0.18	0.67	0.03	0.06	0.05	0.04	0.15
Annual	R^2	0.27	-0.13	0.17	0.07	0.38	0.54	-0.25
	p	0.06	0.38	0.24	0.63	0.008	0.0001	0.09

Examination of colinearity among different predictors showed that elevation and latitude are significantly correlated as the gradient of the Himalayas increases from south to north until the Himalayas meet the Tibetan plateau. Since GRDELV (elevation of station on DEM grid) and ELV (elevation of precipitation station) are the same variable in different format, a high correlation between them is obvious. Although SAINDX (Slope Area Index) is derived from slope and aspect obtained from DEM, we did not find significant colinearity between SAINDX and ASPECT; however, SLOPE is significantly correlated with SAINDX.

In the background of above discussions, correlation Figures (Figure VIII-2 & Figure VIII-3) and correlation tables (Table VIII-2 and Table VIII-3), we divided the spatial pattern of precipitation into two major regions: higher mountains (elevation > 2800 m) and lower mountains and valleys (elevation < 2800 m). The characteristics of precipitation in these two divisions for three major types of climatic systems were as follows.

i) Summer monsoon precipitation: Precipitation rises with increasing elevation up to an average elevation of about 2800 m. The increasing precipitation gradient reverses or loses its trend with increasing elevation above 2800 m. Such pattern can be seen up to an elevation of 3800 m. Reversed trend of precipitation in high elevation zones have also been reported in other part of the Himalayas (Bagchi, 1982) and in the Khumbu Himalayas of the Kosi basin (Higuchi, Ageta, Yasunari, & Inoue, 1982); but the data to support the decreasing trend of precipitation are not adequate. Furthermore, precipitation data collected during the monsoon of 1991 at four locations with elevation ranging from 1800 m to 4100 m in an area of the Indrawati basin (SMEC, 1992) show similar precipitation amount and similar precipitation pattern at all locations. Hence, the low precipitation amount in high elevation areas could be a result of biases in sampling with most of the high elevation stations representing relatively low precipitation zones of the basin. Four of the nine stations above 3000 m are located in the Tamor basin, three in the Dudhkosi basin and two in Tibet.

Information available above the level of 3800 m is scant to assess the nature of precipitation trend. A general assessment of some data collected for short duration during expeditions (LIGG/WECS/NEA, 1988) show no significant precipitation gradient above the level of 3800 m during monsoon.

ii) Winter Precipitation: Topographical gradient of precipitation in winter months (October-March) under the influence of western disturbance is more distinct and statistically more significant when compared with the pattern during the monsoons (Figure VIII-3). A similar precipitation gradient exists over the whole range of topography for which the data are available. For the areas above 3800 m, however, we could not study the pattern of trend because of inadequate information. Besides, the few scattered data on precipitation above 3800 m do not confirm any trend as in the case of monsoon precipitation described in the preceding paragraphs.

iii) Transition Period: April-May, also known as pre-monsoon, is the transition period of atmospheric circulation from westerly dominated weather system to summer monsoon system. Similarly, October, considered as post-monsoon month, brings the transition from summer monsoon to winter monsoon. Precipitation patterns in all these transitional months lack statistically significant topographical precipitation pattern.

Differences in precipitation features can be attributed to differences in the nature of weather systems for different periods described above. Weather systems during the influence of western disturbances are usually associated with well-established weather system (trough) with fairly widespread spatial coverage. Since localized influences such as convective activities, are less dominant, a better spatial pattern can be expected in such weather system compared to the monsoonal precipitation in which local systems are often embedded into large scale monsoon circulation.

Since the western disturbances enter into the Kosi basin from higher latitude in the West, the height of rain producing medium clouds can be expected to be higher than similar monsoon clouds developed in a weather system originating in a lower latitude. These factors, we believe, are the major reasons behind different precipitation gradient in high elevation areas during winter and summer. A detailed investigation of these meteorological processes is beyond the scope of this study; however, such studies are likely to contribute towards improving precipitation modeling in high elevation zones.

Table VIII-4 presents simple statistical models based on the correlation presented in Tables VIII-2 and VIII-3 applicable for different months.

Table VIII-4. Statistical models for topographical variation of average precipitation over the Kosi basin.

	Model	*N*	R^2	*p>F*	*Applicability*
Jan	P = 6.8 + 0.44 * SLOPE + 0.0035 * ELV	61	0.36	0.0001	Range of Data Used
Feb	P = 1.8 + 0.73 * SLOPE + 0.0068 * ELV	61	0.44	0.0001	Range of Data Used
Mar	P = 11.8 + 1.65 * SLOPE + 0.0075 * ELV	61	0.34	0.0001	Range of Data Used
Apr					
May					
June	P = 198 + 0.07 * ELV	52	0.15	0.0050	Up to 2800 m
Jul	P = 263 + 0.14 * ELV	52	0.19	0.0011	Up to 2800 m
Aug	P = 196 + 0.15 * ELV	52	0.22	0.0004	Up to 2800 m
Sep	P = 168 + 0.07 * ELV	52	0.14	0.0054	Up to 2800 m
Oct					
Nov	P = 4.8 + 0.33 * SLOPE + 0.0025 * ELV	61	0.18	0.0032	Range of data used
Dec	P = 5.6 + 0.0029 * ELV	61	0.23	0.0001	Range of data used
Ann	P = 1120 + 0.50 * ELV	52	0.20	0.0010	Up to 2800 m

Analysis of multicolinearity between slope and elevation in all the bivariate equations showed that these two variables were not significantly correlated. The variation inflation factors in all the cases were less than 1.1. Elevation and slope were the main variables influencing the distribution of precipitation over the basin (Tables VII-2 to VII-4). Unlike the results obtained by Spreen (1947), we found that the aspect was the least important predictor of precipitation in the Kosi basin. Biases in the location of stations with respect to aspect could be a reason behind the lack of correlation between precipitation and aspect but this needs further examination with site-based information or with higher resolution DEMs. The influence of slope was significant only for winter precipitation. The regression equations excluding slope, obtained for winter months, are presented in Table VIII-5 below.

Table VIII-5. Alternate statistical models for topographical variation of average precipitation over the Kosi basin for winter months.

Month	*Model*	*N*	R^2	*p>F*	*Applicability*
Jan	P = 10.2 + 0.0038 * ELV	61	0.26	0.0001	Range of Data Used
Feb	P = 7.40 + 0.0076 * ELV	61	0.35	0.0001	Range of Data Used
Mar	P = 24.4 + 0.0089 * ELV	61	0.18	0.0008	Range of Data Used
Nov	P = 7.3 0 + 0.0028 * ELV	61	0.13	0.004	Range of Data Used

Data are given in Appendix C.

The inclusion of slope as one of the predictors in winter months greatly improved the equation for predicting precipitation in terms of the coefficients of determination along with p-values as shown by the difference of statistical indicators in Table VIII-4 and Table VIII-5.

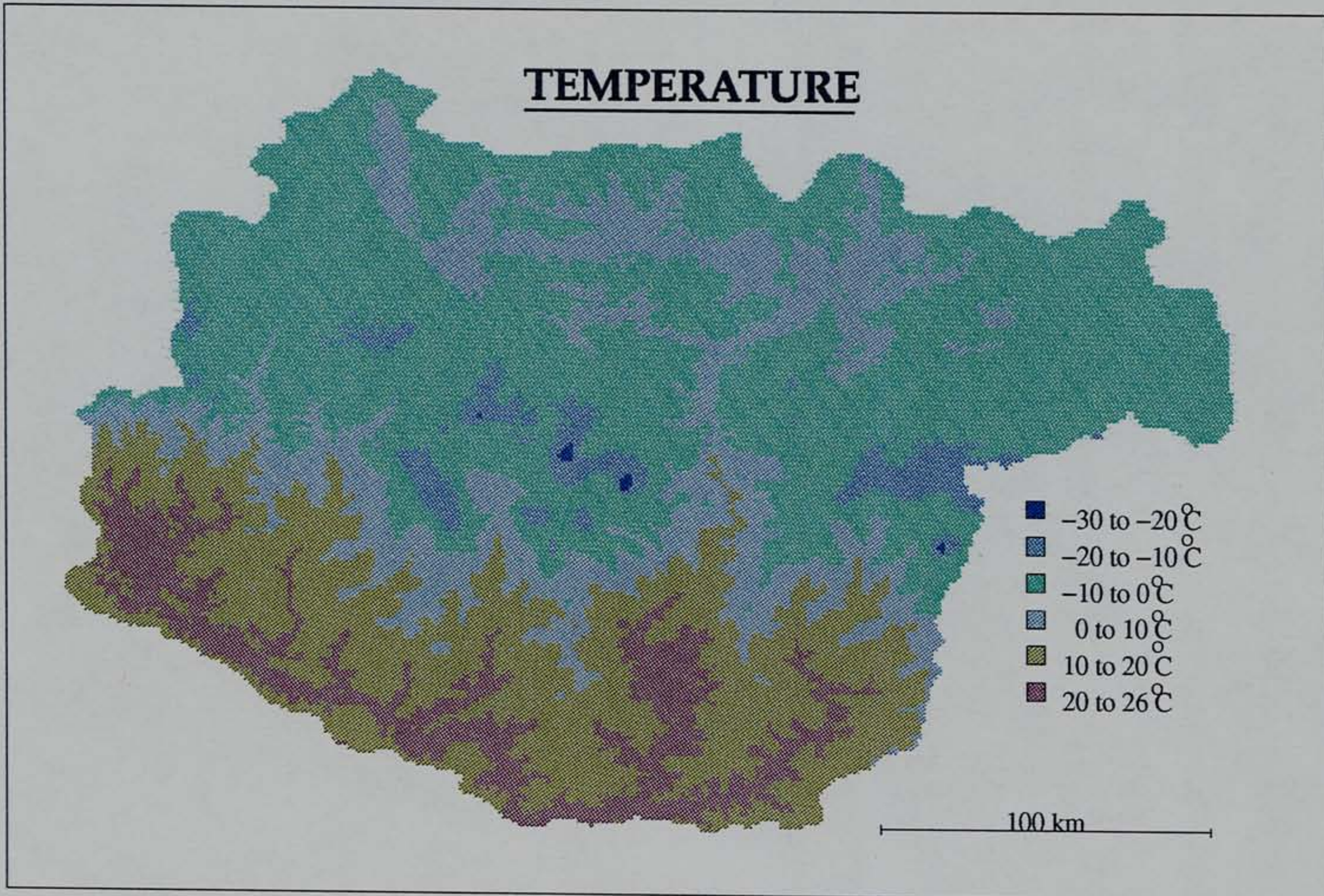


Figure VIII–5. Average annual temperature in the Kosi basin based on an average annual lapse rate of 5.9 degree Celsius per kilometer (see Table VIII–6).

Modeling Temperature

Temperature influences water balance of a basin by directly influencing evapotranspiration and snowmelt. As discussed in earlier chapters, it plays a significant role throughout the basin in the case of evapotranspiration whereas its influence is limited to potential melt areas and snow covered areas in the case of snowmelt. Temperature distribution over the basin is directly related to season and altitude.

We examined the latitudinal variation of temperature over the Kosi basin by extrapolating station temperature into sea level temperature and regressing the extrapolated temperature to latitude. The regression analysis indicated no significant latitudinal variation of temperature. Regression equations of temperature with respect to elevation for different months are presented in Table VIII-6.

Table VIII-6. Monthly temperature models for the Kosi basin.

	Model	R^2	*p>F*
Jan	T = 21.3 - 0.0066 * ELV	0.93	0.0001
Feb	T = 23.1 - 0.0066 * ELV	0.94	0.0001
Mar	T = 27.0 - 0.0070 * ELV	0.97	0.0001
Apr	T = 29.6 - 0.0067 * ELV	0.97	0.0001
May	T = 29.8 - 0.0060 * ELV	0.93	0.0001
Jun	T = 29.2 - 0.0050 * ELV	0.88	0.0001
Jul	T = 28.9 - 0.0047 * ELV	0.88	0.0001
Aug	T = 28.5 - 0.0047 * ELV	0.83	0.0001
Sep	T = 28.8 - 0.0053 * ELV	0.91	0.0001
Oct	T = 27.7 - 0.0060 * ELV	0.95	0.0001
Nov	T = 24.9 - 0.0064 * ELV	0.98	0.0001
Dec	T = 21.8 - 0.0062 * ELV	0.96	0.0001
Ann	T = 26.7 - 0.0059 * ELV	0.96	0.001

Data are given in Appendix D (n = 20)

Table VIII-6 shows that the average monthly temperature is significantly related to elevation with lapse rate varying from 4.7 °C/km in wet months to 7.0 °C/km in dry months. The vertical temperature gradients during active monsoon months are, hence, less than saturated adiabatic lapse rate (6.5 °C/km) indicating highly moist condition of atmosphere near land surface and high influence of warm monsoon winds during this period. The highest average lapse rates of about 7.0 °C observed in dry months are close to the average environmental lapse rate observed in lower troposphere (Linsley, Kohler, & Paulhus, 1988). Figure VIII-5 presents annual average temperature obtained for the basin by using extrapolated temperature values based on annual temperature lapse rate (Table VIII-6) and DEM.

Modeling Evapotranspiration

Reliable estimation of evapotranspiration is a critical aspect in hydrological modeling as it is the major component of hydrological cycle that is not measured directly on operational basis. Although several methods are available for its estimation, the reliability of the results is always questionable. Lee (1980, p. 180) summarizes such difficulties as, "There is no reliable method for estimating evapotranspiration rates based on weather element data or potential evaporation."

We compared evaporation and evapotranspiration estimates using three methods for a selected location in the Kosi basin. The chosen methods include: water balance method, empirical equations, and pan-based method.

Water Balance

The water balance is one of the most widely used methods for estimating evapotranspiration. The method based on longer term balance of hydrological cycle has several problems related to accuracy of rainfall and runoff data including assumptions of soil water storage. Nonetheless, Hewlett (1982, p.89) says, "At present the safest approach to its (evapotranspiration) estimation for the purpose of making decision about forest and wildlands is undoubtedly the water balance and the catchment experiment."

Empirical Equations

Out of several available empirical equations, we selected the following equations for the purpose of this study.

Temperature-Based Method. It is probably the most widely used method as temperature is the only required climatic data in this method. This method, originally developed by Thornthwaite, has been satisfactorily applied in many parts of the world in its original as well as simplified forms (Dingman, 1994; Ward & Robinson, 1990). We used the following equation (Malmstorm, 1969) to compute potential evapotranspiration using temperature data.

$$PET = \frac{e_s(T)}{e_s(0)} * 25, \qquad \text{(VIII-1)}$$

where *PET* is the potential evapotranspiration (mm), $e_S(T)$ is the saturation vapor pressure (mb) at temperature T (°C) for a given month and $e_S(0)$ is the saturation vapor pressure (mb) at 0 °C.

Hargreaves Equation. On the basis of theoretical aspects included in this empirical equation and on the basis of several comparative results, it is one of the most recommended equations in places where temperature is the only available data (Hargreaves, Hargreaves & Riley, 1985; Shuttleworth, 1993). The equation can be expressed as:

$$PET = 0.0023 S_o \sigma_T^{0.5} (T + 17.8), \qquad \text{(VIII-2)}$$

where PET, S_O, σ_T, and T are potential evapotranspiration (mm), water equivalent of extraterrestrial radiation (mm day^{-1}) at temperature T, and mean monthly air temperature (°C) respectively.

Penman Equation-Based Method. The Penman method, based on energy balance and aerodynamics, is the most well known and probably the best method for the estimation of evapotranspiration (Dingman, 1994). Although the method needs several weather variables, such as, radiation, vapor pressure, temperature and wind, most of them are regularly measured in several climatological stations. Assumptions are usually involved for evaluating radiation term in the Penman equation as radiation measuring stations are rare.

Since the climatic stations within the Kosi basin are few and since the computation of evapotranspiration must be extrapolated to wider areas of the basin, we used a regional elevation based method developed by Lambert and Chitrakar (1989) for Nepal. The regression based potential evapotranspiration equation for a given elevation can be presented in the following format:

$$PET = A + B*Z, \qquad \text{(VIII-3)}$$

where PET is the potential evapotranspiration (mm) and Z is the elevation (m). A and B are the coefficients obtained by linear regression. The values of A and B are different for different months.

Pan Based Method

Although technology is available for the measurement of evapotranspiration (Ward & Robinson, 1990), this is the only available method for estimating evapotranspiration on a regular basis with direct evaporation measurement of water contained in a pan. Potential evapotranspiration is estimated by applying a suitable coefficient. This method has been described as one of the preferred methods by Shuttleworth (1993) with results falling within the error margin of 10 to 15 per cent in relatively humid regions.

Comparison

Table VIII-7 below compares the estimates of monthly evapotranspiration made by different methods described above for a location at about 1700 m. The comparison shows that the subannual patterns of estimates are similar giving higher values in summer and lower values in winter.

Table VIII-7. Average monthly Class A pan evaporation and potential evapotranspiration at 1700 m estimated by different methods.

	Class A Pan Evaporation (mm)	*Penman Method Based Potential Evapotranspiration (mm)*	*Temperature Based Potential Evapotranspiration (mm)*	*Hargreaves Potential Evapotranspiration (mm)*
Jan	62	36	49	52
Feb	76	56	54	59
Mar	144	97	69	90
Apr	155	121	86	110
May	121	130	91	118
Jun	88	106	99	108
Jul	73	93	99	105
Aug	74	93	89	100
Sep	64	76	94	89
Oct	76	74	82	82
Nov	73	46	66	62
Dec	64	33	53	51
Ann	1068	963	932	1027

As demonstrated by Table VIII-7, all the methods overestimate potential evapotranspiration for summer monsoon months (June to September) compared with class A pan evaporation. In general, the potential evapotranspiration values obtained from the

Hargreaves method are the closest to the values obtained from the pan based method. Table VIII-7 also indicates that the differences of annual estimates among different methods are small and that the potential evapotranspiration is close to the Class A pan evaporation.

Variation of evapotranspiration in mountainous environment is one of the least understood aspects of regional hydrology. Available studies do not confirm the expected significant relationship between evapotranspiration and elevation. Available surveys of experimental results show inconclusive and contrasting outcomes (Barry, 1981; Peck & Pfankuch, 1963). Lack of correlation between elevation and evaporation has also been reported for the Himalayan region on the basis of evaporation data from eastern Nepal (Alford, 1992). Moreover, all the temperature-based empirical evapotranspiration methods predict none or negative evaporation (condensation) below certain point in temperature scale.

Class A pan evaporation data are available only for three stations in southern side of the Himalayas and two stations in the northern side in the Kosi basin. The altitude of the stations in the southern side ranges from 1595 m to 1810 m within the basin. Figure VIII-6 illustrates the temporal pattern of pan evaporation in southern side (Okhaldhunga) and northern side (Tingri) in the Kosi basin. One more station (Tarahara), located at about 200 m, close to the basin, is included in the figure to compare the pattern with low elevation areas.

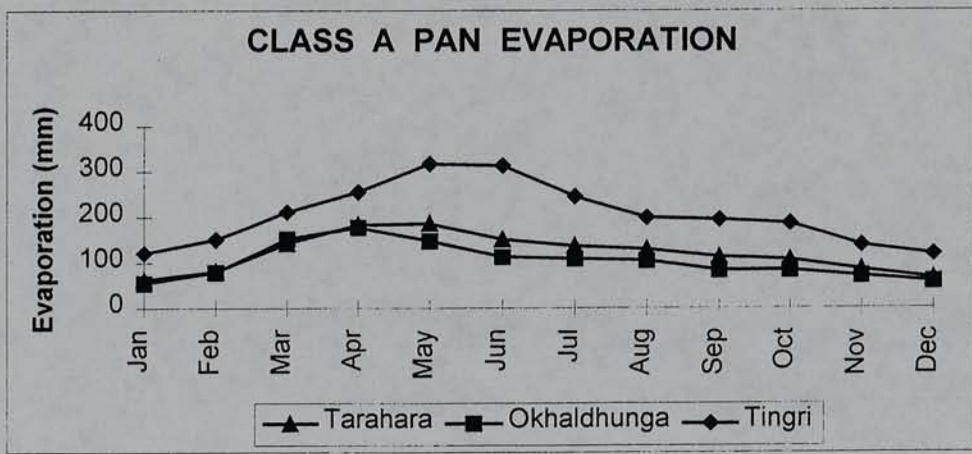


Figure VIII-6. Monthly class A pan evaporation at Tarahara (200 m), Okhaldhunga (1720 m), and Tingri (4300 m).

The figure shows that the pan evaporation pattern between Tarahara (200 m) and Okhaldhunga (1810 m) is similar with the low elevation station recording higher evaporation particularly during the monsoon and post-monsoon period. The pan evaporation in the Tibetan part, on the other hand, is significantly high in all the months in a year despite the location of sites in the high elevation zone at 4300 m (Figure VIII-6).

Some additional studies in other parts of Tibet are available that confirms the high rate of evaporation in high elevation areas of Tibet. Some of these studies show the pan evaporation and saturated soil evaporation rates exceeding nine millimeters on some dry days of summer at an elevation of 5260 m (Xingcheng & Yingqin, 1989). Based on 14-day observations in summer, Ohata et al. (1991) report the snow evaporation rates varying from 0.81 mm of condensation to 3.58 mm of evaporation at 5170 m high location.

The available pan evaporation data within the basin are inadequate to assess the altitudinal variation of evaporation over the basin. We examined the relation on the basis of evaporation data from 17 stations located in different parts of Nepal. The elevation in this data set ranges from 93 m to 1810 m (Figure VIII-7).

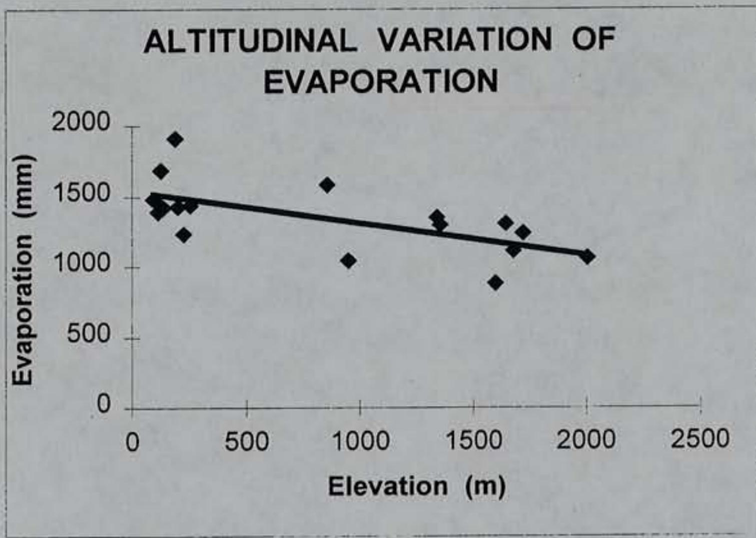


Figure VIII-7. Relation between elevation and Class A pan evaporation recorded in different parts of Nepal.

Regression analysis of these data shows statistically significant trend of decreasing evaporation with respect to increasing altitude. Analysis using monthly data, however, shows that the relation between evaporation and elevation is not significant in winter months. Table VIII-8 below shows the statistically significant relationships for monthly as well as annual evaporation. The relations, obtained using Penman method based computation (Lambert & Chitrakar, 1989), are also included in the table for comparison. Figure VIII-6 exemplifies the relation between annual pan evaporation and elevation in the mountains of the southern Himalayas.

Table VIII-8. Relation between elevation and monthly and annual evaporation

	Class A pan evaporation	*p > F*	*R2*	*Penman PET*
Jan				PET = 50 - 0.008 * ELV
Feb				PET = 74 - 0.010 * ELV
Mar				PET = 125 - 0.017 * ELV
Apr	E = 203 - 0.036 * ELV	0.003	0.45	PET = 158 - 0.022 * ELV
May	E = 231 - 0.061 * ELV	0.0001	0.69	PET = 177 - 0.028 * ELV
Jun	E = 187 - 0.048 * ELV	0.002	0.48	PET = 152 - 0.027 * ELV
Jul	E = 146 - 0.028 * ELV	0.025	0.29	PET = 135 - 0.025 * ELV
Aug	E = 143 - 0.022 * ELV	0.04	0.24	PET = 134 - 0.024 * ELV
Sep	E = 123 - 0.024 * ELV	0.007	0.39	PET = 114 - 0.023 * ELV
Oct				PET = 102 - 0.017 * ELV
Nov				PET = 68 - 0.013 * ELV
Dec				PET = 47 - 0.008 * ELV
Ann	E = 1544 - 0.219 * ELV	0.003	0.46	PET = 1333 - 0.22 * ELV

The equations of Table VIII-8 are based on the evaporation and climatic data recorded in the lower elevation and relatively more humid areas of the southern Himalayas. Available information is not sufficient to validate them in high elevation areas and semi-arid lands of the northern Himalayas. For instance, these equations indicate condensation instead of evaporation (sublimation) in areas above 6000 m. Similarly, the value of annual evapotranspiration given by the above equation for Tingri in Tibet (4300 m) is about 400 mm. On the other hand, the recorded pan evaporation at Tingri shows the average annual evapotranspiration of about 2400 mm (Appendix F) which is 800 mm more than the value we might expect even with the lowest pan coefficient of 0.35 reported in literature (Shuttleworth, 1993). Hence, for the modeling of high elevation evapotranspiration, we assumed the applicability of elevation based equations up to the elevation of 3000 m and further assumed a constant evapotranspiration rate above this elevation, a pattern similar to the areas in the Rocky mountains (Barry, 1981). Table VIII-8 also indicates that the annual evapotranspiration is about 86 per cent of class A pan evaporation.

Discussion

The major limitation of this study is the lack of information available for the Tibetan part and the high Himalayan zones of the basin. Although temperature can be extrapolated over the basin with greater confidence by using the lapse rates, the extrapolation of precipitation and evapotranspiration are likely to suffer from higher levels of uncertainty. Notwithstanding, analysis of hydrometeorological characteristics of the Kosi basin using the available information show two major facts: 1) Himalayan topography plays a significant role, and 2) hydrometeorological characteristics of the Kosi basin in the south of the Himalayas are different from the characteristics of the basin in the north in many respects.

Since only one station located at Tingri represents the Tibetan part of the basin, we do not have adequate information to establish a hydrometeorological pattern over the northern parts. Some available studies made in similar areas of Tibet do not provide consistent conclusions. For instance, Ohata, Takahashi, and Xiangcheng (1989) find significantly higher precipitation in the higher elevation zones than in adjacent valleys of the Kunlun mountains of Tibet. On the other hand Ohata et al. (1991) do not find such altitudinal increase in precipitation in the Tanggula mountains of the Tibetan plateau.

High values of class A pan evaporation in Tibet but relatively dry land-surface and atmospheric conditions with low temperature bring higher uncertainties (due to higher range in possible rates) in the estimation of actual evapotranspiration over these areas. What is the nature of actual evapotranspiration in the snow covered high elevation areas of the Himalayas? The lack of satisfactory answer to this question is not limited to the Himalayas but also to most of the snow covered areas in the world (Barry, 1981). Available information is little, scattered, and the reported values are highly variable. This area is likely to remain a great challenge among scientists for the years to come.

CHAPTER IX

WATER BALANCE

The use of a regional water balance assessment was explored as an additional approach to assess hydrologic response of the Kosi watershed to potential land-use and climatic changes. The equation for long-term water balance can be expressed in its simplest form as:

$$R = P - ET, \quad \text{(IX-1)}$$

where R, P and ET are runoff, precipitation and evapotranspiration of a basin respectively.

As previously mentioned, obtaining a reliable water balance of the Kosi basin and its sub-basins is a formidable task due to the extreme physiographic variation within the basin. In addition, the long-term and regular precipitation network does not exist for areas 4500 m above sea level which represents more than half of the Kosi basin. The highest station with regular and up-to-date data is the station located in Chialsa at 2770 m. Nine other stations operated from few months to few years provide some information on precipitation up to an elevation of 4300 m. The meteorological station of Tingri, located at 4300 m is the only station with long-term data in the northern part of the basin. It is the sole station representing the whole area of the Tibetan plateau in the Kosi basin that covers slightly less than half of the area considered in this study.

Our attempt to obtain precipitation distributions over the basin by gridding the average precipitation using widely-used interpolation techniques, such as, inverse distance weighted interpolation (Bonham-Carter, 1994), spheremap interpolation (Wilmott, Rowe & Philpot, 1985) and kriging (Isaaks & Srivastava, 1989) did not yield reasonable precipitation patterns over the basin. Computation of water balance using such data shows the average annual runoff values higher than the average annual precipitation. Additionally, we believe that the poor rain gauge network in higher elevation areas plus the complexity of the topography are the major reasons behind significant underestimation of basin precipitation. The average elevation of rain gauge stations, including all the stations up to 4300 m, is about 1740 m. On the other hand, the average elevation of the whole basin is 3840 m. Average elevation of the basin in southern side of the Himalayas, covered by a better meteorological network, is about 2500 m. Only about 15 per cent of the stations represent the area between 2000 m to 3000 m which is a relatively high precipitation zone (Chapter VII).

To improve the precipitation field over the basin, we used the elevation based statistical relationships developed in the previous chapter (Chapter VII). Unfortunately, the results were still not satisfactory due to heterogeneity and disparity in the rain gauge network. We, hence, used a great deal of judgment in selecting representative stations for each sub-basin using information on location of stations and the precipitation characteristics and the knowledge of field setting. Other considerations for estimating areal average precipitation over the basin and sub-basins included: use of interpolated values for the Tibetan sub-basins with some judgment based estimates for the northern side of the Himalayas. We further assumed that the average precipitation values of high elevation stations are applicable to the entire range of southern Himalayas in the basin above 2800m.

Appendix O gives the details of selected representative sites for particular sub-basins, the computation and the adjustments of basin precipitation. Table IX-1 below presents the average annual water balance we obtained for the Kosi basin and its major sub-basins.

Table IX-1. Average annual water balance of the Kosi River and its major tributaries.

Station	*Precipitation (P) (mm)*	*Runoff (R) (mm)*	*Evaporation (E = P - R) (mm)*
600	536	358	178
602	2345	1804	541
605	689	498	191
610	1309	1063	246
620	3170	2675	494
627	3748	3265	484
629	2523	2114	409
630	1890	1498	392
640	1684	1129	555
647	1915	1572	343
652	1896	1443	453
660	2206	1781	424
670	1792	1693	99
680	1833	1179	656
690	1984	1731	280
695	1288	919	369

Due to inconsistent and unreliable values, we excluded two stations (606 and 650) in water balance computation. Examination of discharge data for these two stations showed several inconsistencies particularly during the high flow period.

Using Table IX-1 and area of the sub-basins, we can get the area-weighted annual water budget of the basin. Water balance, based on average runoff and average precipitation obtained at the catchment and sub-catchment level computations are given in Table IX-2 below. Figure IX-1 illustrates the seasonal water budget pattern of the Kosi basin and its dry north and humid south.

Table IX-2. Long-term water balance of the Kosi basin and its northern dry area and southern humid area.

	Precipitation (mm) P	*Runoff (mm) R*	*Evapotranspiration (mm) ET = P - R*
Area weighted average of sub-basins within Kosi basin	1296	935	361
Kosi basin	1288	919	369
North Himalayan dry area of the Kosi basin	536	358	178
South Himalayan humid area of the Kosi basin: area weighted average of gauged sub-catchments	1875	1333	542
South Himalayan humid area on the basis of Kosi basin	1931	1424	507

The Table IX-2, presented above, describes water balance of the basin that is based on long-term observed precipitation and actual discharge. The accuracy of the water balance primarily depends on the accuracy of these variables. Although individual discharge is measured with great accuracy (2 to 10 per cent error) in most of the cases, its overall accuracy can be much less than this percentage. Several sources of error are likely to be introduced while obtaining and processing discharge data, for example, the errors in gauge height measurement and the uncertainties in stage discharge relation. The accuracy of discharge data can be much less during flood period when measurements are difficult and less accurate. Similarly, the precipitation estimation for the basin has several sources of error in measurement and in gridding procedures.

As a simple examination of the water balance presented in table (Table IX-2), we used the values of potential evapotranspiration for an elevation of about 1700 m (average elevation of three class A pan evaporation stations) for the Kosi basin in Nepal using Penman equation based computation (Chapter VIII) and the measured pan evaporation data. In addition, we included the evapotranspiration values based on Temperature (Table VIII-7)

Table IX-3. Comparison of the estimates of average annual evapotranspiration or evaporation for a selected location in the Kosi basin using different methods.

Method	*Estimated Evapotranspiration/Evaporation (mm)*
Evapotranspiration based on water balance (Table IX-2)	507
Potential evapotranspiration based on Penman method	963
Potential evapotranspiration based on temperature data	932
Potential evapotranspiration based on Hargreaves method	1027
Average class A pan evaporation (Appendix F)	1068

The Class A pan evaporation, presented above, is the average for three locations with elevation varying from 1595 m to 1720 m. The average elevation of these three stations is 1665m. Comparison of the pan evaporation and potential evapotranspiration computed by different methods shows that PET is about 90 per cent of the class A pan evaporation. The table also shows that the net annual water loss of the basin is about 50 per cent of the annual potential if the annual PET computed for 1700 m is assumed to be applicable for the basin.

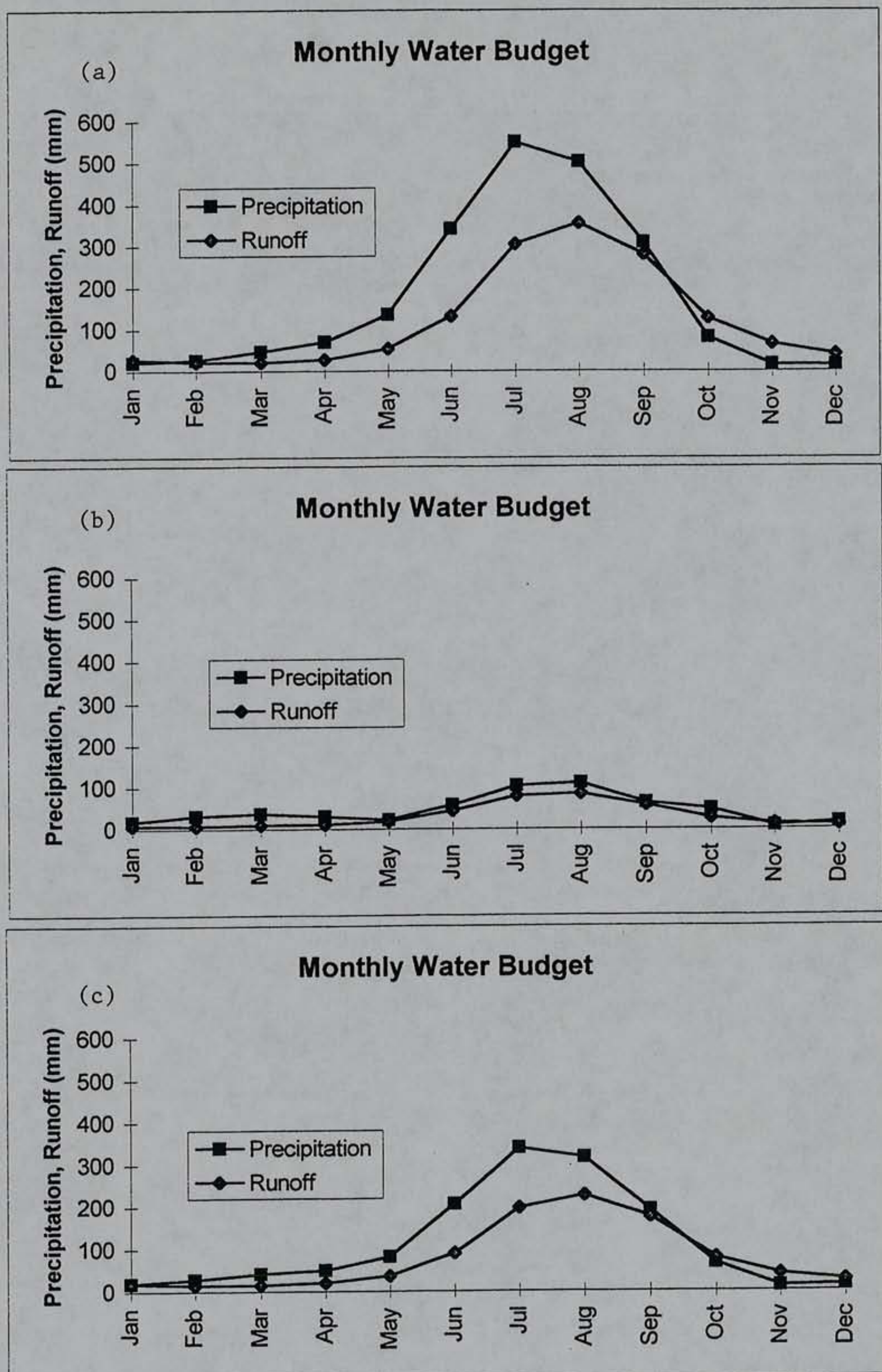


Figure IX-1. Average monthly precipitation and runoff budget for: (a) the humid south of the Kosi basin, (b) the dry north of the Kosi basin, and (c) average for the Kosi basin.

Available information is inadequate to estimate the basinwide PET. Although the high Himalayan and Tibetan highlands provide a conducive environment for evapotranspiration with high solar energy and winds, the process of evaporation over snow is more complex to make reasonable estimates. As shown by the Class A pan evaporation data from Tibetan region (Figure VIII-6), almost half of the rain-shadow area of the Kosi basin has high potential for evapotranspiration. The observed rate of evaporation at two stations in Tibet, however, may not be extrapolated to the glacial areas as the pattern of evapotranspiration is influenced by high condensation rates over snow covered areas (Lang, 1981) and low albedo. Furthermore, available technology for measurement of evaporation over snow surface is not satisfactory (WMO, 1971).

Discussion

Planning of hydrological and meteorological networks in the region, so far, is based on obtaining climatic information. Hence, the existing data base is a good source for obtaining long-term climatology and is reasonably good for studying climatic trends (Chapter VII). Since the areal extent does not cover the major hydrologically-important high elevation areas of the Himalayan basins, the information is deficient for scientific assessment of hydrological processes that occur at the basin scale. Despite detailed consideration of altitudinal variation of precipitation and despite careful judgment in selecting representative stations, the estimations of water balance at sub-catchment level of the Kosi basin show significant disparities. Even for the meteorologically homogeneous areas of the south Himalayas, the computed evapotranspiration varies from 99 mm to 656 mm. The average values presented in Table IX-2, here, are likely to be more reliable than the values obtained for individual sub-catchments (Table IX-1).

A review of the disparities in water balance computation shows that the existing precipitation gauging network underestimates the basinwide precipitation (compare Table IX-1 and Table X-2) in most of the instances. It indicates that the existing precipitation gauging network is not adequate to represent the increasing pattern of precipitation with respect to altitude. Inadequate sampling of the hydrological and meteorological variables in high elevation areas has already been discussed in Chapter IV. The pattern of underestimated precipitation is further illustrated in Chapter XI (see Table XI-2 where all the precipitation values are adjusted with weights higher than one) considering the case of a sub-basin with relatively dense network. Strengthening of the existing hydrological and meteorological network in high elevation areas is hence essential for proper quantification of the variables in water balance equation.

In the backdrop of inadequate information and in the absence of a framework for such studies, our assessment of water balance for the Kosi basin should be considered as approximate. Nevertheless, it utilizes the available spatial hydrological, meteorological, and topographical information to the highest degree currently possible. The study clearly shows the limitations of the existing hydrometeorological monitoring system in the region and provides a backdrop for further scientific studies.

CHAPTER X

HYDROLOGIC RESPONSE

As described in Chapter III, a general consensus exists regarding the issue of monsoon intensification as a result of enhanced global warming. The scale of expected increase in precipitation and evapotranspiration varies depending on models used, type of monsoon activities (strong vs. weak), and uncertainties in the level of predictions (Bhaskaran, Mitchell, Lavery & Lal, 1995; Houghton, 1991; Meehl & Washington, 1993). In this chapter, we assess potential impacts due to alternate scenarios of precipitation and evapotranspiration changes as a result of possible land-use and climatic changes in the Kosi basin.

Scenarios

Temperature Scenarios

A general review of the literature shows that three approaches are in use to predict future temperatures: paleoanalogue method based on paleoclimatic evidence of similar period (Budyko, 1991; Houghton, 1991), extrapolation of recently observed trend (Budyko, 1991), and modeling the global climate using GCMs (Houghton, 1991). During the second quarter of the 21st century, in a scenario of doubled carbon dioxide (Schimel et al., 1995), the expected rises in global temperature by these three methods are 2.5° C, 2.0° C, and 1.8° C respectively. The range of predicted changes, however, varies globally from -3.0° C to 10° C (Schneider & Norman, 1989) depending on method used and region considered.

Predicted rise of.temperature in areas close to the Kosi basin in south Asia varies from 1.0 to 4.0 degree Celsius (Bhaskaran et al. 1995; Houghton, 1991; Schneider & Norman, 1989). Uncertainties in these predicted temperatures may range from -30 per cent to +50 per cent (Houghton, 1991). Hence, possible scenarios for the case of doubled carbon dioxide may include almost nonsignificant temperature change to temperature increases by 6° C. We used four likely scenarios including 1° C, 2° C, 3° C, 4° C, and 5° C for the assessment of the impact on precipitation, evapotranspiration and runoff over the basin.

Precipitation Scenarios

As previously discussed, most global warming studies show an increase in precipitation over the south Asian region as a result of increase in land-sea temperature gradient due to enhanced global warming. Quantification of such increase is mainly a meteorological aspect for which hydrologist must rely on GCM outputs. The expected increases in precipitation over the Indian sub-continent vary from three per cent to twenty per cent (Bhaskaran et al., 1995; Houghton, 1991). Increases at the local level in the vicinity of the Kosi basin can be interpolated to be as high as 50 per cent (Bhaskaran, 1995). In view of these estimates, we considered a scenario of no precipitation change and the four scenarios of increase in annual precipitation including: 5 per cent, 10 per cent, 20 per cent, and 50 per cent.

Evapotranspiration Scenarios

Considering its practicability and better conceptuality, we selected Penman equation based method for the purpose of water balance computation of the Kosi basin. We used the elevation-based regression equations (Table VII-8) derived from the method based on Penman equation for the mountains of Nepal. Out of the fourteen stations used to derive the equations by Lambert and Chitrakar (1989) four are located in the mountainous areas of the Kosi basin.

Using elevation-based temperature and evaporation equations (Table VII-6 & Table VII-8), temperature change scenarios can directly be transformed to evapotranspiration change scenarios. For example, rise of two degrees Celsius in annual temperature is equivalent to a shift of 339 m in elevation origin of the elevation based annual evapotranspiration equations (Table VII-6). This change may increase annual potential evapotranspiration by about six per cent when we use annual evapotranspiration and evaporation equations presented in Table VII-8. This value is comparable to the GCM based estimates of Bhaskaran et al. (1995) and Meehl and Washington (1993) which are about five to nine per cent.

Land-use Change Scenarios

As described in Chapter VI, about 25 per cent of the Kosi basin is covered by forest, the rest being agriculture, grazing land and rocky areas. The forest cover is about 50 per cent if only the south Himalayan part of the basin is considered. Although the perception of rapid deforestation exists in the region, no distinct trend could be established using the available information (Chapter VI). To include major possible scenarios of land-use changes over the basin we included four hypothetical scenarios of forest cover, given as: 100 per cent, 50 per cent, 25 per cent, and complete deforestation.

Water Balance under Changed Scenarios

We used the following equation (Chapter V) along with the scenarios described earlier to assess runoff changes as a result of expected changes in climate and land-use.

$$r = \frac{p - e(1-w)}{w}, \qquad \text{(X-1)}$$

where r, p, and e are the runoff change, precipitation change, and evaporation change respectively expressed as fractional change or percentage change. The runoff ratio (w) is defined as the ratio of long-term precipitation to long-term discharge.

Changes in climate and land-use influence precipitation as well as evapotranspiration in Equation (X-1). As described in the sections dealing with the scenarios we used five different scenarios of temperature change and four different scenarios of precipitation change in four different conditions of land-use. The runoff ratio (w) for the Kosi Basin is about 0.72 (Table VIII-2). In addition, we also analyzed the water balance for runoff ratios of 0.67 and 0.82. The value of 0.67 is the runoff ratio of the Arun River basin (Station No. 600) with most of the drainage area lying in Tibetan Plateau. Runoff ratio of 0.82 is the average for rivers originating mainly in the South facing drainage of the Himalayas.

Appendix P contains the details of the computation of fractional change in evapotranspiration (e) due to changes in temperature, CO_2, and forest. Computation of evapotranspiration change is based on the measured evaporation data of the Kosi Basin. We computed the evapotranspiration changes due to CO_2 using an approximate relation given by Equation V-16. We used Calder-Newson semi-empirical model (Equation V-15) for the computation of fractional evapotranspiration change due to change in forest cover. Since the model is based on data from the United Kingdom, we evaluated the coefficients considering the local conditions of the Kosi basin.

Table X-1 illustrates the result of expected runoff changes under different climate change and land-use change scenarios in the Kosi basin. The illustration is divided into three parts: the relatively dry area of the Kosi basin in the Tibetan plateau, the Kosi basin, and the southern part of the Himalayas.

The figures show that the response of the basin is not dramatic to the changes in temperature and land-use. However, a significant impact can be expected in a climatic scenario of significant change in precipitation. A five per cent increase in precipitation can result in an increase of ten per cent runoff in a scenario of fifty per cent forest cover.

Additional remarks that can be drawn from the Table X-1 are:

- Runoff is more sensitive to change in land-use than change in temperature.
- Runoff decreases with increasing temperature.
- Drier areas are hydrologically more responsive than humid areas. The response of dry areas of the Kosi basin exceeds by one to three per cent the response of wet areas under the scenarios of no precipitation change. The difference is more than 15 per cent under the scenario of 50 per cent change in precipitation.

Table X-1. Expected change in runoff ratio in the Kosi basin in different scenarios of temperature precipitation and land-use changes. The changes in runoff ratio are computed for the wet part (w = 0.82), dry part (w=0.67), and average condition (w=0.72) of the basin.

w = 0.67 Forest = 100 %

			p		
T C	1.00	1.05	1.10	1.20	1.50
1	1.06	1.14	1.21	1.36	1.81
2	1.05	1.12	1.20	1.35	1.80
3	1.04	1.11	1.19	1.34	1.79
4	1.02	1.10	1.17	1.32	1.77
5	1.02	1.09	1.16	1.31	1.76

w = 0.72 Forest = 100 %

			p		
T C	1.00	1.05	1.10	1.20	1.50
1	1.05	1.12	1.19	1.33	1.74
2	1.04	1.11	1.18	1.32	1.73
3	1.03	1.10	1.17	1.31	1.73
4	1.02	1.09	1.16	1.30	1.71
5	1.01	1.08	1.15	1.29	1.71

w = 0.82 Forest = 100

			p		
T C	1.00	1.05	1.10	1.20	1.50
1	1.03	1.09	1.15	1.27	1.64
2	1.02	1.08	1.15	1.27	1.63
3	1.02	1.08	1.14	1.27	1.63
4	1.01	1.07	1.13	1.26	1.62
5	1.01	1.07	1.13	1.25	1.62

w = 0.67 Forest = 50 %

			p		
T C	1.00	1.05	1.10	1.20	1.50
1	1.04	1.10	1.18	1.33	1.78
2	1.02	1.09	1.17	1.32	1.77
3	1.00	1.08	1.15	1.30	1.75
4	0.99	1.06	1.14	1.29	1.74
5	0.98	1.05	1.12	1.27	1.72

w = 0.72 Forest = 50 %

			p		
T C	1.00	1.05	1.10	1.20	1.50
1	1.02	1.09	1.16	1.30	1.72
2	1.02	1.08	1.15	1.29	1.71
3	1.00	1.07	1.14	1.28	1.70
4	0.99	1.06	1.13	1.27	1.69
5	0.98	1.05	1.12	1.26	1.68

w = 0.82 Forest = 50 %

			p		
T C	1.00	1.05	1.10	1.20	1.50
1	1.01	1.07	1.13	1.25	1.62
2	1.01	1.07	1.13	1.25	1.62
3	1.00	1.06	1.12	1.25	1.61
4	1.00	1.06	1.12	1.24	1.60
5	0.99	1.05	1.11	1.23	1.60

w = 0.67 Forest = 25 %

			p		
T C	1.00	1.05	1.10	1.20	1.50
1	1.02	1.10	1.17	1.32	1.77
2	1.01	1.08	1.16	1.31	1.76
3	1.01	1.07	1.14	1.29	1.74
4	0.98	1.06	1.13	1.28	1.73
5	0.97	1.04	1.12	1.27	1.72

w = 0.72 Forest = 25 %

			p		
T C	1.00	1.05	1.10	1.20	1.50
1	1.02	1.09	1.16	1.30	1.71
2	1.01	1.08	1.15	1.29	1.70
3	1.00	1.07	1.14	1.27	1.69
4	0.98	1.05	1.12	1.26	1.68
5	0.98	1.05	1.12	1.25	1.67

w = 0.82 Forest = 25 %

			p		
T C	1.00	1.05	1.10	1.20	1.50
1	1.01	1.07	1.13	1.26	1.62
2	1.00	1.06	1.13	1.25	1.61
3	1.00	1.06	1.12	1.24	1.61
4	0.99	1.05	1.11	1.24	1.60
5	0.99	1.05	1.11	1.23	1.60

w = 0.67 Forest = 0 %

			p		
T C	1.00	1.05	1.10	1.20	1.50
1	1.02	1.09	1.17	1.32	1.77
2	1.01	1.08	1.15	1.30	1.75
3	1.00	1.07	1.14	1.29	1.74
4	0.98	1.06	1.13	1.28	1.73
5	0.97	1.04	1.12	1.26	1.71

w = 0.72 Forest = 0 %

			p		
T C	1.00	1.05	1.10	1.20	1.50
1	1.02	1.08	1.15	1.29	1.71
2	1.00	1.07	1.14	1.28	1.70
3	1.00	1.07	1.14	1.27	1.69
4	0.98	1.05	1.12	1.26	1.68
5	0.97	1.04	1.11	1.25	1.67

w = 0.82 Forest = 0 %

			p		
T C	1.00	1.05	1.10	1.20	1.50
1	1.01	1.07	1.13	1.25	1.62
2	1.00	1.06	1.12	1.25	1.61
3	1.00	1.06	1.12	1.24	1.61
4	0.99	1.05	1.11	1.24	1.60
5	0.98	1.05	1.11	1.23	1.59

p = fractional Increase in precipitation, w = runoff coefficient, and T = temperature

- Runoff ratios smaller than one (decreasing runoff) can be expected in a scenario of temperature rise exceeding four degrees Celsius with insignificant change in precipitation pattern in areas with less than 50 per cent forest cover.

Statistical Assessment

We used monthly precipitation and catchment characteristics, such as land-use and hypsometric division of the basin, to evaluate the influence of these variables and parameters on the hydrology of the basin. Influence of each parameter and variables are assessed by statistical approach evaluating their relation to runoff. Table X-2 contains the major classification of land-use distribution and hypsometric division over the Kosi basin and its tributaries. Similarly, Table X-3 provides the wetness index of the basin. Wetness index is the average monthly precipitation in the basin or the sub-basin obtained by spheremap interpolation (Wilmott, Rowe, & Philpot, 1985) on long-term average precipitation data. Instead of basin precipitation, we used the term 'wetness index' as the amount does not represent the basin precipitation as described in the last chapter showing precipitation lower than runoff in several sub-basins.

Correlation of annual and monthly runoff with catchment characteristics showed high correlation of river discharge with total basin area, area of different hypsometric classes and different land-use classes. Surprisingly, the correlation of annual and monthly discharge with precipitation was insignificant even during the monsoon months. Monsoon discharges were, however, significantly related to monsoon precipitation. Table X-4 presents the nature of the correlation of discharge with basin characteristics.

Table X-2. Land-use and hysometric data of the Kosi basin and its major gauged tributaries.

	MAJOR LAND-USES (km2)													ELEVATION ZONES (km2)								
Stn.	*IA*	*MA*	*LA*	*SG*	*CG*	*AG*	*RB*	*IS*	*L*	*S*	*HF*	*CF*	*ELV*	*LT500*	*KM1*	*KM2*	*KM3*	*KM4*	*KM5*	*KM6*	*KM9*	*Total*
600	0	0	1624	85	515	14422	3766	4637	20	20	307	50	4868	0	0	80	365	757	14395	8729	1121	25447
602	0	71	0	2	0	0	39	11	0	0	278	9	1609	11	117	167	78	28	9	0	0	409
605	28	123	1624	100	519	14462	4108	4833	20	20	1208	197	4744	16	174	475	792	1017	14662	8897	1208	27241
606	55	917	1624	114	531	14459	4146	4864	20	20	2563	220	4485	188	755	1545	1207	1061	14671	8897	1208	29532
610	0	2	0	0	4	1212	283	347	0	235	233	75	4583	0	0	105	190	223	824	969	78	2388
620	0	9	0	0	53	66	115	39	0	0	182	129	3356	0	9	101	144	124	135	71	11	594
627	0	0	0	0	0	0	8	83	0	15	8	0	4098	0	0	0	11	35	55	12	0	113
629	41	511	22	0	0	0	20	183	0	93	374	93	2156	0	186	615	211	152	142	32	0	1338
630	82	636	41	0	57	1281	419	568	0	347	1067	406	3541	0	305	1183	634	521	1100	1072	89	4904
640	0	28	12	0	0	0	0	0	0	0	28	0	1854	0	0	0	50	19	0	0	0	69
647	0	35	0	0	67	602	824	469	0	80	810	60	4141	0	11	289	432	469	663	943	142	2948
650	0	0	0	0	0	19	18	11	0	16	220	46	2815	0	0	27	195	81	23	4	0	330
652	260	1361	60	0	124	1903	1263	1049	0	578	2600	943	3304	7	687	2691	1626	1095	1786	2018	230	10141
660	0	174	0	0	53	35	94	87	0	19	450	9	2874	0	55	225	296	174	62	58	51	921
670	90	218	0	0	149	268	1017	482	0	165	1208	53	3786	0	96	482	845	572	602	670	383	3650
680	416	2388	89	0	340	2207	2378	1620	0	889	6190	1076	3192	225	1715	4860	3084	1848	2450	2746	664	17593
690	466	985	12	100	4	121	1630	318	0	39	2238	34	2854	46	572	1816	1230	652	732	602	298	5948
695	957	4466	1727	213	875	16803	8153	6835	20	948	11363	1330	3839	608	3276	8447	5528	3561	17853	12246	2170	53689

IA = Intense Agriculture (75-100 %)
MA = Medium Agriculture (50-75 %)
LA = Light agriculture (25-50 %)
SG = Subtropical/Temperate Grass Land
CG = Cold Area Grass Land
AG = Arctic Grass Land

RB = Rock and Boulders
IS = Ice and Snow
L = Lake
S = Shrub
HF = Hardwood and Mixed Forest
CF = Coniferous Forest

ELV = Average Altide of Basin (m)
LT500m = Area with Altitude < 500 m
KM1 = Area with Altitude 500m to 1km
KM2 = Area with Altitude 1 to 2 km
KM3 = Area with Altitude 2 to 3 km.

KM4 = Area with Altitude 3 to 4 km
KM5 = Area with Altitude 4 to 5 km
KM6 = Area with Altitude 5 to 6 km
KM9 = Area with Altitude 6 to 9 km

Table X-3. Wetness index obtained by gridding the point precipitation values over the basin and sub-basins

Basin	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann
Arun u/s of 600	7	10	18	24	40	86	130	123	75	28	5	4	536
Sabhaya u/s of 602	18	23	45	117	246	379	444	402	322	131	20	11	2417
Arun u/s of 605	8	12	20	30	53	107	154	145	93	35	6	5	650
Arun u/s of 606	8	12	21	33	61	118	166	155	102	39	6	5	719
Bhotekosi u/s of 610	24	38	52	59	82	198	310	285	191	83	12	18	1309
Balephi u/s of 620	26	34	55	74	135	388	648	594	367	109	17	17	2464
Melamchi u/s of 627	29	37	60	74	157	544	1025	890	489	97	13	19	3454
Indrawati u/s of 629	22	27	43	63	130	418	751	691	380	86	12	15	2662
Sunkosi u/s of 630	22	32	49	64	108	299	505	465	279	86	12	16	1922
Roshi u/s of 640	17	18	31	57	101	255	415	378	200	68	7	7	1561
Tamakosi u/s of 647	18	27	42	61	103	241	380	355	218	75	11	13	1560
Khimti u/s of 650	13	20	39	74	142	341	533	512	286	71	13	11	2069
Sunkosi u/s of 652	19	27	43	63	110	274	449	414	249	78	11	14	1752
Likhu u/s of 660	14	18	32	58	111	275	437	403	242	65	10	9	1662
Dudhkosi u/s of 670	15	18	29	44	29	240	396	370	217	71	9	9	1493
Sunkosi u/s of 680	17	22	37	57	107	264	426	386	235	74	10	12	1650
Tamor u/s of 690	17	25	54	90	150	250	350	307	220	74	16	11	1577
Saptakosi u/s of 695	12	17	30	49	87	183	277	251	160	56	9	8	1125

Data from DHM (various years).

Table X-4. Hypsometric and land-use classes of the basin having the highest correlation with discharge.

	Two best correlated hypsometric divisions		Two best correlated land-use divisions		Forest	Agricultural land	Total Area
Jan	3-4 km	2-3 km	HF	RB			
	(0.983)	(0.948)	(0.945)	(0.928)	(0.943)	(0.988)	(0.932)
Feb	3-4 km	2-3 km	RB	HF			
	(0.975)	(0.926)	(0.946)	(0.923)	(0.920)	(0.984)	(0.952)
Mar	6-9 km	3-4 km	RB	CG			
	(0.951)	(0.943)	(0.964)	(0.937)	(0.870)	(0.967)	(0.973)
Apr	6-9 km	3-4 km	RB	CG			
	(0.958)	(0.946)	(0.975)	(0.936)	(0.872)	(0.972)	(0.976)
May	3-4 km	6-9 km	RB	SG			
	(0.952)	(0.938)	(0.964)	(0.908)	(0.890)	(0.979)	(0.956)
Jun	3-4 km	2-3 km	RB	HF			
	(0.979)	(0.938)	(0.949)	(0.932)	(0.926)	(0.987)	(0.940)
Jul	3-4 km	2-3 km	HF	MA			
	(0.992)	(0.967)	(0.962)	(0.940)	(0.961)	(0.988)	(0.912)
Aug	3-4 km	2-3 km	HF	MA			
	(0.983)	(0.958)	(0.955)	(0.938)	(0.954)	(0.984)	(0.906)

Table X-4 continued

	Two best correlated hypsometric divisions		Two best correlated land-use divisions		Forest	Agricultural land	Total Area
Sep	3-4 km (0.988)	2-3 km (0.968)	HF (0.966)	MA (0.945)	(0.963)	(0.990)	(0.909)
Oct	3-4 km (0.990)	2-3 km (0.972)	HF (0.969)	MA (0.950)	(0.967)	(0.989)	(0.903)
Nov	3-4 km (0.983)	2-3 km (0.962)	HF (0.961)	MA (0.942)	(0.958)	(0.988)	(0.908)
Dec	3-4 km (0.979)	2-3 km (0.949)	HF (0.949)	MA (0.926)	(0.945)	(0.988)	(0.924)
Ann	3-4 km (0.987)	2-3 km (0.959)	HF (0.956)	MA (0.934)	(0.953)	(0.99)	(0.921)

(Values in the parentheses indicate correlation coefficient. The abbreviations are defined in Table X-2.)

Table X-4 above shows that the areas of the watershed between two to three kilometers were the most sensitive for hydrologic response. This is the dominant area that contributes to seasonal snowmelt runoff. The high correlation of rocky area to discharge further suggests that the role of groundwater contribution from rocky areas of the Himalayas was also an important determinant of runoff. Although both the agriculture areas and the forest areas were highly correlated with discharge, the correlation coefficients of agriculture areas were higher than the coefficients of forest areas of the basins.

Discussion

In the context of a sparse hydrometeorological network, the water balance based method is probably the best conceptual approach to evaluate hydrological responses to climatic and land-use changes over a basin. Due to several uncertainties in the prediction of climatic and land-use scenarios, we used the water balance based approach with several possible scenarios including some extreme cases. Since the methods used are based on relative changes instead of absolute changes, the predicted relative responses can be considered fairly reliable when the whole basin is considered as an aggregate unit.

Comparison of Table X-4 with the results of discharge trend computed in Chapter VI shows that we need to pay more attention to the assessment of the areas between two to three kilometers. The statistical assessment which shows high significance of the areas in the range of seasonal snowmelt might have been influenced by the climatic changes resulting in reduced snowmelt runoff during melt seasons.

The statistical analysis indicates that the hydrological response of the basins is less sensitive to the change in precipitation as compared to its response to the basin characteristics under the conditions tested. Since most of the basin characteristics (basin area, geology, soil etc.) are less likely to change with respect to the changes in climate and vegetation, a dramatic impact of such changes on hydrology of the basin is, hence, less likely.

The approaches used to examine hydrological response, here, are based on basic and simple principles. These methods cannot be applied to analyze the changes in different parts of basin which are found in actual situations. We deal this aspect of modeling hydrological response using a conceptual distributed hydrological model in the following chapter.

CHAPTER XI

HYDROLOGICAL MODELING

Assessment of water balance in the Kosi basin (Chapter IX) indicated several deficiencies in the supporting data base. Although estimates were made for some locations in the data deficient high Tibetan plateau of the basin for annual average values (Chapter IX), no such estimates were practicable for modeling at higher temporal and spatial resolution. We, therefore, selected the Tamor River basin, a sub-basin of the Kosi basin for the purpose to apply distributed hydrological modeling at a monthly time step. The basin, draining the third highest mountain peak in the world, lies entirely in the southern side of the Himalayan range. It is the only basin lying entirely in Nepal with long hydrological records (1948-1994).

Model Parameters

Chapter V provides a brief description of the Water Balance Model (WBM) used to model the water balance of the Tamor basin. The model consists of five major input variables and parameters including: soil texture, land cover, elevation, temperature and precipitation.

Soil Texture

No soil texture map is available for the basin at useful resolution for grid-based modeling. The available low resolution soil texture map (Food and Agriculture Organization [FAO], 1974) classifies not only the whole area of the Tamor basin but also the largest subbasin of the Kosi basin having lithosols group of soil. On the other hand, a significant variation of soil is found in the northern part as well as southern part of the Himalayan region in terms of texture, mineral content, depth and other characteristics (Ghildyal, 1981; Pandey, 1987; Shah, 1985; Wenhua, 1993).

Soil layers in the high mountain areas are relatively thin due to the influence of a rocky landscape and steep slope. Lower elevation areas are dominated by granular sandy soil mixed with gravel. Similarly, the valleys in high elevation areas consist of glacial coarse soil whereas the low elevation valleys are dominated by sandy loam and silty clay.

Since no soil texture map is available for the basin and since the soil characteristics are highly influenced by the altitudinal variations, we used the following simple soil texture classification based on elevation zones (Table XI-1) for modeling water balance using WBM.

Table XI-1. Classification of soil texture for WBM input.

Elevation Zone	*Soil Texture*	*Code for WBM*
Area above 5000 m	Lithosol	8
Area between 3000 m to 5000 m	Sandy Loam	4
Area below 3000 m	Mixed texture	7

Considering the classification of Table XI-1, major part of the basin (about 62 per cent) contains sandy loam (Figure XI-1). About 23 per cent and about 15 per cent of the areas are covered by lithosol and mixed texture respectively.

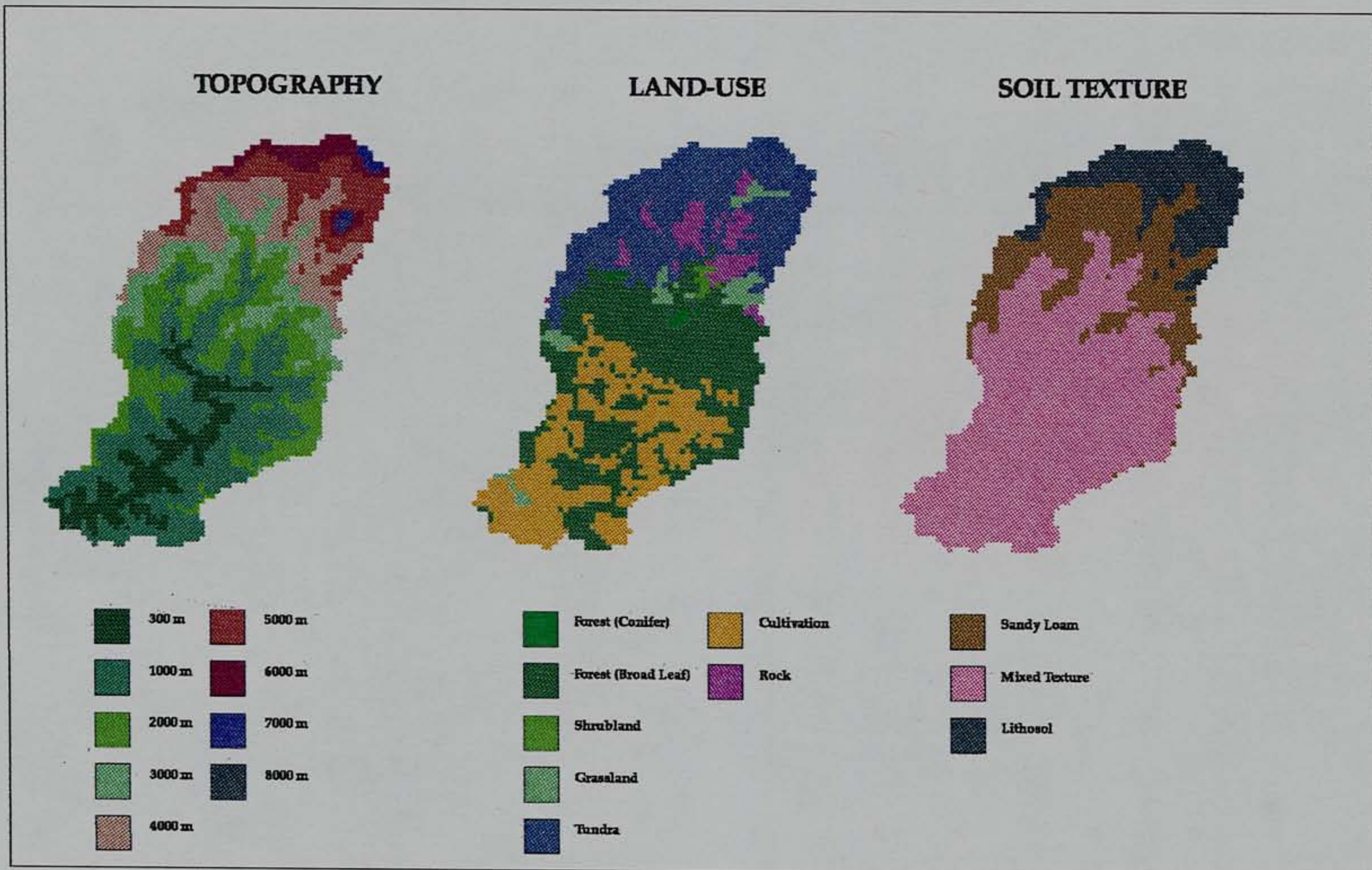


Figure XI–1. WBM input for the Tamor river basin: layers of topography, land–use, and soil texture.

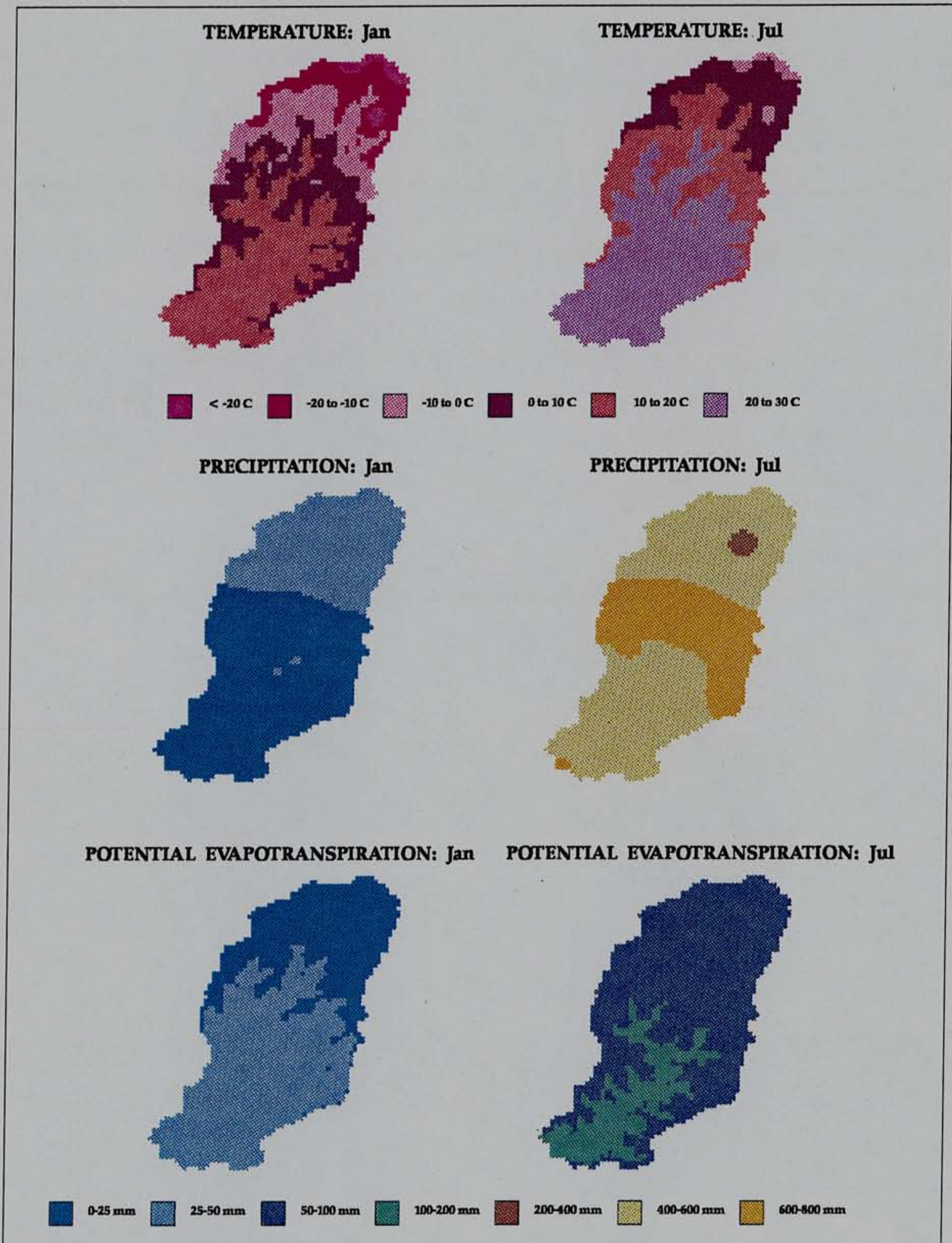


Figure XI–2. WBM input for the Tamor river basin: layers of temperature, precipitation, and potential evapotranspiration for a selected dry and a selected wet month.

Vegetative Cover

We reclassified the available detailed vegetation map (Chapter IV, Figure IV-3) of the Tamor basin into the major groups of vegetative cover used in WBM (Figure XI-2). The reclassified land-use map of the Tamor River basin for the late 1970s shows the following major land-use distribution: conifer forest (0.6 per cent), broad-leaf and mixed forest (37.4 per cent), shrub-land (0.6 per cent), grassland (3.7 per cent), tundra (27.8), cultivation (24.5 per cent) and rocks (5.4 per cent).

Since the changes in vegetation and its impact on hydrology are the major issues considered in this study, we used the following scenarios in WBM model:

a) Present land-use (38 per cent forest)

b) Conversion of all the broad leaf forest area into cultivation (0.6 per cent forest)

c) Conversion of all cultivation land into forest (62 per cent forest)

d) Conversion of all forest, shrub and grass land below 4000 m into cultivation (0.1 per cent forest)

e) Conversion of all cultivation, shrub, and grass-land below 4000 m into forest (73 per cent forest)

Temperature

Temperature layer, used as input in WBM, is the average temperature recorded at four climatological stations in the Tamor basin: 1307, 1401, 1404, and 1405 (Figure VI-1; Appendix D). We distributed the average temperature over the basin using the monthly lapse rate values (Table VI-5) and DEM 30 (DEM with 30 arc-sec resolution). Figure XI-2 includes the average temperature map obtained for the Tamor basin with these procedures for two selected months.

We used the following scenarios in WBM to assess the possible hydrological impact of enhanced global warming:

a) Present temperature

b) Modest rise in temperature (1 °C and 2 °C)

c) Expected maximum rise in temperature in a scenario of doubled carbon dioxide (4 °C and 5 °C, see Chapter IX)

Precipitation

The density of rain gauges in the basin is about 450 km^2 per station which is the highest for similar basins in Nepal. Since most of the stations are located in low elevation areas or valleys in the basin, the estimates of basin precipitation are low. We, hence, used the following weights (Table XI-2) for correcting monthly precipitation. The weights are computed using the information of elevation represented by a station, relation between precipitation and elevation (Chapter VII) and the average water balance of the Tamor basin. Average precipitation obtained for two selected months is included in Figure XI-2.

Table XI-2. Weights used for individual stations to compute basin precipitation

	Jan	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*
1307	2.2	1.8	2.0	1.3	1.3	2.2	2.2	2.9	2.7	1.3	2.2	1.8
1308	2.2	1.8	2.0	1.3	1.3	2.2	2.2	2.9	2.7	1.3	2.2	1.8
1401	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3
1402	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3
1403	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3
1404	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3
1405	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3
1406	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3
1413	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3
1414	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3
1418	1.3	1.3	1.3	1.3	1.3	1.3	2.2	2.1	2.1	1.3	1.3	1.3
1419	1.3	1.3	1.3	1.3	1.3	2.2	1.7	1.8	1.7	1.3	1.3	1.3
1420	1.3	1.3	1.3	1.3	1.3	1.6	1.8	1.7	1.6	1.3	1.3	1.3

The precipitation scenarios, we used for hydrologic response study using WBM, include:

a) Present condition

b) Five per cent rise in precipitation

c) 20 per cent rise in precipitation

d) 50 per cent rise in precipitation

Model Results

Table XI-3 below presents the average values of the water balance components based on the results of the WBM. Figure XI-3 illustrates the results for two selected months. Figure XI-4 compares the actual average basin runoff with the average basin runoff obtained by WBM.

Table XI-3. Actual runoff and water balance components of Tamor River basin computed using WBM.

	Actual Runoff (mm)	*Computed Runoff (mm)*	*Average Temperature (mm)*	*Average Precipitation (mm)*	*Average PET (mm)*	*Average Actual ET (mm)*	*Soil Moisture (mm)*
Jan	31	24	4	25	32	22	88
Feb	23	12	5	34	52	32	75
Mar	24	6	6	73	88	56	67
Apr	34	5	9	118	110	80	85
May	73	33	13	200	115	100	120
Jun	184	162	17	385	93	92	140
Jul	365	346	18	571	80	80	141
Aug	431	404	18	510	81	81	140
Sep	309	345	15	355	63	62	140
Oct	144	190	11	104	65	59	128
Nov	63	96	7	23	39	33	108
Dec	41	48	6	14	28	21	95
Ann	1722	1671	11	2412	846	718	1327

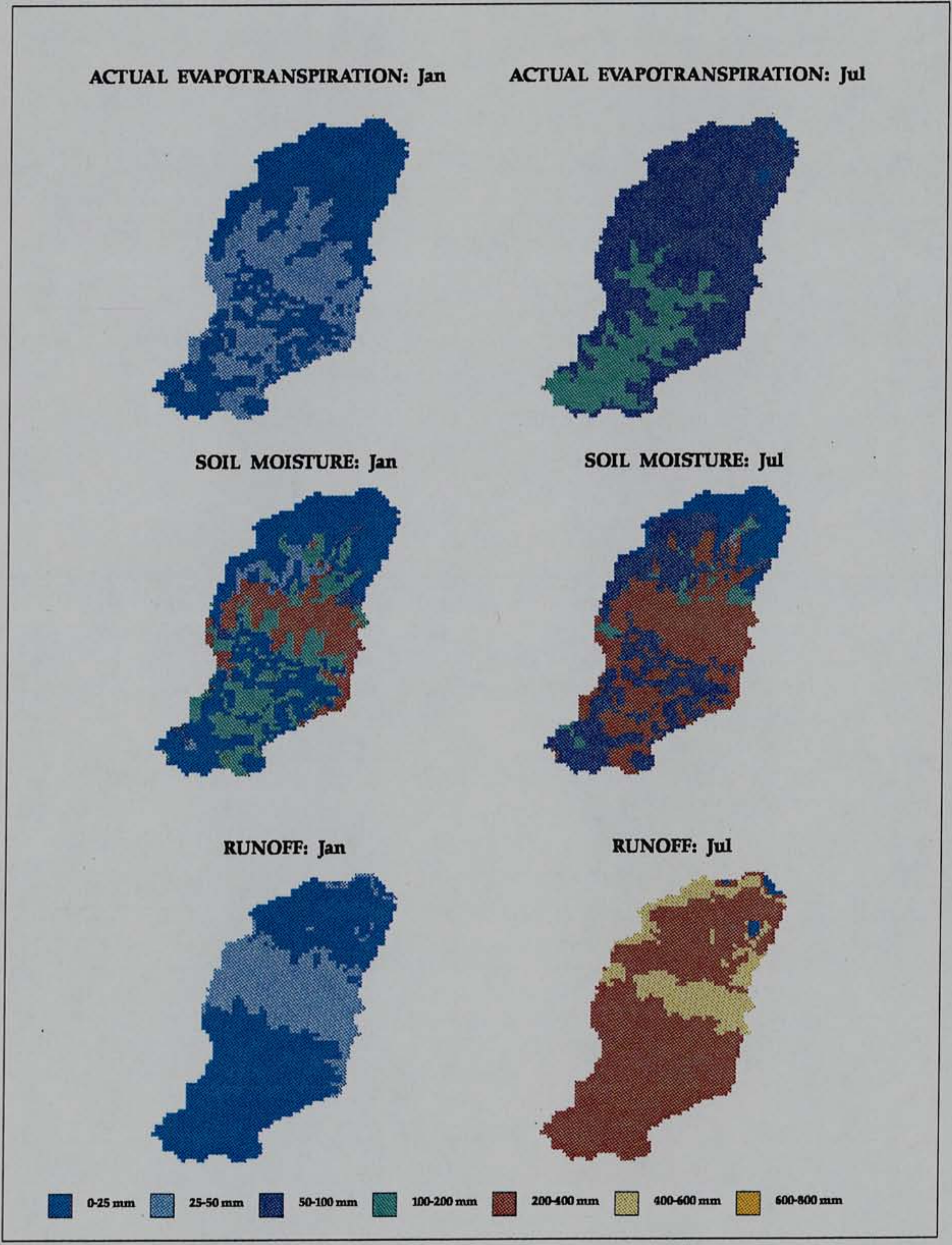


Figure XI–3. WBM output for the Tamor river basin: layers of actual evapotranspiration, soil moisture, and runoff for a selected dry and a selected wet month.

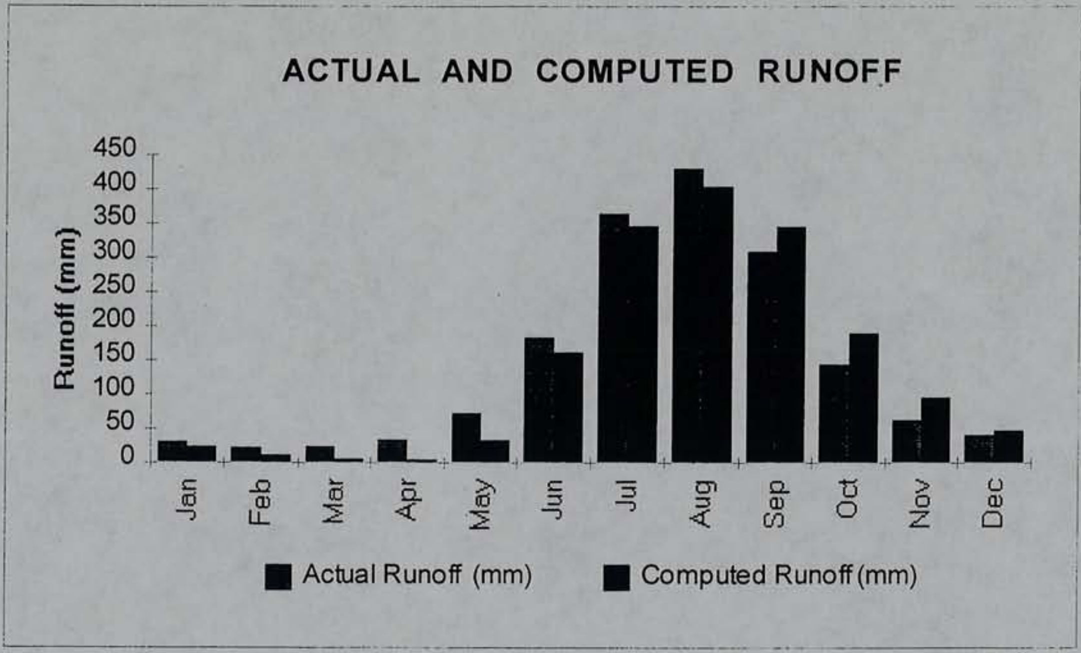


Figure XI-4. Actual average runoff and the runoff computed by WBM for the Tamor River basin.

Figure XI-4 indicates that the average basin runoff estimated by WBM compares well with the actual discharge of the river during wet periods of the year. WBM underestimates the discharge during low flow season. The average annual basin runoff computed by WBM (1671 mm) is only three per cent less than the actual average annual basin runoff (1722 mm).

Figure XI-5 illustrates the hydrologic response of the Tamor River basin for selected dry month and wet month of a year in different hypothetical scenarios of temperature, precipitation, and land-use. Land-use and precipitation pattern remaining the same, the figure shows that the annual runoff may decrease by 9.0 per cent under the scenario of rise in temperature by five degrees Celsius.

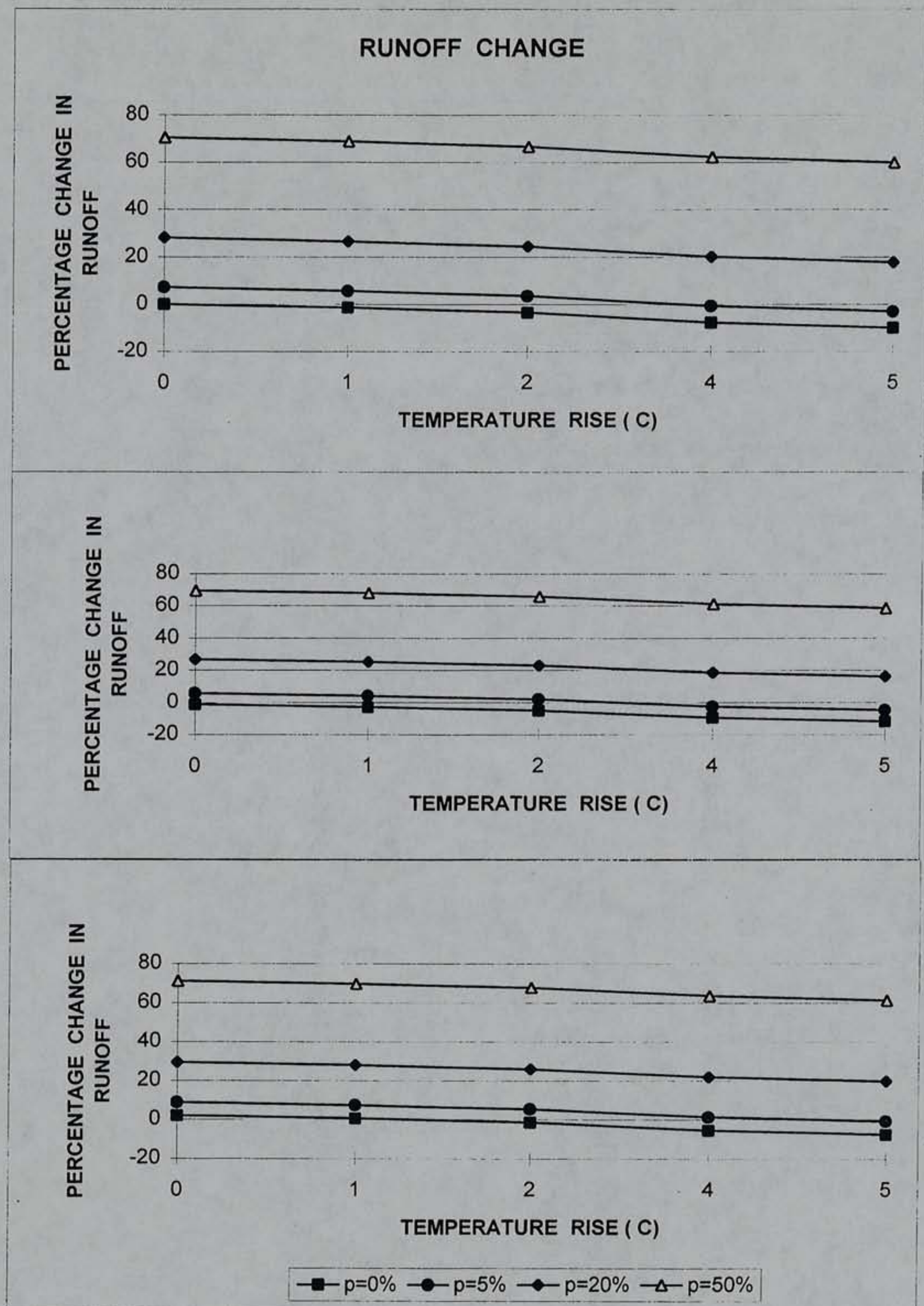


Figure X-5. Expected runoff change in the Tamor river basin in different scenarios of temperature and precipitation: (a) Existing land-use (b) Change of all lands below 4000 m into forest cover (c) Change of all lands below 4000 m into agricultural land. p indicates increase in precipitation.

Changing all agricultural land below 4000 m into forest reduces the runoff by 1.3 per cent of the original value in the model at the existing temperature and precipitation conditions. Similarly, conversion of all agricultural land below 4000 m into forest may result in a runoff decrease of about 11.8 per cent in a scenario of 5 °C rise in temperature. It is the maximum reduction obtained among selected scenarios.

Among the several scenarios of temperature, precipitation and land-use, the maximum increase in annual runoff (71 per cent) was obtained with the following combination: 50 per cent increase in precipitation, conversion of all forest into agriculture, and no change in temperature pattern. The model results also demonstrate that the forest has a significant role in influencing hydrologic response of the basin in lower precipitation scenarios.

Discussion

Results obtained for different scenarios of possible climate and land-use changes are similar to the results obtained for the Kosi basin using water balance approach (Chapter VIII). The major difference between these two approaches is the degree of response. The WBM based approach shows the higher degree of watershed response to land use and climatic changes compared to lumped water balance approach.

Lumped water balance is a simple approach that can be applied with relatively little information. Lumped water balance is probably the only approach that can be applied for the studies of data deficient area, such as the Kosi basin. This approach can also be useful for obtaining first approximate values for data-rich areas.

Application of lumped water balance approach is logical for the Kosi basin as the application of distributed deterministic models requires numerous assumptions to substitute for unavailable data. We, hence, applied the lumped approach for the Kosi basin as a whole and distributed deterministic approach to a sub-basin of the Kosi basin. Use of a plant efficiency factor to the evapotranspiration rate due to increased level of CO_2 is a favorable feature in the lumped water balance approach. WBM does not include the effect of CO_2 on plant physiology.

CHAPTER XII

IMPACT ON SEDIMENT FLUX

The Kosi River is considered as one of the most notorious rivers of the region not only for its frequent disastrous floods but also for the sediment the floods transport downstream. Primarily, because of heavy sediment deposition in downstream plain areas, the river has shifted over 115 km during the last 200 years (Gole & Chitale, 1966) destroying several thousand kilometers of land in Nepal and India (Alam, 1980). On the basis of unpublished data, Ives and Messerli (1989) rank the Kosi River among the highest sediment yielding rivers of the world.

The role of vegetative cover in controlling soil erosion has been recognized for centuries with several experiments and studies for quantifying such effects over the last several decades (Lee, 1980). Vegetative covers are likely to reduce direct impact of rainfall in washing away soil on the surface. Such covers also reduce surface water movement by facilitating water loss through interception and evapotranspiration and through induced infiltration. The vegetative component is one of the six major factors used in the Universal Soil Loss Equation, USLE (Wischmeier & Smith, 1978). Because of such relations, human activities are usually blamed for the massive sediment delivered by the Kosi basin to the Ganges plain and further downstream to the Bay of Bengal (Chapter III). One of the major solutions proposed for sediment control of the Kosi River includes upstream watershed management (WEC, 1979; Zollinger, 1979).

Among several factors, controlling the erosion and sedimentation processes in the Himalayas, topography and precipitation are the most influential. Actively uplifting steep topography and intense monsoon precipitation are the major forces controlling sediment dynamics. More than 80 per cent of annual precipitation falling during four months of summer monsoon provides conducive environment for surface mass wasting (Carson, 1985). Frequent intense convective precipitation events during premonsoon as well as summer monsoon periods cause extensive surface erosion.

The records of extreme precipitation in Nepal show that most of the stations located above 2000 m have recorded daily precipitation amount exceeding 300 mm (Department of Hydrology & Meteorology [DHM], Various Years). The records show the extreme daily precipitation amount as high as 505 mm at a location in the Kosi basin. Similarly, the topography of some of the northern parts and all the southern part of the basin is characterized by moderate to steep slopes. Analysis of DEM30 (Figure II-3) shows that more than 65 per cent of the basin areas have slope in the range of five to fifteen degrees. Although about 25 per cent of the basin areas have slope less than 5 degrees, most of the areas in this range lie in the Tibetan plateau. Such areas with mild slope in the southern Himalayas of the basin are less than two per cent. Hence, the southern part of the basin is more prone to water-induced soil erosion and sediment discharge than the areas lying in the Tibetan plateau.

How much of the sediment delivered by the Kosi River to the Ganges plain is contributed by land-use and climatic changes? Despite the effort of several researchers, no reliable estimate is available to answer this question. Estimates vary from negligible impact to as high as 40 per cent out of the total sediment delivered by the basin (Carson, 1985; WEC, 1979). Ramsay (1986) and Ives and Messerli (1989) have given a descriptive summary of several studies based on satellite imagery, reconnaissance survey, landslide observations, field studies, and plot studies in Nepal. These studies, although, show the significance of soil erosion in two basic forms: sheet or rill erosion and mass wasting, no study provides adequate information to divide the process into natural and anthropogenic. Mass transport of sediment to downstream areas by occasional Glacier Lake Outburst Floods (GLOF, WECS, 1987) and natural dam breaks (Sharma, 1988) add further complications in assessing human impact on sediment.

Sediment Information

DHM operates sediment sampling stations on two major tributaries of the Kosi basin: Sunkosi at Kampughat and Tamor at Mulghat. Although DHM follows the standard WMO procedures to compute sediment concentration using the filtration technique, our assessment indicated that the data were usable neither for time series analysis nor for modeling sediment transport. The reasons are: irregular data, poorly maintained stations, and poorly trained personnel for field and laboratory work. In summary, sediment monitoring does not have due priority. Non-existence of bed load sampling, poor sediment discharge relationships, and difficult conditions for sampling sediment during floods are additional reasons behind poor quality of sediment data.

In contrast to the standard sediment measurement and laboratory procedures of the DHM, a station on the Kosi River maintained by CWC, India, operates using more simple procedures. A full-time observer collects the sediment sample by dipping a metallic bottle type sampler at five points at a cross-section. The observer analyses the sample for size as well as weight at the sampling site using simple drying and weighing techniques. Correction factors are applied to obtain the average for the cross section (Rao, 1956). Although the procedure and instrumentation are not adequate for obtaining accurate data, timely processing and regular observations make the CWC data more informative than the DHM data.

Data collected by CWC was available only for the Kosi river from 1948 to 1977. Our analysis of sediment trends for the Kosi basin is, hence, based on the observation of a single location; for that reason the analysis lacked information on spatial characteristics of trend.

Analysis of Trend

Figure XII-1 below presents the data of total annual sediment load available for the Kosi River at Chatara from 1948 through 1977. The patterns of sediment load, although very high in some years, did not show any distinct trend.

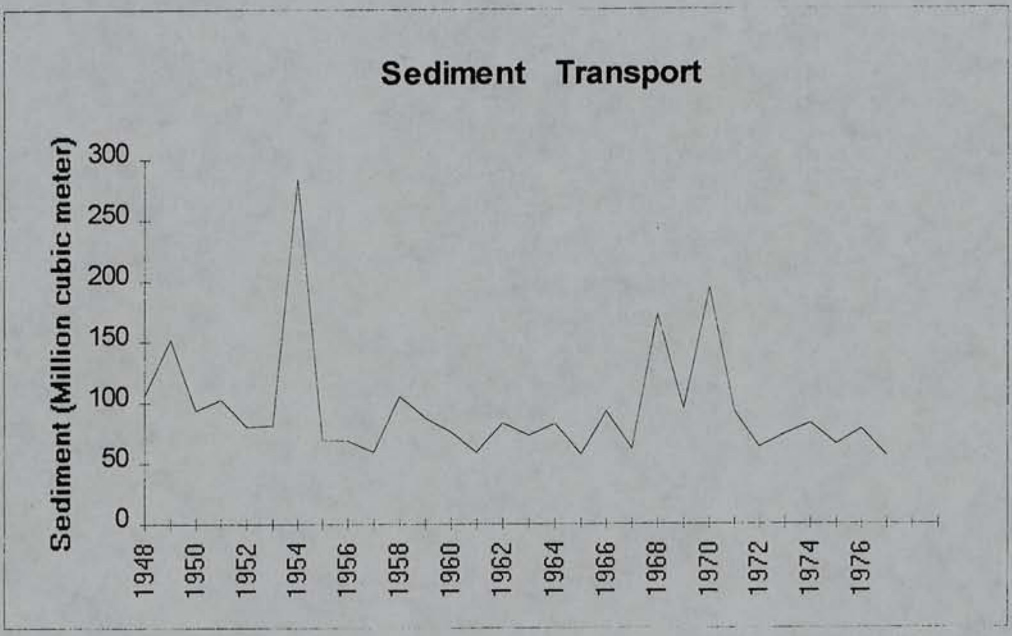


Figure XII-1. Annual sediment load measured on the Kosi River at Chatara

Data from CWC (1981)

Table XII-1 below presents the statistics of parametric and nonparametric tests applied to the time series of suspended sediment load presented in Figure XII-1. The table shows a slightly negative trend of sediment over the period of record; but the trend is insignificant in terms of parametric statistics as well as nonparametric statistics.

Table XII-1. Parametric and nonparametric trend of sediment load on the Kosi River at Chatara.

	Nonparametric			Parametric			
Sediment Load	*Z-statistics*	*Z-critical*	*p-value*	*Slope*	R^2	*F-statistics*	*p-value*
Normal Scale	-1.80	0.964	0.072	-1.18	0.05	1.4	0.25
Logarithmic Scale	-1.93	0.973	0.054	-0.005	0.07	2.0	0.17

Response to Land-use and Climatic Changes

Abundant literature is available dealing with the role of vegetation in controlling soil erosion; but most of them, including the most well known USLE (Wischmeier & Smith, 1978) and its modified forms (Onstad, 1984), are applicable only for plot or field scale. Although the USLE-type of equations have been used to model erosion in some basins (Ferro & Minacapilli, 1995), such an approach is almost meaningless in the Himalayan region where mass wasting in the form of landslides and debris flow is the significant source of sediment (Carson, 1985; WEC, 1987).

Reported sediment delivery rate of the three major tributaries: Sunkosi, Arun, and Tamor are 135 tons/ha, 45 tons/ha, and 240 tons/ha (Sharma, 1988). We assessed the landslide area using land-use data (Survey Department, 1984) for these three basins. The landslide areas are 0.09 per cent in the Sunkosi basin, 0.02 per cent in the Arun basin and 0.14 per cent in the Tamor basin. Although the computations do not include Tibetan part, and although these values are lower than the values reported in some publications (Shrestha, 1989), the figures suggest that the sediment delivery of the basins is highly related to mass wasting. Such relation can be expected to be more significant for medium sized basins. Based on three years of observation in a small catchment (110 km^2) in the middle mountain of the Kosi basin, ICIMOD (1995) reports "... between 55 and 80 per cent of the annual loss of soil occurred in two storms ... during the pre-monsoon season ...."

The Regression approach that relates sediment delivery to basin characteristics and climatic characteristics (Walling & Webb, 1983) is probably the best option available considering the type of available information and nature of processes at work in the basin. Not much information is available even for the statistical modeling of sediment at the basin level for the Kosi basin. We hence reviewed the regression equations developed by Sharma and Kansakar (1992) using most of the available suspended sediment data in the Himalayan basins of Nepal. These regressions of sediment delivery dependent on land-use, hypsometry, river characteristics, and precipitation indicate that sediment delivery is significantly related to river discharge, area of rock and meadow, area below 2000 m, monsoon precipitation, and agriculture area. Similarly, the annual sediment yield is negatively related to river length, forest area, and snow area.

The Sharma and Kansakar (1992) model relating sediment delivery to snow area, and agriculture area and monsoon precipitation can be expressed as:

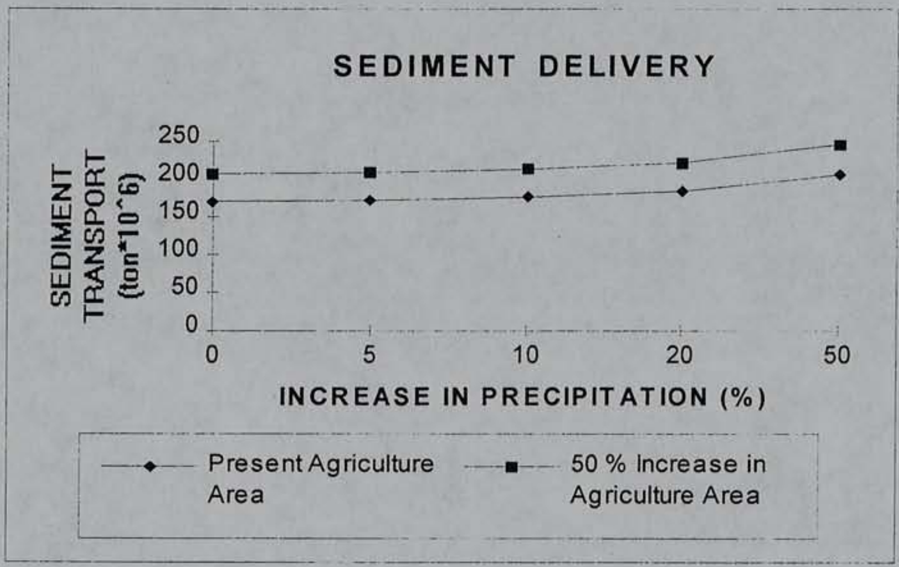
$$Sy = [-0.89 + 0.47 * \sqrt{Q} - 0.059 * \sqrt{IS}]^2 \qquad \text{(XII-1)}$$

$$Sy = [-3.91 + 0.071 * \sqrt{AA} + 0.058 * \sqrt{RB} + 0.101 \sqrt{MP}]^2 \qquad \text{(XII-2)}$$

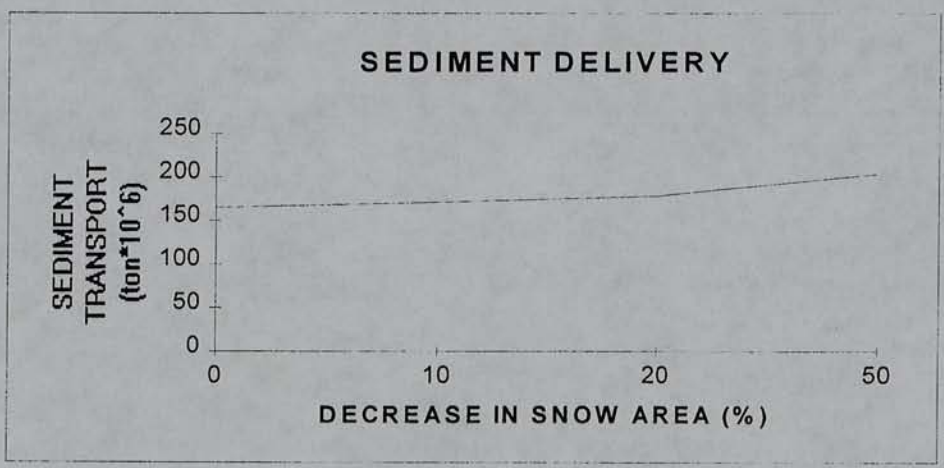
Where, Sy, Q, IS, AA, RB, and MP are sediment yield (million ton), discharge (m^3/s), ice and snow area (km^2), agriculture area (km^2), rock and boulder (includes meadow in this expression) area (km^2), and monsoon precipitation at the basin centroid (mm) respectively. Since the predictors of Equation XI-1 and Equation XI-2 differ from the available classification of land-use (Table IX-1), we used seventy-five per cent of the alpine and cool temperate grazing land as meadow. Equation XII-1 and Equation XII-2 compute a sediment load equal to 164 million tons and 170 million tons respectively under the existing condition of land-use and climate. Considering the accuracy of data and model, these figures compare reasonably well with the sediment transport figure of about 135 million tons/yr (1.4 times the reported value of 95.4 million cubic meters/yr) reported in CWC (1982).

Concerning land-use and climatic changes, the expected changes, in the variables described above, are the changes in forest area, agriculture area, snow area and precipitation. Both the changes in snow area (due to change in temperature) and changes in precipitation pattern are likely to influence the sediment delivery of the catchment. Under the different scenarios of change in snow area and monsoon precipitation, the expected changes of sediment delivery given by the Equation XII-1 and the equation XII-2, are shown in Figure XII-2.

Figure XII-2 shows that 50 per cent increase in agriculture area is likely to increase sediment transport by about 15 per cent to 20 per cent. A similar type of response can be expected if the snow-covered area decreases significantly in the predicted scenarios of enhanced global warming.



(a)



(b)

Figure XII-2. Predicted change in sediment delivery of the Kosi basin in possible scenarios of (a) change in precipitation and agriculture area and (b) change in snow area.

Since floods are the major source of sediment transport, the monsoon plays a significant role. Although the intensity of precipitation is usually more important in eroding soil and causing flash floods, seasonal totals can also be critical as they influence the volume of flood flows. Figure XII-2 indicates that an increasing seasonal precipitation amount up to 20 per cent resulted in a moderate rise in sediment load. The increase in precipitation by more than 20 per cent is likely to cause significant increase in sediment delivery rate of the basin. More than 20 per cent increase in annual sediment yield can be expected in a scenario of 50 per cent increase in annual precipitation amount; land-use remaining the same. Similar effects can be expected with the increase in cultivated area.

Discussion

Soil erosion, sediment transport, and sediment deposition are important geomorphologic processes of the Himalayan environment driven by precipitation and resulting streamflows over the watershed. Assessment of sediment movement over watersheds provides a useful indication of changes in land-use, precipitation pattern, and streamflow pattern. In addition, assessment of erosion and sedimentation has a significant economical value as the rates of soil erosion in the Himalayas and siltation over the Gangetic plain are some of the major concerns of the region (Chapter III).

Assessment of available sediment data over the Kosi basin does not indicate a significant trend of sediment discharge from 1948 to 1977. This finding indicates that the climatic changes and land-use changes of the past were insignificant to bring noticeable changes in sediment characteristics of the basin. It supports the findings of Chapter VII which shows that the basinwide trends of hydrological and meteorological characteristics are insignificant over the Kosi basin.

Since the long-term time series data on sediment are available for a single location in the Kosi basin, we can not make definitive assessment. Moreover, the data are intermittent without complete information from 1977.

Several meteorological, hydrological, geological, and land-use variables influence sediment transport. Since the sediments are carried away by rivers, river discharge can be expected to have the best relation to sediment concentration. On the other hand, the scatter diagrams of sediment concentration versus discharge for most of the rivers in Nepal are highly scattered (WEC, 1987). It exemplifies the complexities involved in erosion and sedimentation processes in the Himalayas. Conceptual modeling of the erosion and sedimentation process is, hence, likely to be speculative because of inadequate data and because of high degree of inherent complexity. Since long-term sediment data for the Kosi basin is available for only one location, spatial modeling approach is impractical. Hence, we analyzed the basin response to different land-use and climate change scenarios by extrapolating the regional sediment model of Nepal. Considering these limitations, the outcomes of this study should be considered as approximate and first order.

CHAPTER XIII

STRATEGY FOR MONITORING HIMALAYAN HYDROLOGY

Chapter VII shows that the existing hydrological and meteorological network is fairly good for assessing climate change in the lower elevation areas of the Himalayas. Long-term data for high elevation areas, which occupy a significant portion of the Himalayas, are severely lacking for proper climate change assessment. Establishment, operation, and maintenance of such networks in these areas are extremely difficult due to remoteness of the sites, high operational cost, and the lack of necessary logistic support. In addition, technological development and technical expertise needed to monitor the complex hydrological and meteorological processes under the influence of snow, ice, and glacier physics are not adequate in the region.

Existing Infrastructure

Despite the arduous task, the network initiated for the Kosi basin in the 1940s included high elevation precipitation stations. As described in Chapter IV, eight precipitation gauging stations were established 3000 m above sea level, out of which two stations were located above 4000 m. Most of these stations were closed after few years of operation limiting an important information source on Himalayan hydrology.

Excluding the few observational attempts described above, the Himalayan hydrology in Nepal did not receive serious attention from the scientific community until the 1960s. Japanese scientists developed a long-term research program called "Glaciological

Expedition in Nepal" (GEN) in collaboration with the government of Nepal in 1973 (Higuchi, 1992). Three phases of the expedition were able to produce a series of references on mass balance, heat balance, and geochemical analyses of several glaciers. The importance of the studies of the Himalayan environment was recognized by several other international scientific communities in the 1970s and 1980s as indicated by a series of symposiums and seminars on mountain hydrology of the Himalayas in the region and elsewhere in the world (Adhikary, 1993).

The central Himalayas of Nepal were considered as 'one of special interest' by the Man and Biosphere Program (MAB) of UNESCO as early as 1973 for the studies of human-environment relations (UNESCO, 1973). Despite several seminars and symposiums that followed these recommendations, the status of long-term data collection systems in the high Himalayan region has not improved as indicated by the closure of several high altitude stations. Similarly, the water balance of the Himalayan region cannot now be quantified properly due to lack of hydrological and meteorological information.

Realizing the importance of hydrological and meteorological studies of the high Himalayan region, the government of Nepal established the Snow and Glacier Hydrology Unit (GHU) under the Department of Hydrology and Meteorology in 1987. The unit, with the German Technical Assistance (GTZ), has established hydrological and meteorological stations at six locations covering different parts of the Himalayas in Nepal for regular hydrological and meteorological observations. Two of the stations established by the unit lie in the Kosi basin.

Recently, UNH has initiated a program in collaboration with DHM for scientific research of the high Himalayan areas. The program, initiated in 1993, involves scientists from DHM and UNH for carrying out research works. The hydrologists and glaciologists of both institutes are involved in studies related to hydrology, meteorology, chemistry, and other environmental and paleoenvironmental aspects of the high elevation areas in the Nepali Himalayas.

Shortcomings

The major shortcoming of the hydrological researches in the Himalayas are the unavailability of hydro-meteorological information for long-term monitoring of climate and for modeling watershed processes. For instance, the researches carried out under GEN are primarily focused on small catchments for a certain duration of a season. The 12 months record of 1985-86, recorded at an elevation of 3920 m in the Langtang Himalayas of central Nepal, is the longest continuous record obtained under GEN. All the studies carried out under GEN are based on either site-specific analyses or catchment-scale analyses with catchment size not exceeding 340 km^2.

The efforts of DHM to obtain long term hydro-meteorological data at six locations in different parts of the Himalayas above 3000 m have been partially successful for precipitation. No continuous records of discharge data are published and evaporation measurements do not exist. These data are hence insufficient for time series analysis, water balance studies, and streamflow modeling.

The hydrometeorological infrastructure developed so far in the Himalayas can be considered good for obtaining accurate data for some hydro-meteorological variables at a few locations. Except in a few instances, such as the year-long records of Langtang station recorded under GEN, the quality as well as quantity of data is poor for proper water balance studies and is inadequate for time series analyses. Although the GEN data base, developed for a small watershed in the Langtang region of the central Nepal, are reasonably good; they are still inadequate for obtaining reliable water balances. The available information can be used to partially answer the question of precipitation over the basin but not the evapotranspiration. Besides, these data are too short for time series analyses with a time frame extending beyond the length of one year. One major point is that the collection of good quality continuous hydrometeorological data for the whole year was possible due to the direct supervision of Japanese scientists for almost the whole period of data collection. Unavailability of such backing on long-term basis is one more shortcoming for the development of a Himalayan hydrology monitoring program.

Strategy

Any strategy to make a successful hydrological monitoring and investigation program should consider the constraints imposed by nature in the Himalayas. Moreover, the technology needs to be simple enough so that information can be acquired with the minimum loss of data.

We propose a strategy to start with simple water balance questions:

- How much precipitation falls over the basin?
- How much water flows out of the basin?
- How much water returns to the atmosphere by evapotranspiration?
- How much sediment do the rivers carry with them?

For obtaining an answer to these questions, we should consider the following facts:

- Regular monitoring of hydrometeorological variables is almost impossible beyond certain elevation (above 4000-5000 m).
- Monitoring of hydrometeorological variables in snow and ice conditions requires a specialized and higher level of training and may require nontraditional approaches.

Accurate answers to all these questions will require many measurements and studies. Hence the strategy should aim at reasonable answers that can be supported with the measured data directly, to minimize many adjustments required in this study. Since the monitoring of large watersheds for hydrology and meteorology requires enormous technical and economical resources, we propose a hydrological research program in a modest sized (meso-scale) watershed with the following strategies.

1. Intensive monitoring of river and sediment discharge (few stations but details and higher accuracy of data) and extensive monitoring of precipitation, evaporation, and temperature (several stations but simple methods).
2. Periodic (at least once a year) monitoring of areal extent and characteristics of snow using remote sensing techniques.
3. Periodic (every five to ten year intervals) monitoring of land-use over the whole basin using remote sensing techniques.
4. Exploitation of the best available sites for establishing primary stations.

5. Development of selected primary stations into bench-mark stations for monitoring long-term hydrology and development of model stations for experiments with hydrological variables and technologies.
6. Development of infrastructure to facilitate scientific communities of the universities and relevant organizations to carry out of experiments and researches.
7. Application of the straight forward and least sophisticated methods so that the failure of instruments and the problem of highly trained personnel can be minimized.
8. Priority to the measurement of seasonal totals of precipitation and evaporation at most of the sites with the help of a cumulative type of measurement system, such as, storage rain gauge.
9. Priority to the re-establishment of closed stations and upgrading the existing network.
10. Operation of backup (secondary) gauging sites for the primary gauging stations.
11. Real-time or almost real-time processing of observations and measurements.
12. Higher level of supervision and monitoring.
13. Extension of hydro-meteorological and land-use monitoring programs to include the monitoring of several components of environmental and biogeochemical cycle, such as, demography, socio-economy, socio-culture, biology, nitrogen cycle, carbon cycle, phosphorous cycle and so on, so that a link can be established among ecological, biogeochemical and hydrological cycles.

Since the development of Himalayan hydrology by including the whole Himalayan region is a major task that demands the cooperation of several countries sharing the

Himalayas, a better strategy (relative to the current situation) would be to isolate a suitable and representative watershed for the studies. The program should then be extended to other watersheds utilizing the experiences gained from the studied watersheds.

Appendix P contains a brief description of the Tamor River basin. We propose this river basin for initiating detailed studies of the Himalayan hydrology with the strategies described in this chapter. Tamor River system lying entirely in Nepal and bordering India and China is a suitable river basin in terms of its size, location, and representation of the Himalayan environment. The river basin drains the watershed of the mount Kanchanjangha, the third highest peak of the world. The river, presently gauged at Station 690 (Figure IV-2), has the steepest river profile among seven major tributaries of the Kosi basin (Figure II-3) and probably the highest annual sediment yield among similar basins in the world (Ives & Messerli, 1989).

DISCUSSION

High degrees of uncertainty in the process evaluation of the Himalayan environment have already caused great confusion among the concerned people and planners of the region. Our attempts at basin-scale hydrological studies in the Himalayan region have brought to light several shortcomings. There are, hence, urgent requirements to upgrade basin-scale studies in the region at higher resolution to reduce the level of existing uncertainties.

Since the scope of basin-scale studies is extensive, the best approach is to focus on few moderately sized basins with proper hydro-meteorological monitoring systems. Besides the representation of a region in the Himalayas, the moderately sized basins have a great deal of importance for vertical representation that may include the whole tropospheric depth. The other major advantages of studies in such basins are the existence of all types of climate, vegetation, and biogeochemical processes found on earth within limited areas. Untouched by the modern industrial revolution, most of the Himalayan basins and sub-basins are intact with little direct anthropogenic impacts making them ideal as bench mark against which future changes can be assessed.

CHAPTER XIV

CONCLUSIONS AND RECOMMENDATIONS

Human and livestock interactions with forest and agriculture are central to the agrarian population living in the Himalayan mountains. Such interactions have existed in the region for centuries but with little concern as the anthropogenic changes in the region remained insignificant for a long period. The population growth rate in the region changed from almost negligible to more than two percent per annum since the middle of the 20th century. Increasing population pressure on land resources and global climatic changes have added a complex dimension to the existing interactions among population, environment, and land resources.

We explored the extent of the problems in terms of environmental indicators, such as meteorological and hydrological variables. We examined hydro-climatic trends and analyzed hydrologic response of the Himalayan basin to expected land-use and climate change scenarios considering the case of the Kosi basin. The Kosi basin, lying in the central Himalayas, has a meso-scale dimension.

Assessment of anthropogenic information available for the basin showed the existence of a modest population pressure with a growth rate of about one percent per annum over the basin during the last four decades. Comparison of land-use data of the 1960s (and earlier period) with the data of the late 1970s did not reveal noticeable differences within the basin.

Analysis of the existing hydrometeorological data for the last four decades showed some evidence of increasing temperature as well as precipitation similar to that predicted under the scenarios of enhanced global warming by GCM. The computed trends, although statistically significant for some localized areas, were not significantly homogeneous over the Kosi basin.

Although spatially heterogeneous, the decreasing trends of discharge, particularly during low-flow season, shown by the mainstem river and its major tributaries need careful additional considerations. In the background of increasing precipitation and increasing temperature in some areas, such decreasing trends of discharge are likely to indicate one or more of the following factors: decreasing snow-cover areas as a result of a rise in snowline, negative annual mass balance of snow, increasing evapotranspiration losses, and decreasing winter precipitation in high elevation areas. Proper assessment of these likely phenomena needs careful assessment of the hydro-meteorology of high elevation areas of the Himalayan basins on a long-term basis.

We examined the hydrological sensitivity of the basin to the possible land-use change and climate change scenarios using several approaches: water balance, statistical correlation, and distributed deterministic modeling. Results of all the approaches indicated a strong influence of basin characteristics compared to monthly climatic characteristics. Among the climatic variables, hydrologic response was much more sensitive to the changes in precipitation; the response being more significant in the drier areas of the basin.

A scenario of temperature rise by 4 °C caused a two to eight percent decrease in runoff depending upon the model used. The percentage change in runoff was in general higher than the percentage of expected precipitation change in a scenario applying existing temperature. Based on the sensitivity of sediment transport to the precipitation and land-use, we found that the sediment yield of the basin may increase by about 20 percent in a scenario of 50 percent rise in precipitation. The predicted increase was 15 to 20 percent in a scenario of 50 percent increase in cultivated areas.

Assessment of the hydrological response of the Himalayan basin to expected climatic changes have more scientific importance than operational value as the results are based on scenarios with high degree of uncertainties and models with inadequate validation. Close monitoring of hydrological and meteorological variables in the Himalayan region with emphasis on regular data collection in the high elevation zones is the major prerequisite for evaluating and modeling climatic and anthropogenic changes over the region. Implementation of such a recommendation may need the evaluation of non-traditional methods besides traditional techniques considering the remoteness of most of the areas of the Himalayan basins.

The study presented in this dissertation shows a general picture of the Himalayan hydrology including its relation to the atmospheric and geographic environment. No attempts have been made to go into the details of specific hydrological processes as each process has its own dimension of complexity forced upon by the Himalayan diversities. We consider that the present work is an essential pioneering step for advancing and developing the knowledge of the Himalayan hydrology. We hope that this study will provide a satisfactory impetus to improve the data base system and will provide a general background for more specific studies of key hydrological variables and their interrelations.

Existing hydrometry in the region showed deficient infrastructure for basin scale scientific studies. Standard operational hydrological procedures are inadequate to understand the temporal and spatial behavior of hydrological variables. We, hence, recommend the establishment of a moderately-sized (few thousand square kilometers) benchmark basin in the Himalayas for the study of basin-scale hydrological processes. Such a basin will help to monitor climatic and land-use trends and to develop appropriate hydrological technologies for the Himalayan environment. Monitoring of sediment transport and deposition processes should also be an integral part of such an exercise with its scope to include other biogeochemical variables.

Most of the Himalayan basins are untouched by the modern industrial revolutions and attendant water resources development. Most of the high elevation areas of the basins are intact with no significant direct anthropogenic influence. These characteristics make them ideal for developing bench-mark basin to monitor global climatic and other environmental changes. Moreover, the existence of all types of geographical conditions and biogeochemical processes within a moderately sized basin makes it suitable as a hydrological laboratory to test and develop new hydrological monitoring technologies and gain insights into hydrological processes.

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APPENDICES

APPENDIX A

METEOROLOGICAL STATIONS IN THE KOSI BASIN

Stn. No.	Location	Type	Elevation (m)	Longitude (Decimal degree)	Latitude (Decimal degree)	Slope	Aspect degree	Slope/ Aspect Index
1006	Gumthang	P	2000	85.87	27.87	13	90	128
1008	Nawalpur		1592	85.62	27.80	3	195	42
1009	Chautara	T	1660	85.72	27.78	4	168	59
1016	Sarmathang		2625	85.60	27.95	12	95	126
1023	Dolalghat		710	85.72	27.63	5	295	70
1024	Dhulikhel	T	1552	85.55	27.62	1	321	21
1027	Bahrabise		1220	85.90	27.78	2	241	40
1028	Pachuwarghat		633	85.75	27.57	10	254	120
1058	Tarkeghyang		2480	85.55	28.00	23	263	167
1062	Sangachok		1327	85.72	27.70	5	179	75
1102	Charikot		1940	86.05	27.67	5	157	76
1103	Jiri	T, E, S	2003	86.23	27.63	6	173	75
1104	Melung		1536	86.05	27.52	9	131	109
1106	Ramechhap		1395	86.08	27.32	4	230	57
1107	Sindhuligadhi		1463	85.97	27.28			
1108	Bahuntilpung		1417	86.17	27.18			
1113	Thodung		3120	86.35	27.62	9	296	102
1115	Nepalthok		1098	85.82	27.45	8	121	93
1201	Namche	T	3450	85.72	27.82	15	176	139
1202	Chaurikharka		2619	86.72	27.70	17	103	158
1203	Pakarnas		1982	86.57	27.43	11	9	115
1204	Aiselukharka		2143	86.75	27.35	7	222	89
1206	Okhaldhunga	T, E, S, W	1720	86.50	27.32	6	245	88
1208	Dwarpa	T	1829	86.85	27.22	11	214	121
1210	Kuruleghat		497	86.42	27.13	6	72	64
1211	Khotang Bazar		1295	86.83	27.03	10	174	123
1213	Udaypur Gadhi	T	1175	86.52	26.93			
1217	Khumjung		3750	86.72	27.82			
1218	Tengboche	T	3857	86.77	27.83	18	315	149
1219	Salleri		2378	86.58	27.50	5	127	77
1220	Chialsa	T, S, W	2770	86.62	27.52	2	180	43
1222	Diktel		1623	86.80	27.22	3	319	53
1224	Sirwa		1662	86.38	27.55	8	280	103
1225	Syngboche		3700	86.72	27.82	3	169	43
1301	Num		1497	87.28	27.55	13	321	133
1303	Chainpur	T	1329	87.33	27.28	5	192	74
1304	Pakhribas	T, E, S, W	1680	87.28	27.05	11	186	123
1305	Leguwaghat		410	87.28	27.13	9	305	102
1306	Munga		1317	87.23	27.03	12	198	122
1307	Dhankuta	T, S, W	1445	87.35	26.98	6	110	78
1308	Mulghat		365	87.33	26.93	11	341	116
1309	Tribeni		143	87.15	26.93	6	56	65
1310	Barahakshetra	T	146	87.17	26.87			

Appendix A Continue

Stn. No.	Location	Type	Elevation (m)	Longitude DD	Latitude DD	Slope	Aspect Degree	Slope/ Aspect Index
1314	Terhathum	T	1633	87.55	27.13	13	62	129
1315	Kharelalantar	T	541	87.25	27.25	9	189	106
1316	Chatara		183	87.17	26.82			
1317	Chepuwa		2590	87.42	27.77	18	166	155
1318	Paripatle (Horti.)	T	1364	87.30	27.02	13	273	135
1322	Machuwaghat		158	87.17	26.97	5	211	73
1324	Bhojpur	T, E, S, W	1595	87.05	27.18	8	215	105
1325	Dingla		1190	87.15	27.37	12	31	114
1401	Olangchunggola	T	3119	87.78	27.68	26	65	177
1402	Pangthumdoma		2818	87.82	27.68	12	212	121
1403	Lungthung		1780	87.78	27.55	15	79	144
1404	Taplethok		1383	87.78	27.48	14	358	131
1405	Taplejung	T, S	1732	87.67	27.35	15	213	137
1406	Memengjagat		1830	87.93	27.20	7	219	89
1413	Kamachin		4242	87.98	27.73	6	142	76
1414	Nup		4000	87.87	27.72	2	150	28
1418	Angbung		1219	87.72	27.27	8	338	100
1419	Phidim	T	1205	87.78	27.13	18	352	148
1420	Dovan		763	87.60	27.35	14	43	129
2001	Tingri	T, E	4300	87.13	28.72	11	162	124
2002	Nyalam	T, E	3750	85.92	28.18	6	219	0
2003	Gyangtse *	T	4040	89.60	28.92			
2004	Phari Dzong *	T	4300	89.08	27.73			
2005	Xigaze *	T	3836	88.88	29.25			
2006	Yadong *	T	4300	88.89	27.45			

Note: T = Temperature
E = Class A pan evaporation
S = Sunshine duration
W = Wind

All stations record 24-hour precipitation.

* Stations are outside the Kosi basin in Tibet. We used the data for these stations only to interpolate average precipitation over the Tibetan part of the basin.

APPENDIX B

HYDROMETRIC STATIONS IN THE KOSI BASIN

Stn. No.	Name of river	Name of site	Longitude (Decimal degree)	Latitude (Decimal degree)	Stn. Elv. (m)	Ave. Elv. (m)	Area (km2)	Length (km)	Stream Order Strahler	Stream Order Schreve
600	Arun	Uwagaon	87.33	27.60	1294	4868	25447	371	5	95
602	Sabhayakhola	Tumlingtar	87.20	27.31	450	1609	409	35	1	1
605	Arun	Turkeghat	87.19	27.32	414	4744	27241	419	5	101
606	Arun	Simle	87.15	26.93	180	4485	29532	473	5	110
610	Bhotekosi	Barabise	85.89	27.79	840	4583	2388	108	3	8
620	Balephikhola	Jalbire	85.77	27.80	793	3356	594	53	2	2
627	Melamchikhola	Helambu	85.53	28.02	1820	4098	113	18	1	1
629	Indrawati	Dolalghat	85.71	27.63	750	2156	1338	46	2	6
630	Sunkosi	Pachuwarghat	85.75	27.55	589	3541	4904	146	3	17
640	Rosikhola	Panauti	85.51	27.58	1480	1854	69	13	1	1
647	Tamakosi	Busti	86.09	27.62	849	4141	2948	99	3	11
650	Khimtikhola	Rasnalu	86.21	27.58	1520	2815	330	35	1	1
652	Sunkosi	Khurkot	86.01	27.32	455	3304	10141	189	4	35
660	Likhukhola	Sangutar	86.22	27.34	543	2874	921	67	2	2
670	Dudhkosi	Rabuwa	86.65	27.26	460	3786	3650	112	3	12
680	Sunkosi	Kampughat	86.82	26.88	200	3192	17593	302	4	55
690	Tamor	Mulghat	87.32	26.93	276	2854	5948	166	3	21
695	Saptakosi	Chatara	87.17	26.89	140	3839	53689	477	5	187

Note: Some of the latitude and longitude records obtained from DHM data base are edited to bring the location on simulated river channel. Average elevation data are based on DEM30. DEM30 is also the source of the computed drainage area.

APPENDIX C

AVERAGE MONTHLY AND ANNUAL PRECIPITATION (mm)

Stn.	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann
1006	22	33	64	95	190	588	959	883	563	156	23	13	3498
1008	15	22	33	62	120	393	649	663	349	86	11	13	2410
1009	13	20	33	56	116	303	531	557	312	64	10	12	2055
1016	26	34	45	69	154	594	1074	992	543	110	21	12	3760
1023	11	13	29	48	80	180	286	268	141	43	7	9	1130
1024	18	19	32	58	101	253	410	374	196	68	8	8	1533
1027	13	25	55	104	179	467	779	737	396	86	11	17	2868
1028	10	12	24	43	89	151	234	191	144	47	5	15	971
1058	33	42	72	80	166	549	1060	877	484	92	10	26	3491
1062	11	14	25	61	134	195	364	366	239	63	9	16	1514
1102	15	24	41	69	147	316	535	526	303	86	14	12	2098
1103	16	22	44	83	153	373	589	576	301	74	15	13	2196
1104	15	18	35	73	145	303	424	415	217	59	8	11	1737
1106	18	14	24	47	75	150	257	203	111	39	8	7	969
1107	27	17	43	96	199	447	686	581	428	151	17	11	2722
1108	17	17	36	73	188	342	520	383	307	103	12	14	2017
1115	14	12	28	46	76	137	255	181	142	63	5	14	1005
1201	33	20	32	27	44	138	226	220	151	69	13	18	1042
1202	15	23	40	54	105	313	591	563	326	76	13	11	2127
1203	16	15	32	44	87	258	478	464	262	71	7	7	1741
1204	19	12	29	76	193	439	598	527	319	114	16	12	2352
1206	16	15	29	60	141	318	447	399	235	74	11	9	1776
1208	11	7	41	75	135	338	336	323	200	96	14	6	1577
1210	13	11	25	45	71	141	259	189	132	40	5	7	939
1211	13	13	26	39	103	200	318	197	160	46	6	7	1133
1213	17	15	25	53	157	330	512	421	349	124	15	9	2042
1217	18	24	28	29	39	131	196	190	109	44	6	11	841
1218	16	24	30	27	28	141	265	259	127	65	7	2	1034
1219	15	16	30	50	88	245	470	437	255	61	7	9	1636
1220	10	13	29	50	95	287	522	487	278	83	11	8	1888
1222	10	16	24	59	146	271	370	305	230	66	6	13	1505
1224	11	17	32	63	125	299	448	410	265	65	10	9	1734
1225	21	22	24	25	30	129	236	220	141	68	7	17	971
1301	32	46	84	187	379	634	668	570	462	217	40	22	3345
1303	11	12	29	80	180	207	310	274	198	63	15	6	1372
1304	11	15	27	54	137	248	426	334	216	63	11	18	1559
1305	6	7	21	66	133	131	191	168	111	42	8	3	875
1306	14	10	29	49	102	211	315	251	170	61	6	7	1220
1307	9	14	27	48	83	179	253	163	107	55	5	7	940
1308	9	11	21	44	104	171	285	180	133	47	8	6	1035
1309	16	14	20	51	125	287	490	365	286	84	7	4	1754
1310	19	14	33	57	123	441	678	606	438	149	7	1	2540

Appendix C continued

Stn.	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann
1316	17	16	23	56	144	373	573	467	342	134	13	7	2166
1317	45	74	129	153	244	417	496	439	361	152	40	21	2588
1318	14	10	28	56	106	210	311	119	133	64	6	8	1054
1322	12	13	22	49	116	258	378	260	184	66	8	3	1375
1324	22	10	32	66	146	232	294	220	173	77	16	9	1299
1325	14	15	33	74	179	291	406	418	346	106	10	9	1912
1401	28	47	94	54	109	247	353	364	249	89	19	8	1713
1402	24	33	73	78	95	230	404	303	178	80	27	14	1541
1403	19	31	66	94	132	367	521	493	357	104	19	10	2205
1404	16	27	66	113	200	408	596	572	392	125	26	10	2551
1405	19	23	56	125	232	315	426	403	301	83	14	10	2002
1406	15	21	50	124	219	328	483	394	286	104	16	10	2042
1413	29	44	54	89	101	192	222	263	207	92	30	30	1168
1414	15	40	86	53	83	174	203	173	97	24	20	6	1015
1418	21	12	47	124	234	276	258	233	158	60	16	2	1394
1419	14	19	38	81	152	167	347	261	200	45	8	13	1355
1420	11	16	45	116	205	260	344	301	226	51	11	10	1580
2001	32	55	63	49	30	66	90	86	85	80	12	26	674
2002	0	0	0	3	8	36	93	111	28	4	0	1	284
2003	0	0	2	2	14	49	84	92	44	5	1	0	293
2004	4	5	19	24	25	47	102	100	51	29	3	1	410
2005	0	0	1	2	15	70	131	146	59	6	1	0	431
2006	12	46	46	86	88	129	150	146	99	45	9	8	864

APPENDIX D

AVERAGE MONTHLY AND ANNUAL TEMPERATURE (^{O}C)

Stn.	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann
1009	11.8	14.1	17.2	20.8	22.6	21.6	22.5	22.2	21.8	19.7	15.9	13.4	18.6
1036	13.4	17.1	18.1	22.3	25.1	26.8	27.0	26.9	25.8	22.3	17.8	13.8	21.4
1103	6.2	7.9	11.4	14.7	16.7	19.4	19.9	19.9	18.5	15.2	10.6	7.3	14.0
1201	0.0	0.7	3.9	8.1	10.2	14.3	13.5	12.0	10.7	7.1	2.7	1.2	7.0
1206	9.5	11.1	15.0	18.2	19.3	20.5	20.3	20.4	19.4	17.5	14.1	11.1	16.4
1209	10.2	12.2	16.1	19.2	19.9	20.8	21.1	21.2	20.3	18.4	14.8	11.8	17.2
1218	-2.9	-2.2	0.8	4.2	6.6	8.9	9.4	8.9	7.3	5.5	1.0	-0.9	3.9
1220	2.7	3.9	7.8	10.7	12.4	14.7	15.3	15.2	14.0	10.8	6.8	3.8	9.8
1225	-3.5	-2.3	0.7	4.0	6.3	8.5	9.5	9.1	7.3	4.6	1.3	-1.5	3.7
1303	13.3	15.1	19.1	21.9	22.8	24.0	23.9	24.0	23.0	21.0	17.8	14.6	20.0
1304	9.6	11.1	15.1	18.3	19.1	20.4	20.3	20.6	19.5	17.3	14.2	11.0	16.4
1307	18.1	18.6	19.1	19.4	19.3	19.1	18.7	18.1	17.3	16.4	15.6	15.4	17.9
1310	17.0	19.4	23.9	27.9	28.6	28.0	27.5	27.5	27.0	25.3	21.7	18.3	24.3
1318	10.9	12.7	16.9	19.6	20.7	21.9	22.0	22.3	21.3	18.9	15.5	12.5	17.9
1324	9.8	11.2	14.4	18.2	19.2	20.5	20.8	15.5	20.0	17.9	14.1	10.5	16.0
1401	0.5	0.8	3.5	6.7	8.0	10.7	11.6	11.4	10.4	7.2	4.6	3.3	6.6
1404	12.2	13.9	17.4	20.1	21.3	22.7	22.7	22.4	21.7	19.9	16.4	13.5	18.7
1405	8.9	10.4	14.1	17.2	18.2	20.7	21.0	20.9	19.9	17.0	13.2	10.2	16.0
2001	-8.5	-4.7	-2.8	2.4	6.6	11.4	12.0	12.1	9.1	3.2	-3.2	-7.3	2.5
2002	-5.7	-2.0	-1.4	2.6	5.8	9.5	10.9	10.7	8.4	3.7	-0.9	-2.8	3.2

APPENDIX E

AVERAGE MONTHLY AND ANNUAL DISCHARGE (m^3/s)

Stn.	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann
600	72.3	73.8	88.3	108	162	418	740	800	562	246	119	82.3	289
602	6.02	5.12	4.76	7	15.9	30.8	54.7	55.8	49.6	25.3	12.5	8.04	23
605	111	111	128	162	248	608	1080	1140	867	393	192	136	431
606	162	151	184	208	294	609	1540	2040	1360	576	305	223	638
610	23.2	20.4	19.3	23.9	34.8	85.4	189	261	162	77.4	41.5	27.9	80
620	12.4	10.7	10.1	11.4	15.3	47.2	130	161	116	49.8	24.2	16.5	50
627	3.16	2.76	2.96	2.73	3.93	8.18	31.1	36.3	26.9	12.7	6.06	4.1	12
629	20.4	17.2	15.3	17	24.7	88.2	243	277	215	87.8	43.2	27	90
630	58.6	49.3	47	48.6	71.8	216	607	771	509	226	119	77.2	233
640	1.29	1.1	0.98	0.88	0.94	1.81	4.64	6.04	4.93	3.4	2.03	1.58	2
647	30.5	25.5	24.2	29.6	52.5	167	431	465	309	129	62	40.2	147
650	5.9	5.1	4.5	5	7.7	27.6	67.9	69.4	45.9	21.2	11.1	7.3	23
652	110	92	84.5	93.7	141	438	1230	1580	964	469	226	144	464
660	14.4	11.9	10.9	12.6	16.9	48.3	135	158	114	55.4	28	18.7	52
670	45.6	38.1	36.7	42.8	69.3	234	551	586	412	194	90.1	57.9	196
680	158	136	124	135	192	623	1790	2040	1510	676	306	201	658
690	68.6	55.8	53.3	77.6	163	423	810	957	708	320	145	90.5	323
695	362	304	307	392	719	1800	3950	4540	3510	1590	812	499	1565

Note: DHM station numbers 600.1, 604.5, and 627.5 are reported and used as 600, 605, and 627 respectively in this study for simplicity in processing Station Id.

APPENDIX F

AVERAGE MONTHLY AND ANNUAL CLASS A PAN EVAPORATION RATE (mm/day)

Stn.	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann
1206	1.8	2.8	4.9	5.9	4.8	3.8	3.5	3.3	2.8	2.7	2.3	1.9	3.4
1304	2.0	2.5	4.4	4.6	4.4	3.4	2.6	2.6	2.4	2.8	2.5	2.0	3.0
1324	2.2	2.8	4.6	5.0	2.6	1.6	0.9	1.3	1.2	1.9	2.5	2.3	2.4
2001	3.9	5.4	6.8	8.5	10.2	10.4	7.9	6.4	6.5	6.0	4.6	3.8	6.7
2002	2.9	3.0	3.6	4.5	5.6	5.6	5.3	5.0	4.0	3.7	3.4	3.3	4.2

APPENDIX G

AVERAGE MONTHLY AND ANNUAL SUNSHINE DURATION (hr/day)

Stn.	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann
1036	6.6	7.4	8.7	7.8	5.7	4.4	4.4	6.6	5.5	7.9	8.7	7.7	6.8
1103	6.6	6.9	7.3	7.1	6.4	4.0	2.6	3.4	3.8	5.9	6.7	6.5	5.6
1206	7.1	7.4	8.3	8.3	7.1	4.7	3.2	4.2	4.1	6.7	7.6	7.4	6.3
1304	6.1	6.3	7.2	6.9	6.3	3.0	1.9	2.4	2.9	5.2	6.0	5.9	5.0
1307	7.6	7.8	8.1	8.2	7.1	5.0	3.1	4.4	4.9	7.8	8.1	7.8	6.7
1324	7.2	6.8	7.0	7.3	6.5	5.1	2.9	5.0	4.6	7.1	8.2	7.7	6.3
1405	6.3	7.0	6.9	6.8	6.6	5.4	3.4	5.9	4.8	7.3	7.0	6.2	6.1

APPENDIX H

AVERAGE MONTHLY AND ANNUAL WIND SPEED (km/hr)

Stn.	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann
1206	7.0	10.1	12.8	14.8	11.9	9.5	8.0	7.4	7.7	6.6	6.2	5.9	8.9
1304	6.7	6.6	7.8	8.1	7.6	6.4	5.6	5.7	4.0	6.1	6.7	6.5	6.6
1307	7.8	8.7	8.6	8.6	8.2	8.2	7.6	7.7	7.5	7.3	7.4	7.4	7.9
1324	3.0	3.3	4.2	3.9	3.1	2.6	2.0	2.1	2.1	2.4	2.8	2.8	2.9

APPENDIX I

ANNUAL PRECIPITATION (mm) FOR SELECTED STATIONS

Year	1303	1316	1403	1006	1008	1023	1102	1104	1115	1202	1203	1204	1206	1211	1301	1303	1306	1307	1308	1309	1316	1325	1403	1404
1948	1360	1939	2665																					
1949	2759	2286	2763																					
1950	1472	2118	2138																					
1951	925	2731	2222																					
1952	1877	2068	2196																					
1953	1315	1834	2365																					
1954	919	2645	2278																					
1955	1294	1878	2352																					
1956	1062	2458	2299																					
1957	808	2164	2086																					
1958	1059	1851	2174																					
1959	1205	1969	1379																					
1960	1167	2260	1200	2880	2221	587	2137	1926	2520	4475	1739	2358	2117	1358	6348	1167	1262	528	816	1987	1970	1479	1200	2697
1961	1241	1970	2320	2228	2308	798	2534	1512	1515	2227	1930	2404	1951	1029	4015	1241	1145	988	850	1657	2232	1776	2320	2482
1962	1311	2232	2056	3449	2720	1192	2271	1768	945	2282	1840	2305	1067	1225	2740	1311	1773	919	1251	1972	2179	1837	2056	2568
1963	1219	2179	2664	3347	2257	924	2368	1753	736	2322	1742	3865	2132	1125	1226	1219	1223	931	1011	2335	2446	1708	2664	2626
1964	1494	2446	1865	3640	2638	875	2758	1564	727	2049	1545	1681	1695	872	3178	1494	1178	886	1502	1911	2061	1820	1865	2210
1965	1441	2061	2229	3224	2115	945	1991	1551	879	1734	1431	2418	1894	1148	3849	1441	1138	684	1006	1684	2937	1892	2229	2431
1966	1473	2937	2122	3626	1947	799	1911	1602	739	1859	1689	2777	1729	1186	4245	1473	1443	1074	1081	2098	2060	1473	2122	2385
1967	1173	2060	2036	3337	2390	838	1770	1744	659	1687	1549	1572	1612	862	3661	1173	1127	782	1132	1540	2536	1329	2036	2088
1968	1614	2536	2774	3692	2477	1432	2352	2035	830	2218	2041	3161	2059	1544	4350	1614	1511	980	1014	2078	1388	1958	2774	3016
1969	1355	1388	2046	3295	2013	785	1729	1792	704	1737	1647	2760	2014	766	1885	1355	1110	622	633	1740	1943	1117	2046	2583
1970	1142	1943	3221	3592	2245	1698	2044	2766	1420	1935	1994	3363	2015	1150	1447	1142	1186	802	931	1627	2472	1806	3221	2443
1971	1878	2472	2372	3537	2942	1481	2296	2618	1204	2935	1925	2217	2232	1381	2786	1878	1165	1053	1071	2076	2179	1913	2372	2690
1972	1266	2179	2685	3169	1953	1329	1977	1656	969	2105	1277	1374	1310	1029	2622	1266	1061	639	976	1765	2547	1614	2685	2721
1973	1609	2547	2408	3490	2585	1701	2554	2067	1062	1987	2144	2478	2039	1246	3657	1609	1363	1121	1186	1793	2391	2081	2408	2520
1974	1349	2391	2222	3688	2426	1147	1953	1339	1295	2034	1703	2406	1580	1182	5273	1349	1404	1223	1401	1797	2759	2544	2222	3050
1975	1354	2759	2097	3108	2683	1377	2087	1520	893	2118	1804	2171	1676	1249	4430	1354	1582	1298	1365	2388	2778	2012	2097	2616
1976	1220	2778	2322	3971	2857	1276	2107	1454	734	2100	1651	2152	1942	884	4596	1220	1188	926	1117	1862	2149	1619	2322	2626
1977	949	2149	2478	3981	2395	1244	1897	1229	396	2189	1527	1466	1468	820	5366	949	815	805	747	1146	1787	1753	2478	2766
1978	1474	1787	2466	4543	3028	1660	2635	1605	958	1769	2037	2145	2241	1242	4250	1474	1570	994	1067	1797	2228	1903	2466	2704
1979	1343	2228	2257	3297	2112	1001	1804	1275	826	1819	1755	2450	1715	1274	5812	1343	1115	1087	1151	1782	1432	2218	2257	2315
1980	1759	1432	2448	3853	2359	949	2363	1723	648	2621	1589	2463	1178	950	4918	1759	1177	856	1042	1409	2151	1795	2448	2854
1981	1442	2151	2320	2977	2379	1210	1991	1631	1018	2193	1692	1794	1364	1124	3668	1442	1136	920	1001	1795	1633	2008	2320	2625
1982	952	1633	1987	3353	2215	1005	1826	1662	665	1795	1418	1454	1401	897	2902	952	1046	731	708	1080	2157	1723	1987	2244
1983	1601	2157	1786	4569	2238	1296	1776	1703	868	1871	1718	2276	1771	1239	3070	1601	878	962	1251	2004	2719	1995	1786	2565
1984	1432	2719	1751	4621	2355	1150	2025	2089	1246	1855	1863	2434	1855	1716	3208	1432	1263	1201	1605	2360	1773	1935	1751	2216
1985	1792	1773	1985	4375	3183	1523	2716	2023	1321	2367	2132	2797	2086	1157	4574	1792	1075	864	888	1594	1760	2116	1985	3297
1986	1513	1760	1419	3939	2444	1184	1767	1582	933	1541	1649	2189	1724	1121	3851	1513	1182	963	949	1387	2198	1616	1419	2685
1987	1727	2198	2110	4473	2320	1177	2165	2078	1303	1873	1403	2401	1589	1394	3878	1727	1329	1510	1658	1966	1879	2227	2110	2740
1988	1466	1879	2078	4421	2785	1025	1795	1626	896	2317	1796	2199	1733	1461	3685	1466	1192	1101	1343	1789	2218	2564	2078	2716
1989	1466	2218	2699	2975	2276	898	1752	1413	687	2054	1999	2603	2047	982	3396	1466	1268	1230	1214	1622	2142	2508	2699	2974
1990	1916	2142	2252	3609	2524	1165	1697	1866	1038	2542	1747	2335	1805	1044	5060	1916	1232	1155	1048	1623	2409	2011	2252	2578
1991	1158	2409	2671	2548	2073	1048	1754	1524	470	2540	1639	2141	1718	1166	5509	1158	1058	1043	855	2063	1862	2240	2671	3030
1992	1079	1862	1950	3185	2051	1084	1563	1632	510	1778	1517	2124	1488	887	4609	1079	935	817	918	1042	2042	1370	1950	2643
1993	1188	2042	1922																					

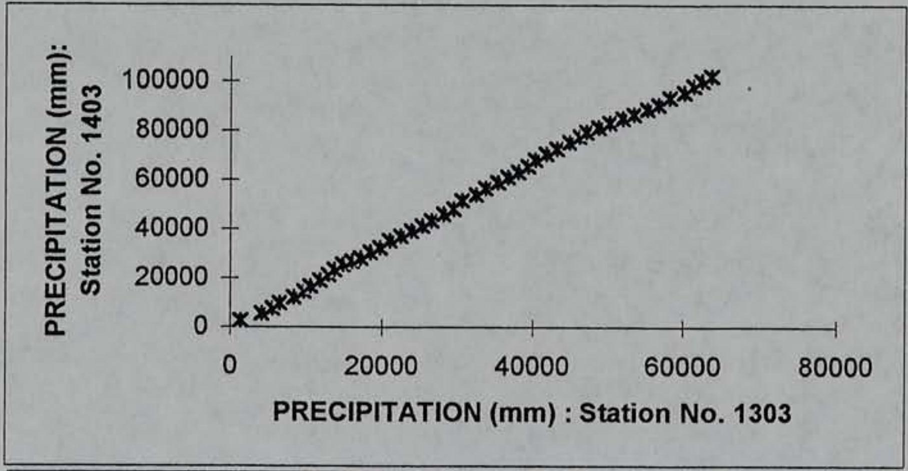
APPENDIX K

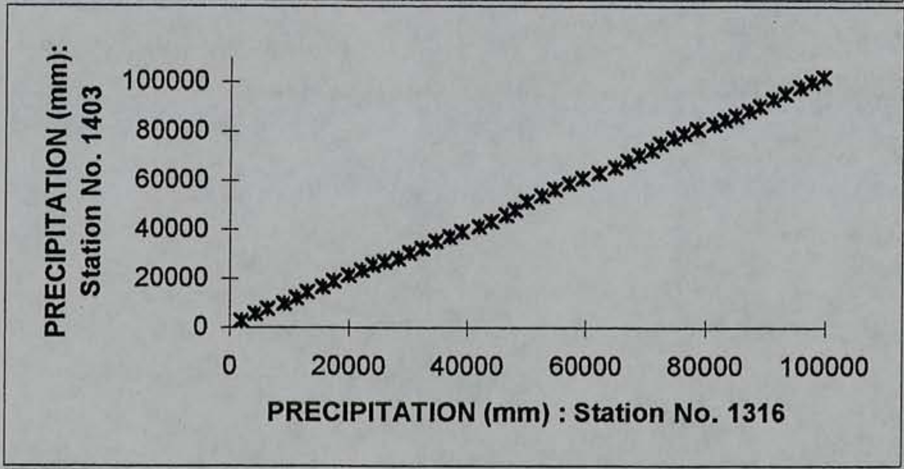
ANNUAL DISCHARGE (m^3/s) FOR SELECTED STATIONS

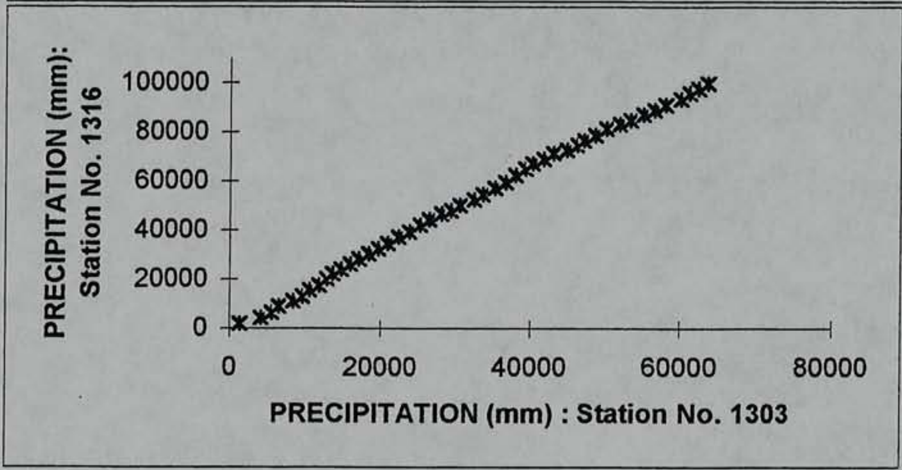
Year	Station 620	Station 670	Station 680	Station 690	Station 695
1948			706	336	1854
1949			918	397	1827
1950			745	285	1642
1951			775	292	1154
1952			727	323	1357
1953			684	287	1321
1954			717	422	1891
1955			621	314	1327
1956			629	313	1307
1957			641	322	1319
1958			645	290	1537
1959			678	291	1420
1960			801	280	1608
1961			626	322	1514
1962			760	354	1745
1963			727	384	1684
1964			685	310	1583
1965			658	411	1348
1966			740	337	1581
1967			595	427	1505
1968	46.7	205	882	357	1864
1969	42.4	204	786	337	1439
1970	50.5	205	590	338	2014
1971	61.4	278	734	291	2000
1972	49.1	177	734	343	1579
1973	55.7	217	754	376	1691
1974	54.1	223	668	335	1848
1975	50.4	212	618	300	1702
1976	42.9	194	774	315	2043
1977	47.9	205	770	325	1490
1978	53.6	233		323	1670
1979	40.7	195		303	1410
1980	41.9	202		302	1870
1981	46.2	203		235	1820
1982	48.8	186		272	1230
1983	74	196		155	1410
1984	56.1	233		272	1580
1985	75	223		317	1730
1986	67.4	176		408	1190
1987	51	185		365	1610
1988	57.6	197		391	1720
1989	56.1	191		346	1730
1990	54.9	205		384	1750
1991	46.7	190		266	1750
1992	36.6	141		330	1320
1993	49.5	178		249	1570
1994				324	1350

APPENDIX L

DOUBLE-MASS CURVE OF PRECIPITATION (1948-1993) FOR SELECTED STATIONS

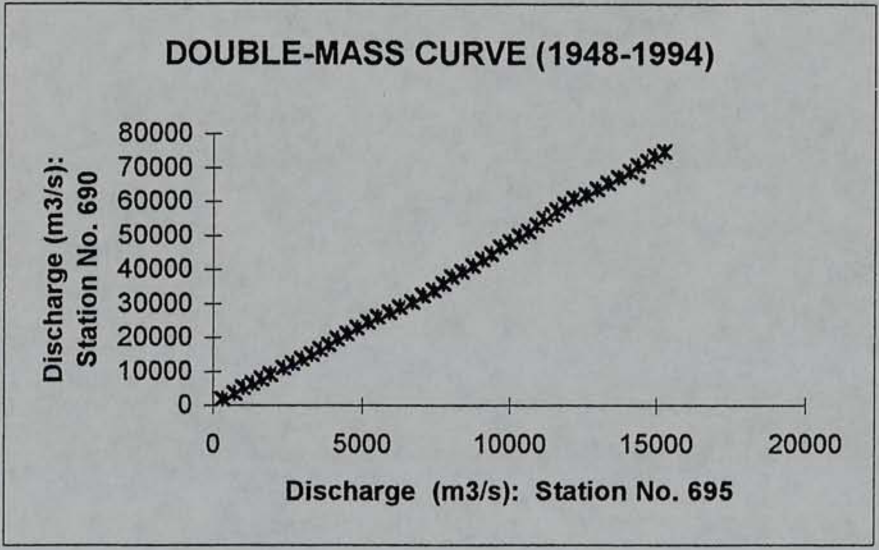


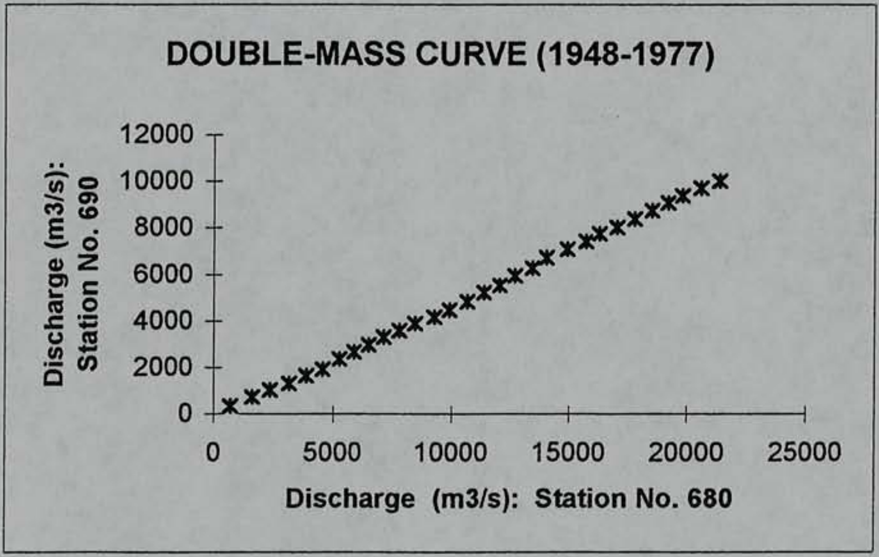




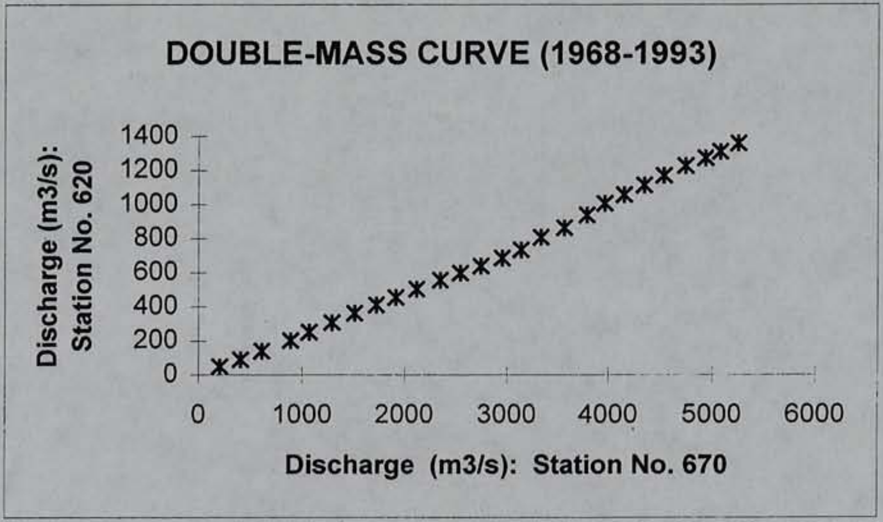
APPENDIX M

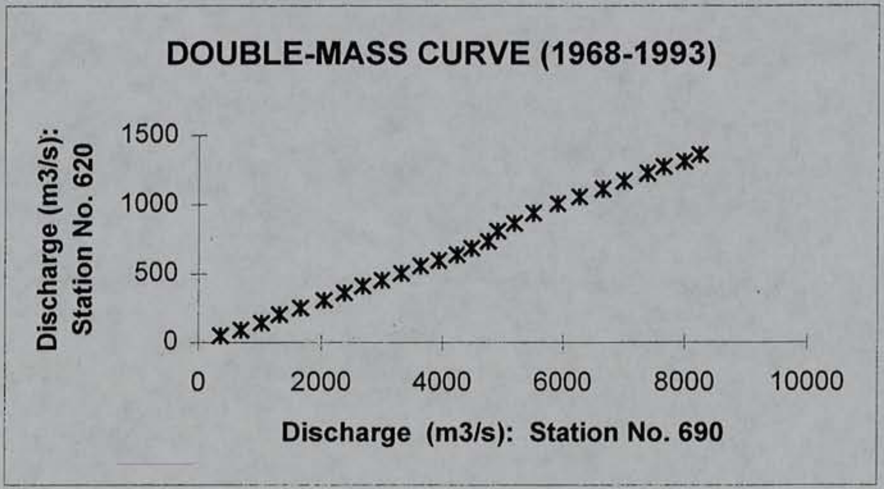
DOUBLE MASS CURVE OF DISCHARGE FOR SELECTED STATIONS

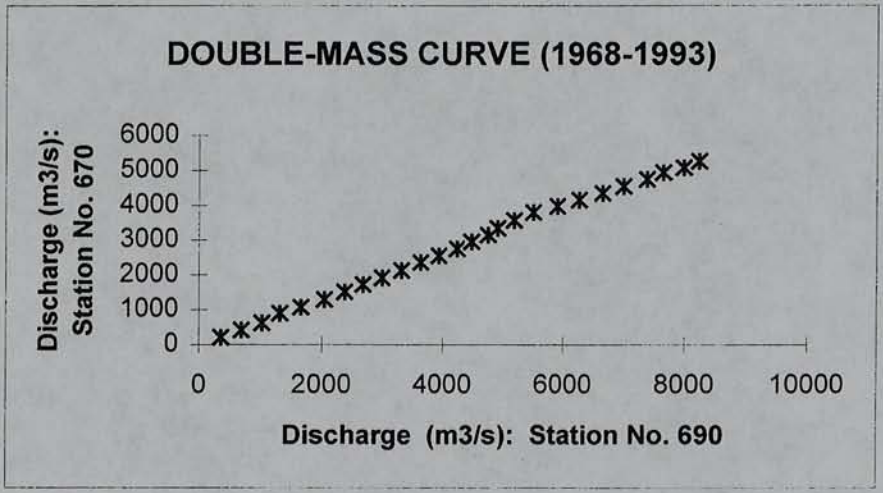




Appendix M continued







APPENDIX N

Z-STATISTICS OF MONTHLY AND ANNUAL NONPARAMETRIC TRENDS

N-1. Maximum temperature

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann	Z.j
1036	1.00	-0.12	0.52	1.11	1.15	2.29	1.25	0.50	2.31	0.30	0.18	0.00	3.17	0.87
1103	0.91	-0.34	-0.70	1.17	1.33	3.93	3.45	3.91	3.37	2.28	2.12	1.65	7.01	1.92
1201	-0.76	0.00	-1.17	-0.41	0.00	0.67	1.22	1.29	1.84	-0.18	-0.80	-0.86	0.26	0.07
1206	-1.70	-1.04	-1.05	0.66	-0.37	0.25	-1.85	-1.84	-1.99	-0.93	0.29	-1.30	-3.17	-0.91
1209	-1.53	-1.11	0.49	0.00	-0.98	-1.66	-0.80	-0.11	-2.31	-0.83	0.27	-1.59	-3.01	-0.84
1220	1.09	0.56	-0.60	0.75	1.99	1.79	0.00	0.28	0.06	-0.06	0.88	0.72	2.11	0.62
1303	1.68	1.39	1.10	-0.17	-0.79	1.20	0.73	1.67	2.28	2.13	2.02	2.25	4.62	1.29
1304	0.00	0.00	-0.40	1.34	1.24	1.44	1.15	0.99	1.14	1.29	1.68	0.59	3.08	0.87
1307	-0.21	-1.54	-2.08	-0.91	-0.48	0.15	-0.94	-0.58	-0.79	0.00	0.33	0.82	-1.83	-0.52
1310	-0.20	-1.84	1.64	-0.25	-0.25	-1.59	0.00	0.22	-1.60	-1.15	1.04	-1.65	-1.68	-0.47
1318	-0.62	-0.18	-0.24	0.88	1.16	2.15	1.54	2.43	0.86	2.14	1.71	0.37	3.75	1.01
1404	-0.25	0.10	1.39	1.39	-0.25	-0.65	0.00	-0.50	-1.24	1.16	1.73	0.00	0.82	0.24
1405	-0.81	-1.19	-0.75	-0.22	-0.64	1.38	0.18	0.95	-0.66	0.22	0.68	-0.91	-0.42	-0.15
Zi.	-0.11	-0.41	-0.14	0.41	0.24	0.88	0.46	0.71	0.25	0.49	0.93	0.01		0.31

N-2. Minimum temperature

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann	Z.j
1036	1.50	0.50	-0.15	-1.70	0.00	-1.36	-0.75	-2.04	-1.23	1.00	-1.80	-0.89	-2.29	-0.58
1103	-1.48	0.00	-0.79	-3.96	-1.32	-1.17	0.74	1.63	0.49	-2.77	-2.51	-0.74	-3.45	-0.99
1201	0.27	3.11	0.00	0.93	1.18	0.86	1.52	0.87	1.68	-0.72	0.00	-0.12	3.06	0.80
1206	2.93	1.67	1.86	1.68	0.78	2.86	3.51	3.85	3.76	2.42	3.25	4.14	9.51	2.73
1209	-0.16	-1.54	0.44	0.27	0.66	-0.62	-0.44	-0.39	-1.67	1.49	-0.28	0.00	-0.64	-0.19
1220	2.31	2.25	1.55	0.84	1.15	2.55	2.70	2.67	2.29	1.84	2.88	2.24	7.41	2.11
1303	-1.84	-1.67	0.02	-0.05	-0.71	-0.14	-0.05	0.55	0.53	-0.16	-1.11	-1.57	-1.82	-0.52
1304	-0.04	0.62	-0.60	0.32	0.27	0.64	-0.45	-0.50	0.61	0.70	-1.18	-0.23	0.04	0.01
1307	0.52	-0.64	-1.54	-1.00	-1.60	-0.49	-0.24	0.18	0.09	-0.24	-0.67	0.88	-1.40	-0.40
1310	2.88	0.74	2.98	2.03	0.80	-0.95	1.60	2.38	2.15	2.28	2.60	1.99	6.31	1.79
1318	-0.47	-0.90	-0.62	-0.24	-0.11	-0.71	0.22	1.23	-0.28	1.32	1.16	-0.14	0.11	0.04
1404	0.60	-0.30	0.74	0.40	0.05	-0.90	-1.21	-1.20	-1.00	0.30	-0.25	-0.05	-0.83	-0.24
1405	1.11	0.87	0.95	0.23	0.81	1.17	1.86	1.61	0.94	0.61	-0.73	-0.45	2.61	0.75
Zi.	0.62	0.36	0.37	-0.02	0.15	0.13	0.69	0.83	0.64	0.62	0.11	0.39		0.41

N-3. Average temperature

Stn	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann	Z.j
1036	1.37	0.87	0.30	-0.75	0.37	0.00	0.00	-1.10	0.64	1.06	-2.25	-1.44	-0.69	-0.08
1103	-0.65	0.60	-0.50	-2.07	-0.37	1.94	2.18	4.01	2.40	0.28	-0.62	1.17	2.82	0.70
1201	-0.24	0.60	-0.37	0.25	-0.25	0.99	0.42	1.38	1.53	0.00	-0.12	-0.34	1.47	0.32
1206	0.31	0.22	0.27	1.00	-0.09	1.63	-0.14	-0.38	0.16	1.29	2.20	0.14	1.92	0.55
1209	-0.31	-1.04	0.75	0.31	0.12	-1.95	-0.74	0.00	-2.14	0.22	0.39	-1.10	-1.53	-0.46
1220	1.52	-0.21	0.46	1.22	1.40	2.53	1.97	1.56	2.12	1.30	2.03	1.09	5.16	1.42
1303	0.54	0.02	0.53	-0.25	-0.94	0.75	0.74	1.52	2.34	1.56	0.90	1.27	2.75	0.75
1304	0.05	0.32	-0.55	0.79	1.19	1.13	0.44	0.50	1.00	1.10	0.59	0.45	2.14	0.58
1307	-0.01	-0.08	-0.10	-0.08	-0.02	0.00	-0.02	-0.01	0.00	0.00	0.00	0.03	-0.02	-0.02
1310	0.94	-0.45	2.09	0.65	0.25	-1.50	0.75	0.99	-0.10	1.95	2.33	-0.45	2.19	0.62
1318	-0.70	-0.69	-0.48	0.31	0.50	0.22	0.99	2.62	0.76	1.45	2.02	0.00	2.30	0.58
1404	-0.25	0.00	1.29	1.34	0.00	-0.74	-0.20	-0.85	-1.29	1.29	1.19	-0.33	0.38	0.12
1405	0.40	-0.10	0.33	-0.22	-0.09	1.49	1.42	1.00	-0.24	0.68	0.26	-0.91	1.19	0.33
Zi.	0.23	0.01	0.31	0.19	0.16	0.50	0.60	0.87	0.55	0.94	0.69	-0.03		0.42

N-4. Precipitation

Stn	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann	Z.j
1006	0.29	1.63	0.75	1.51	1.11	-2.20	-1.12	0.12	-0.04	1.27	0.98	1.47	1.62	0.48
1008	0.06	0.42	0.39	0.67	2.03	-0.87	1.99	-1.01	-0.24	-0.64	0.47	2.58	1.66	0.49
1009	-0.36	0.01	-0.06	0.38	2.45	1.24	0.10	-1.13	-0.69	-1.71	0.96	1.79	0.88	0.25
1016	-1.09	-0.77	-1.18	-1.40	-1.28	-1.89	0.12	0.00	1.03	-0.91	-1.63	0.11	-2.68	-0.74
1023	0.55	2.21	0.86	1.39	2.91	0.08	1.09	-0.80	1.31	1.07	1.71	3.79	4.60	1.35
1024	-0.85	-0.41	0.27	1.68	0.03	0.38	0.28	-1.22	1.06	0.57	-0.91	1.88	0.79	0.23
1027	0.36	1.70	0.00	0.73	2.21	0.57	0.93	0.81	0.93	-2.03	-0.74	0.59	1.79	0.51
1028	-1.09	0.77	0.65	-0.77	1.69	-0.61	0.59	-0.10	0.25	-0.27	-0.23	1.80	0.73	0.23
1062	-0.14	1.17	0.34	-0.55	0.48	-1.44	-0.89	0.89	-0.08	-0.41	-0.64	0.35	-0.26	-0.08
1102	-0.54	-0.82	-0.06	0.78	0.73	-1.52	-1.17	-3.28	-2.25	-1.84	0.23	3.15	-2.05	-0.55
1103	-0.07	1.09	-0.63	1.63	1.22	-0.45	-0.95	-1.20	-0.68	-2.00	0.22	2.30	-0.02	0.04
1104	0.61	-0.42	0.22	0.37	1.37	-1.01	1.29	-1.51	-0.57	-1.93	0.00	2.30	0.17	0.06
1106	-0.26	1.16	0.96	0.00	2.45	-0.81	0.95	0.00	2.87	0.42	-0.09	2.42	2.86	0.84
1107	-0.45	1.90	-0.29	0.54	0.74	0.84	1.90	0.55	2.96	1.96	0.58	0.69	3.50	0.99
1108	-0.09	1.17	-0.11	0.53	0.37	-1.50	0.71	-0.02	0.16	0.53	0.36	1.51	1.00	0.30
1115	0.11	1.69	0.02	-0.53	1.14	-0.40	1.09	-1.07	0.65	0.12	-0.16	1.58	1.17	0.36
1116	-0.34	-0.53	0.23	-0.79	0.15	-2.08	-1.41	-0.37	0.03	-1.04	0.87	2.03	-1.34	-0.27
1201	-0.36	-0.09	0.08	-0.45	0.22	-0.57	0.78	1.57	0.62	0.46	0.30	-0.63	0.60	0.16
1202	2.21	3.71	-0.38	1.33	0.16	-0.51	-0.14	-0.54	0.06	-1.29	0.52	1.81	2.02	0.58
1203	0.16	1.49	-0.22	0.78	1.56	1.27	1.14	-2.40	-1.07	-0.68	1.91	2.39	1.83	0.53
1204	0.81	1.53	1.65	-0.65	-0.20	-1.52	0.80	-1.89	0.22	-0.40	1.65	1.53	0.94	0.29
1206	-0.72	-0.21	-0.88	-0.65	0.91	0.14	1.77	-2.42	0.93	0.11	-1.03	2.43	0.10	0.03
1208	0.34	0.00	0.00	1.89	-0.95	0.04	0.12	-0.25	-1.13	1.19	2.78	0.15	1.12	0.35
1210	0.03	1.09	-0.13	-1.26	1.89	-1.28	0.34	-0.44	1.70	0.52	0.30	2.09	1.31	0.41
1211	0.48	0.91	-1.08	0.37	0.49	-0.44	0.23	-1.45	0.62	-1.72	0.97	2.92	0.56	0.19
1213	-1.45	1.41	0.75	1.06	1.68	-1.01	1.41	-1.97	1.27	-0.79	-0.71	1.93	1.00	0.30

Appendix N-4 continued

Stn	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann	Z.j
1217	0.30	1.27	2.38	1.72	0.80	0.08	0.77	1.22	-0.42	-0.73	0.51	1.73	2.83	0.80
1218	2.00	1.02	0.39	-0.81	0.00	-0.92	-1.65	-0.49	2.02	1.40	-0.38	-0.47	0.45	0.18
1219	-0.11	-0.47	-1.04	0.25	-0.17	-0.40	-1.22	-1.76	-1.60	0.00	-0.70	1.59	-1.73	-0.47
1220	-0.66	2.25	-1.34	-1.47	1.40	-0.75	1.17	-0.68	0.64	0.84	0.22	2.08	1.14	0.31
1222	-0.24	0.57	0.14	-0.85	-0.26	-0.19	-0.51	1.39	0.69	-2.39	0.16	1.08	-0.11	-0.03
1224	-0.32	0.72	1.71	2.92	1.59	1.94	2.59	0.99	0.09	1.07	1.48	1.18	4.71	1.33
1301	-0.26	1.55	0.33	0.76	0.13	1.19	3.04	1.95	1.56	-0.13	-2.24	-0.40	2.21	0.62
1303	0.95	1.02	1.57	1.53	1.74	-0.08	0.35	-0.97	1.76	0.35	2.10	1.83	3.51	1.01
1304	-0.45	0.00	-0.60	-1.09	-0.30	-0.74	-0.10	0.25	1.09	-0.49	-1.23	0.61	-0.95	-0.25
1305	-0.63	3.11	1.12	2.04	0.98	-0.57	-0.09	-1.43	0.15	-0.09	0.92	1.93	2.12	0.62
1306	0.21	3.23	-0.31	1.55	1.72	-0.89	-0.11	-0.44	-0.63	-0.01	-0.09	2.39	1.82	0.55
1307	2.29	2.97	-0.29	0.40	3.09	-0.99	0.42	-0.44	3.01	0.95	2.08	2.64	4.58	1.35
1308	0.42	3.14	-0.50	2.36	3.34	0.20	0.73	-0.44	2.41	0.14	1.12	1.74	4.23	1.22
1309	-0.33	0.67	0.56	1.34	1.44	-0.58	-0.02	-1.78	-0.07	0.37	1.71	2.67	1.53	0.50
1310	0.40	-0.12	-0.57	0.79	0.65	1.90	2.33	-2.15	1.07	0.32	0.44	0.18	1.56	0.44
1316	0.27	0.87	-0.11	0.87	1.91	-1.11	-0.64	-1.47	0.45	0.64	0.79	2.19	1.21	0.39
1317	0.57	1.23	-1.18	1.56	1.60	0.66	-0.28	0.02	2.06	0.15	-0.57	1.91	2.26	0.64
1318	-0.08	0.00	-0.49	0.14	0.56	-1.16	0.39	0.67	1.31	1.81	0.00	2.09	1.42	0.44
1322	-1.12	0.53	-1.13	0.91	1.33	-0.84	-0.28	-1.98	-0.39	-0.01	1.14	1.31	-0.27	-0.04
1324	-0.73	2.53	0.35	1.96	2.36	-2.42	0.46	-1.06	1.80	-0.13	1.83	2.29	2.63	0.77
1325	0.19	0.41	1.89	1.90	2.59	-0.11	1.13	-1.03	0.33	-0.58	1.72	1.69	2.91	0.84
1401	0.21	0.87	0.20	-1.09	-1.38	-0.27	-0.56	0.58	-0.40	-1.16	0.20	-1.61	-1.19	-0.37
1402	-2.50	0.21	-0.77	-0.48	0.00	-1.24	-2.36	0.00	-1.43	-0.40	-1.05	-0.64	-3.10	-0.89
1403	0.43	1.42	-1.50	2.09	0.52	0.15	-0.09	-0.38	-1.82	-0.53	-0.47	1.50	0.33	0.11
1404	0.31	1.53	-0.81	1.71	1.29	1.52	2.55	1.80	2.04	0.05	0.88	2.96	4.59	1.32
1405	-1.17	1.05	0.24	0.75	1.96	-0.83	0.56	-1.89	0.53	0.46	-0.09	1.53	0.87	0.26
1414	-1.01	0.73	0.24	-0.51	0.24	0.73	-1.34	0.00	-1.50	-1.72	-0.55	0.00	-1.69	-0.39
1418	1.28	-1.78	0.84	-0.71	2.21	0.36	-0.58	0.00	0.72	0.41	-0.38	0.76	0.95	0.26
1420	-0.46	1.67	1.13	-0.23	0.23	-1.22	-1.22	-0.68	-0.14	-0.41	-0.45	-1.05	-0.84	-0.23
Zi.	-0.04	0.98	0.08	0.53	1.04	-0.40	0.32	-0.53	0.46	-0.17	0.32	1.47		0.34

N-5. Discharge

Stn	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann	Z.j
602	2.01	2.45	3.01	0.03	-0.42	-0.36	0.83	2.77	2.17	2.04	1.95	1.72	5.24	1.52
605	-2.64	-2.14	-2.23	-1.31	-1.86	-1.29	0.91	0.61	-0.98	-1.97	-3.33	-3.18	-5.64	-1.62
610	1.13	1.78	1.82	1.23	1.23	-1.01	-0.26	1.21	0.54	0.39	0.88	1.82	3.14	0.90
620	1.72	1.68	1.68	1.20	2.28	1.39	0.77	1.64	1.05	0.59	1.37	1.77	5.00	1.43
630	-0.24	-0.53	-0.85	-0.71	0.42	0.43	-0.13	-2.02	-0.83	-0.68	-0.86	-0.86	-2.07	-0.57
640	0.74	1.27	1.01	1.24	0.37	0.22	-0.50	-0.82	0.48	1.06	0.82	1.35	2.09	0.60
647	0.23	1.13	0.87	0.21	-1.52	0.17	1.69	-1.44	0.12	-0.29	-1.11	-0.41	-0.11	-0.03
650	1.41	1.24	1.54	1.36	2.53	2.57	4.84	3.62	3.62	1.58	1.94	2.21	8.40	2.37
652	-0.54	-0.07	-0.09	-0.66	-0.65	-1.19	-1.51	-0.21	0.44	-0.86	-1.26	-0.88	-2.20	-0.62
660	-0.96	-1.65	-1.50	-0.95	0.19	0.69	0.02	-1.98	-2.25	-1.92	-0.58	-0.06	-3.15	-0.91
670	-1.91	-1.44	-1.29	-1.39	-0.18	-0.28	-0.77	-0.62	0.75	-1.41	-2.61	-2.34	-3.98	-1.12
690	-0.82	-1.02	0.13	-1.61	-2.39	-2.34	-1.09	0.11	0.41	-0.82	-2.09	-1.52	-3.79	-1.09
695	-2.04	-2.44	-2.20	-0.79	0.60	0.38	0.80	0.33	0.96	-0.42	-0.34	-1.89	-2.03	-0.59
Zi.	-0.15	0.02	0.15	-0.17	0.05	-0.05	0.43	0.25	0.50	-0.21	-0.40	-0.18		0.02

APPENDIX O

COMPUTATION OF AVERAGE BASIN PRECIPITATION

*Stn. No.** (1)	*Ave Elevtn** *(m)* (2)	*Representative Precipitation Stations* (3)	*Average Precipitation *(mm)* (4)	*Average Elevation of Precipitation Stations. (m)* (5)	*Elevation Difference (2) - (5) or 2800 - (5)* (6)**	*Adjusted Precipitation (4)+ 0.5 *(6)* (7)	*Average Basin Precipitation*** (mm)** (8)
600	4868	Based on gridded data with interpolation	536				536
602	1609	1301, 1303, 1325	2210	1339	270	2345	2345
605	2948	1301, 1303, 1325	2210	1339	1461	2940.5	689
606	1354	1301, 1304, 1306, 1309	1759	1065	289	1903.5	817
610	4583	Based on gridded data with interpolation	1309				1309
620	3356	1006, 1008, 1009	2645	1751	1049	3169.5	3170
627	4098	1016, 1058	3625	2553	247	3748.5	3748
629	1986	1016, 1023, 1024, 1058, 1062	2286	1739	247	2409.5	2523
630	1573	1023, 1024, 1028	1211	965	608	1515	1890
640	1854	1024	1533	1552	302	1684	1684
647	4141	1102, 1103, 1104, 2002	1676	2322	478	1915	1915
650	2815	1103, 1104, 1224, 1225	1889	1734	1066	2422	2422
652	1451	1104, 1106, 1107, 1115	1608	1373	78	1647	1896
660	2874	1103, 1104, 1206, 1219, 1220	1847	2081	719	2206.5	2206
670	3786	1201, 1203, 1204, 1206, 1218, 1219, 1220	1699	2615	185	1791.5	1792
680	1243	1108, 1206, 1210,1211, 1213, 1222	1569	1288	-45	1546.5	1833
690	2854	1307, 1308, 1401,1402, 1403, 1404, 1405, 1413, 1414, 1418, 419, 1420	1580	1992	808	1984	1984
695	895	1211, 1307, 1308, 1309, 1310, 1322	1463	592	303	1614.5	1288

* Excludes the area covered by upstream stream gauging station

** Column (3) is used if the elevation on column (3) is not more than 2800 m.

*** Area weighted average prcipitation of the whole basin measured at the give Station No.

APPENDIX P

COMPUTATION OF EVAPOTRANSPIRATION CHANGES DUE TO CHANGE IN CLIMATE AND LAND-USE

1) Evapotranspiration change due to change in forest area. (e_1)

The Calder-Newson model (Calder & Newson, 1979; Calder, 1994) is given as:

$$E = ET + f\,(aP - bET), \qquad \text{(P-1)}$$

where, E = Total annual loss including interception.
f = Fraction of catchment with full canopy = .66 * forest area.
a = Interception ratio = 0.35 to 0.40 for P > 1000mm.
P = Annual precipitation (mm) = 1270
b = Fraction of year when canopy in wet = 0.000122 P = 0.000122 * 1270 = 0.15

Also the number of rainy days in the Kosi basin as given in DHM climatological records ≅ 100 days. Assuming wet canopy for one third of rainy days, we can compute b as follows (Calder & Newson, 1979):

$$b = 1.5 * (\text{Number of rain hours per year/Number of hours in a year}) \qquad \text{(P-2)}$$

$b = (1.5*100*8)/8760 = 0.14$

ET = Evapotranspiration in unlimited water supply condition.

Annual Penman potential evapotranspiration is equal to 0.86 times the Class A pan evaporation (Table VIII-8). lope of the elevation vs. annual pan evaporation/potential evapotranspiration relation is also almost equal in both of the cases (Table VIII-8) Hence, Measured values of annual pan evaporation (Appendix F) is used for this term with application of a factor of 0.86 for the southern Himalayan region and 0.35 for the northern Himalayan region. Note that no attempt is made for accurate computation of evapotranspiration under unlimited water supply condition. Recorded evaporation data are used without altitudinal correction. Therefore, the computation in this exercise is more like evaporation index. Since only the ratios are used for hydrological impact assessment, we argue that the accuracy of these estimates cannot have a significant influence on results.

Evapotranspiration rate in Tibet = (4.2 + 6.7)*0.35*365/2 = 696 mm/yr
Evapotranspiration rate in Nepal = (3.4 + 3.0 + 2.4)*0.86*365/3 = 921 mm/yr

3) Evapotranspiration change due to co_2 change (e_3)

$$e_3 = 1 - 0.3\,d,$$

where d is the fraction of forest which is 1.0 for the 100% forest (Wigley and Jones, 1985).

For 100% forest cover, $e_3 = 1 - 0.3 \times 1 = 0.70$
For 50% forest cover, $e_3 = 1 - 0.3 \times 0.5 = 0.85$
For 25% forest cover, $e_3 = 1 - 0.3 \times 0.25 = 0.925$
For 0% forest cover, $e_3 = 1 - 0.3 \times 0 = 1$

APPENDIX Q

OUTLINE: PROPOSED HIMALAYAN BENCH-MARK BASIN

Proposed Basin: Tamor River Basin

Primary Objective:

Develop benchmark stations for long term monitoring of hydrological and meteorological variables for assesing climatic changes

Secondary Objective:

1) Basin-scale studies of hydrological processes and their link to ecological and biogeochemical processes.
2) Develop models and experimental stations for research on hydrological processes and hydrological technologies

Features of the Basin:

Area = 6000 km^2
Elevation = 150 m to 8598 m
Average Annual Discharge = 323 m^3/s
Estimated Sediment Yield = 7100 $tons/km^2$

Existing Facilities:

Precipitation Network = 16 stations = 375 km^2 per station
Climatological Network = 5 stations = 1200 km^2 per station
Synoptic Station = 1 station = 1 station per 6000 km^2
Primary Streamflow Gauging Station = 1
Secondary Streamflow Gauging Station = 1

Research Strategy: See Chapter XIII

Basin Location: See Figure IV-2

Basin Characteristics: See Chapter II, Chapter XI