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International Centre for Integrated Mountain Development

HYDROLOGICAL ASPECTS OF THE HIMALAYAN REGION

Donald Alford

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Hydrological Aspects of the Himalayan Region

Donald Alford

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Foreword

This paper was initially prepared by the author for the "International Symposium on Mountain Environmental Management in the Hindu Kush-Himalayan Region", which was organised jointly by ICIMOD and UNESCO/MAB at ICIMOD Headquarters during April 1989. It was subsequently revised by the author in its present form. This paper deals essentially with two major aspects of water resources in the Himalayas, viz, (i) the impact of human use of the natural environment on the hydrological regime of watersheds in the Himalayas, and (ii) analysis of existing data of the Kosi Watershed of Eastern Nepal, as an illustration of examination of the interactions that have an impact on the water budget of a mountain watershed in the Region. As the author has pointed out, '*primary data describing water resources are essentially unavailable for the Hindu Kush-Himalayan Region*'. However, it is also seen that even available data have not been well analysed to understand the hydrological aspects of major or minor rivers in this Region.

It is hardly necessary here to emphasise the importance of water resources in the overall development of the Hindu Kush-Himalayan Region. As the world's highest towers of snow and ice, the Himalayas are also the largest storehouse of fresh water and sources of such mighty rivers as the Indus, Ganges, Brahmaputra, and Mekong. As the abode of snow, as their very name suggests, they have not only been the sources of these mighty and perennial rivers but have been the sustaining sources of major ancient civilisations in these river basins also.

Despite the vast regional potential for development of water resources for multifarious uses, scientific understanding of the complex interaction between natural forces and human impact on the hydrologic regimes in these highly energised and sensitive mountain environments are far from adequate. Furthermore, the unique combination of extreme factors, such as intense seasonal precipitation and highly steep topography due to a sharp rise in altitude within a narrow width, has not only inhibited the collection of data in the difficult mountain watersheds, but has also placed serious limitations on the use of standard hydrological principles, techniques, and models which are basically developed in the more temperate and less extreme environments of Europe and North America. Thus it is not possible to apply general solutions developed elsewhere to the hydrological problems of the Region, as is emphasised by the author in his conclusions. The paper also indicates that simple models could probably be developed to deal with such problems and improve the use of resources for development.

I am happy to say that ICIMOD is already engaged actively, jointly with the UNESCO/IHP and in cooperation with national institutions of the participating countries of ICIMOD and the WMO, in developing a **Regional Programme on Mountain Hydrology** in the Hindu Kush-Himalayan Region. This joint initiative has been welcomed by all concerned.

In the above context, I hope that the publication of this paper will help towards a better appreciation of the problems associated with proper understanding of the hydrological processes in the Himalayas which affect both the uplands and lowlands in the Region. It might also help towards realisation of the urgent need for regional cooperation and international support for the ongoing and proposed programmes on hydrological studies in the Region, such as the one already initiated jointly by ICIMOD and UNESCO/IHP. It is also hoped this publication will be of use not only to hydrologists but also to all those who have interest in the development of water resources in these complex mountain environments.

Dr. E. F. Tacke
Director General

Preface

The countries of South Asia -- Pakistan, India, Nepal, Bhutan, and Bangladesh -- are dependent to varying degrees on the annual cycle of water flowing into, through, and from Himalayan and Trans-Himalayan mountain ranges. Though water resources of South Asia are of obvious importance in the development of the region, the flow of water through Himalayan watersheds has received almost no serious scientific consideration.

In general, mountain hydrologic systems are relatively unstudied. Where studies have been undertaken, as in the European Alps or the mountains of western North America, only a few workers have attempted regional generalisations. Most of the information has been presented as site-specific studies of individual basins. The bulk of the results discussed in the technical literature has been obtained from so-called "black-box" studies of basins of relatively small size. Such studies commonly consider only a single relationship; such as that between changes in vegetation cover and the resulting changes in streamflow or sediment transport. Such studies lump all other controls on the water or sediment balance together as an unstudied variable -- the "black-box". Black-box studies are very difficult to generalise. It is often the case that factors that are critical in determining variations in the water or sediment budget of a basin -- such as climate -- are varying simultaneously with the control under study.

The initial impetus for the present study was provided by a request from Dr. Colin Rosser, the former Director of ICIMOD, to prepare a paper on water resources and environmental management for a Workshop on Mountain Environmental Management, jointly sponsored by ICIMOD and UNESCO/MAB. Both the purposes of the workshop and the nature of this paper changed over the course of time. From a study of the role of environmental management in managing the water resources of the Hindu Kush-Himalayan Region, the focus of the study gradually narrowed to a consideration of the hydrometeorological aspects of a smaller part of the region -- the Nepal Himalayas. The final result reflects concerns that existed or evolved during the preparation of the paper, namely that:

- the relationship between human use of the natural environment and subsequent changes in the hydrologic regime of Himalayan watersheds has not been well-defined; and
- the existing data bases describing this relationship for the region have not been analysed in any meaningful way.

This paper represents an attempt to consider the water resources of the Himalayan Region from these two aspects: (1) what are the basic interactions that determine the water budget of a mountain watershed in the region and, specifically, (2) what do the data bases tell us about the nature of these budgets? In many ways, these are not compatible topics. A consideration of basic water budget interactions in any environment involves a discussion of the most elementary hydrometeorological and geomorphological principles, while an analysis of the existing data bases represents a higher level of sophistication. Of necessity, this means that the paper will contain aspects of interest to at least two very different audiences. I hope that readers from both professional and lay audiences will recognise the needs of the other, as well as the fact that far too much time has passed without any serious discussion of either aspect of the problem of water resources' development in the mountains of South Asia.

For a variety of reasons, primary data describing water resources are difficult to obtain for the Hindu Kush-Himalayan Region. This paper, therefore, is based almost exclusively on secondary sources of information. Emphasis has been placed on the nature of the concepts associated with the interpretation of water resources' data and the bulk of the references cited in the text deal with the literature describing these concepts in more detail. In almost all cases, references are only single illustrative examples of an extensive literature describing the sciences of hydrology, climatology/meteorology, and fluvial geomorphology. They are included primarily to direct the interested reader to this literature. The discussion of the water resources of eastern Nepal is based upon specific data available in publications of the Government of Nepal.

Much of the data upon which this study is based were assembled and organised during the Spring of 1989, during which time the political differences between India and Nepal forced a virtual closing of ICIMOD. The bulk of the manuscript, therefore, has been written from my home in Montana, USA. I would like to thank Dr. Colin Rosser for making this study possible. I am particularly grateful to Prof. Suresh Raj Chalise for his patient encouragement. Thanks, too, to Dr. Corneille Jest who helped me keep my sense of perspective. In fact, there are far too many people who helped me through the data collection phase of this study to be listed, and I hope that each of them remembers something of what we shared.

Donald Alford

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I. Introduction

Water is a factor in virtually all resource development undertakings in South Asia. Water resources' development or management represents an attempt to meet an existing or potential demand for water or a related resource, such as energy or food. Commonly, attempts to meet these demands are based upon engineering modifications of the existing water supplies. Engineering modifications, in turn, are dependent upon a quantitative understanding of the temporal and spatial variability of those supplies. It is apparent that a major component of attempts to develop or manage water resources in any environment must be scientific studies of the resource, in advance of need, if project planning is to be realistic. Within any river basin, attempts to meet demands that exceed the natural supply of water will be, at best, only partially successful. Also, attempts to ignore the annual excesses of water which move through the system will only contribute to further inundation of the natural flood plains.

There are two primary needs in understanding the water resources of South Asia:

- it is essential to assess accurately the existing demands for water, and
- the nature of the water supply must be understood if these demands are to be met.

Demographics determine the nature of demands upon water resources. Economics and engineering determine the extent of technologies available and the willingness of a society to apply those technologies. Hydrology determines the extent to which the supply will meet that demand. It is the purpose of this paper to consider some aspects of the hydrology of the headwaters of some of the major rivers of South Asia. A case study illustrating certain aspects of the nature of the water supply of the mountain watersheds of the region is also included. This case study is based upon a preliminary analysis of hydrometeorological data from Nepal.

Water Resources and Environmental Management

Whereas water resources may be defined with relative precision, the term "environmental management" is somewhat more ambiguous. In the context of factors affecting the flow of water through a watershed, the "environment" may be defined as:

- climate,
- geology,
- topography (or terrain), and
- vegetation.

"Environmental management", from a water resources' perspective, is a matter of determining the extent to which a change in any one, or some combination, of these factors will produce a corresponding change in the timing, volume, or quality of water flowing through the watershed. Alternatively, it is a matter of inducing a change in one or more of the factors so as to produce some desired change or correct a perceived imbalance. Environmental interactions are complex, and at least two of the factors -- climate and geology -- cannot be "managed" in any meaningful way. In the case of these two factors, it is essential to understand how each relates to the water and sediment balance of a watershed, but the only realistic management alternative is to make allowances for the prevailing conditions of climate and geology in the management planning. In every case, from a water resources' perspective, the primary goal of environmental management should be to understand the interactions within the environment well enough to predict, with reasonable accuracy, the probable outcome of any particular course of action.

Terrain and vegetation can be "managed", in the sense that the type and density of vegetation covers may be purposefully altered and terrain may be shaped, as in the case of terracing on the mountain slopes of Nepal, or altered by a variety of engineering structures, e.g., dams. The extent to which a change in vegetation or terrain will affect the water or sediment balance will be dependent upon the existing conditions of geology and climate, the nature of the changes in the vegetation or terrain, and the scale on which the change is effected. In all cases, however, **it must be recognised that those factors that can be managed may not be the critical factors in determining the water and sediment balance of the watershed.** Only a study of the interrelationships at a specific site can determine if, in fact, "environmental management" of any sort will have a positive or a negative effect on the water resources at, and downstream from, that site (Hamilton 1987).

Almost without exception, large water resources' development or management projects are based upon an understanding of the water regime derived from a limited database. It is critical to be able to extrapolate these data spatially in order to understand the significance of any form of environmental manipulation for water resources. Extrapolation techniques have been proposed for the mountain environment, but they have not been widely tested (Alford 1985). At the same time, individuals siting environmental monitoring instruments in mountain watersheds rarely are aware of the diversity of the environment that surrounds them.

Water is an integral aspect of all facets of the mountain environment and enters into virtually every resource development or management project in some way. All disciplines involved in resource planning or management have developed numerous technologies for modifying the natural characteristics of volume, rate, timing, or quality of water at a site. Basically, all technologies are variations of a few basic themes: storage of water during a period of surplus for use in a period of deficit, transfer of water from an area of surplus to one of deficit, or improving water quality. While there are only a handful of ways in which the hydrological regime of an area may be changed beneficially, in practice, there is a virtually endless number of variations, combinations, and permutations of these basic themes (Dunne and Leopold 1978).

For most environments, such as forests, or grasslands, or deserts, entire books have been filled with discussions of appropriate technologies to modify the timing and volume of water flows. As the list of environmental elements considered grows linearly, the list of possible technologies to modify the water associated with that element grows exponentially. This means that any discussion of water resources' technologies, within the context of environmental management, is essentially open-ended. For this reason, the discussion in this paper will deal with the basic concepts involved in individual environmental factors, rather than with specific technologies designed to deal with a specific problem in a particular place.

Approaches to water resources' engineering or management -- attempts to alter the volume, timing, location, or quality of the water supplies of a region -- have evolved largely in the "two-dimensional" environment of the lowlands. These operational models are often misleading when applied to the high-energy, three-dimensional environments of large mountain ranges. Only in very recent years have attempts been made to develop water resources within large mountain ranges such as the Hindu Kush-Himalayan Region.

A major difference between mountain and lowland environments is related to the extent of spatial environmental uniformity -- the degree to which the characteristics of one place in the watershed may be predicted by studies in a second place. In a lowland watershed there is commonly a great deal of uniformity among environmental associations from place to place within the watershed. Environmental management procedures which are successful in one part of the watershed may be transferred to another place with some degree of confidence. In a highland watershed, on the other hand, the distinguishing environmental characteristic is spatial heterogeneity. Two points within the watershed, separated only by a distance of a few kilometres, may differ from one another as much as the polar ice caps differ from an equatorial jungle. The central dogma of a successful manager of mountain environments will be that measurements are not necessarily valid for any point other than the one at which they were made. A project that succeeds completely at one point within a mountain watershed may be much less successful at another.

Uncertainty

For at least a portion of the Hindu Kush-Himalayan Region -- Nepal -- much has been made recently about the problems of uncertainty associated with the information upon which resource management or development decisions must be based (Thompson and Warburton 1985 and Kattelman 1987). It has been argued that this information is fundamentally unsound, incorrect, in some cases even manufactured, and, perhaps, given the political realities and poor institutional linkages that characterise environmental management and development in the region, irrelevant. This is not a matter that can be resolved absolutely, but there are aspects that are pertinent to the data on which this paper is based and which should be discussed.

In the case of the physical environment that determines the availability of water and the variations among elements of the hydrologic cycle over the region, reproducible information is provided by time-series' measurements made continuously by recording instruments, from periodic observations, or from geodetic surveys of watersheds. The instruments may be stream-gauges, precipitation gauges, or thermographs. The geodetic surveys result in the preparation of topographic maps. There are problems with the accuracy and representativeness of these types of data, but these problems are dealt with extensively in the literature on climatology, hydrology, and geodesy. Standard tests exist for determining, at least, the internal consistency of such data (Miller 1981 and Ward 1975).

There is no doubt that errors do exist in the hydro-meteorological database for the Hindu Kush-Himalayan Region, just as they exist in databases for all of the major mountain ranges on earth. The challenge to the scientist studying this environment, or to the environmental manager or planner, is to use these data in as effective a manner as possible. This effectiveness will stem more from the conceptual models that are used in the planning or management process than from the absolute accuracy of the data (Baker 1944). The problem is not with the "uncertainty" of the database but with the ways in which the data are organised, interpreted, and used to develop management policies (Dunne and Leopold 1978 and Alford 1987).

The information on which this paper is based has been taken from a variety of sources, including the hydrometeorological data collected by HMG, Nepal (Department of Irrigation, Hydrology, and Meteorology 1976 and 1977, unpublished), and it presumably has varying degrees of accuracy. It has not been possible in most cases to analyse the original data sources and so the absolute accuracy could not be determined. Every attempt has been made to ensure that the data used possessed internal consistency, that is, that the cumulative volumes of discharge, as measured in a series of nested basins, were consistent with the discharge reported for the major basin. Patterns of precipitation and runoff, as reported in the literature, were compared to ensure, at least, qualitative agreement. All values have been rounded off to one or two significant figures, introducing minor differences in values contained in various tables or illustrations. These differences are well within the limits of the normal errors of measurement to be expected in hydrometeorological data.

II. Mountain Hydrologic Interactions

Mountain hydrology is the study of hydrologic processes and interactions within mountain watersheds (Alford 1985), not, as is often presented implicitly in the general literature, the study of the aggregate flow of water from those watersheds as measured at adjacent, lowland, gauging stations. This necessitates a shift in emphasis in the application of analytical methodologies and approaches developed for studies of water resources in lowland environments. While the discharge of rivers, as measured at discrete stream-gauging stations, remains important, it is much more important to understand something of the variation in production of runoff into stream channels between adjacent stream gauges -- the mesoscale interactions among terrain, climate, and streamflow. Without this sort of understanding, development of water availability estimates for uninstrumented sites, or forecasts of water availability with time, will remain problematical.

Water resources are only a single factor in any environment, and such resources cannot be understood without some understanding of the larger system, of which they are a part and with which they interact. This larger system is defined primarily by interdependent interactions among topography, climate, geology, vegetation, and human modifications of these elements of the environment. In mountainous regions, as a first approximation, the most critical factors are topography and meteorology (Barry 1981 and Baker 1944). The topographic factors of local relief, slope angle, and aspect influence the timing, volume, and spatial variability of water and energy in a mountainous terrain (Alford 1985). In the mountains there is no regional climate as such, but rather a mosaic of local "topoclimates" (Thornthwaite 1953) determined by variations in slope angle, aspect, and relative altitude (Flohn 1974 and Geiger 1966).

These interactions define the "water budget" of mountain watersheds (Miller 1981). To be successful, water resources' management should be based upon an understanding of the water budget in the management area (Dunne and Leopold 1978). In order to derive a water budget for mountainous terrain, it is first necessary to answer the following fundamental questions.

- What is a "mountain watershed" and how does it differ from lowland watersheds from which the bulk of traditional hydrological concepts have originated?
- What are the dominant controls on the water budget of mountain watersheds in the Himalayan Region?
- To what extent can hydrological models, based upon local studies in one portion of the Himalayan Region, be generalised to apply to the remainder?

The Mountain Watershed

There is no single, simple difference between "mountain" and "lowland" watersheds, but rather a combination of factors that, taken together, distinguish one from the other as will be clear from the characteristics discussed below.

a) A mountain watershed has a high degree of local relief. This emphasises the terrain aspects of altitude, aspect, and slope angle as primary factors in determining water and energy budgets. In a lowland basin, latitude and global atmospheric circulation patterns are the dominant controls.

b) A mountain watershed is characterised by increased geomorphic activity relative to the lowland basin. Geomorphic, or "landforming" processes, such as mass movements and fluvial transport of sediments, are at a maximum in mountain watersheds for any given set of biophysical characteristics.

c) Mountain watersheds can be characterised by local botanical zonation, with either or both altitude and slope aspect. Altitudinal zonation is most pronounced near the equator, in high, tropical mountains, and gradually diminishes in importance towards the Poles, to be replaced by zonation determined by aspect. In a lowland basin, zonation of vegetation is determined primarily by latitudinal differences.

At least for the present, the definition of a "mountain" or a "mountain watershed" must be determined by the purposes for which the definition is required. The classical definition has emphasised botanical zonation (Messerli 1983), but this is not particularly useful for hydrological studies.

For hydrological purposes, the mountain watershed is best considered in geophysical, rather than botanical, terms, reflecting variations in water and energy exchange as a function of topography and meteorology rather than zonation of vegetation.

In mountainous terrain, the interaction between topography and meteorology produces a situation in which the following takes place.

- Precipitation varies complexly with the aspects of altitude and terrain. There is commonly an "orographic" gradient, in which precipitation amounts vary along altitudinal gradients. Generally, "windward" slopes (those facing into prevailing storms) will be wetter than "leeward" slopes (those facing away from these storms). With increasing altitude, the percentage of precipitation falls as snow increases.
- Evaporation losses decrease with altitude as available energy decreases (Lambert and Chitrakar 1987).
- Steep mountain slopes cause water produced by rain or snowmelt on the surface to run off quickly into stream channels (Petts and Foster 1985).
- In many cases, shallow mountain soils and impermeable geologic formations can provide little storage for soil moisture and groundwater.
- Vegetation may be zoned based on both altitude and aspect, limiting the hydrological impact of either removal or replacement to within narrow geographical limits for any single mountain watershed.

Water and Energy Budgets

The hydrologic cycle, a concept familiar to those concerned with water resources' management, is a useful qualitative model describing the flow of water through the ocean-atmosphere-land continuum. Much more useful for purposes of resource development planning and management, however, is the concept of the water budget and the associated energy budget. Water moves through ecosystems as a series of flows and storages (Figure 1). Flows are associated with relatively high energies while storages represent a state in which there is temporarily insufficient energy to produce further movement. Examples of flows are precipitation, evapotranspiration, and surface runoff. Storages exist in the form of seasonal snow deposits or glaciers, lakes, and groundwater. Water and energy budgets provide a method for determining the nature and magnitude of these flows and storages. Water resources' management is primarily concerned with altering or duplicating one or the other, e.g., the reservoir behind a dam duplicates storage naturally provided by snow and lakes. The dam, by raising the water level, increases the energy associated with flow.

As in any environment, the flows of water and energy in mountain watersheds are defined in terms of standard input-output continuity equations based upon the water budget equation (Ward 1975 and Geiger 1966):

Streamflow (Qv) = Precipitation (P) - Evapotranspiration (Et) - Storage (-S) gain (or + storage loss (+S)).

Although the water budget equation involves a simple concept, in practice the evaluation of the relationship is difficult because of a number of reasons. Both precipitation and evaporation (an index of evapotranspiration) are measured at single points within a basin, while surface runoff and groundwater recharge are commonly measured as areal averages. A fundamental problem in evaluation of a water budget for a basin involves, in the first instance, the conversion of all variables to a common set of dimensions. This means that either precipitation and evapotranspiration have to be converted to areal averages (volume/area), or surface runoff and groundwater recharge to point values with dimensions of depth/area. In lowland areas, with little or no relief, this is not a particularly difficult task, and elementary textbooks on climatology or physical geography describe many ways to determine spatial patterns for this type of data (Mather 1974). In mountainous terrain, however, these methods are of limited value, without some understanding of how the various elements of the budget equations vary with local variations in altitude, slope angle, and aspect (Barry 1981 and Alford 1985).

"... *because of the characteristic irregularities of topography, surface and subsurface texture, and contrasts of albedo, high mountain areas present extremely difficult problems of hydrometeorological or energy exchange observation and sampling, and are poorly suited to the modelling or mathematical treatment of data*" (IAHS 1982: Preface).

Obviously, a major problem in mountain hydrology is the quantification of these "characteristic irregularities". A major premise on which this study is based is that the value of any element of the water budget, as measured at a single point in a mountain region, is non-representative of the region as a whole. The basic datum for the study of mountain hydrology is the quantitative relationship among a number of such measurements, as they vary with altitude, or with slope aspect, or angle - the slope of the gradient describing this variation. The divergence of individual measurements from this gradient can be measured by means of simple statistical tests and can be expected to vary directly with the importance of local, topographic factors. The importance of these water and energy budget gradients can be expected to vary widely throughout the region, as the relationships among the various elements of precipitatior evaporation, transpiration, or streamflow vary with altitud and aspect. The significance of these topographic gradient lies in the recognition of their existence, with th unequivocal implication that global solutions to wate resources' management will not, in all probability, exist There is a clear need for an analysis of the spatial an temporal variations of water and energy budgets within th region, using both the available databases and the besi available concepts provided by studies in simila environments in other mountain ranges (IAHS 1982, Croi and Bailey 1964, Baker 1944, and Alford 1985).

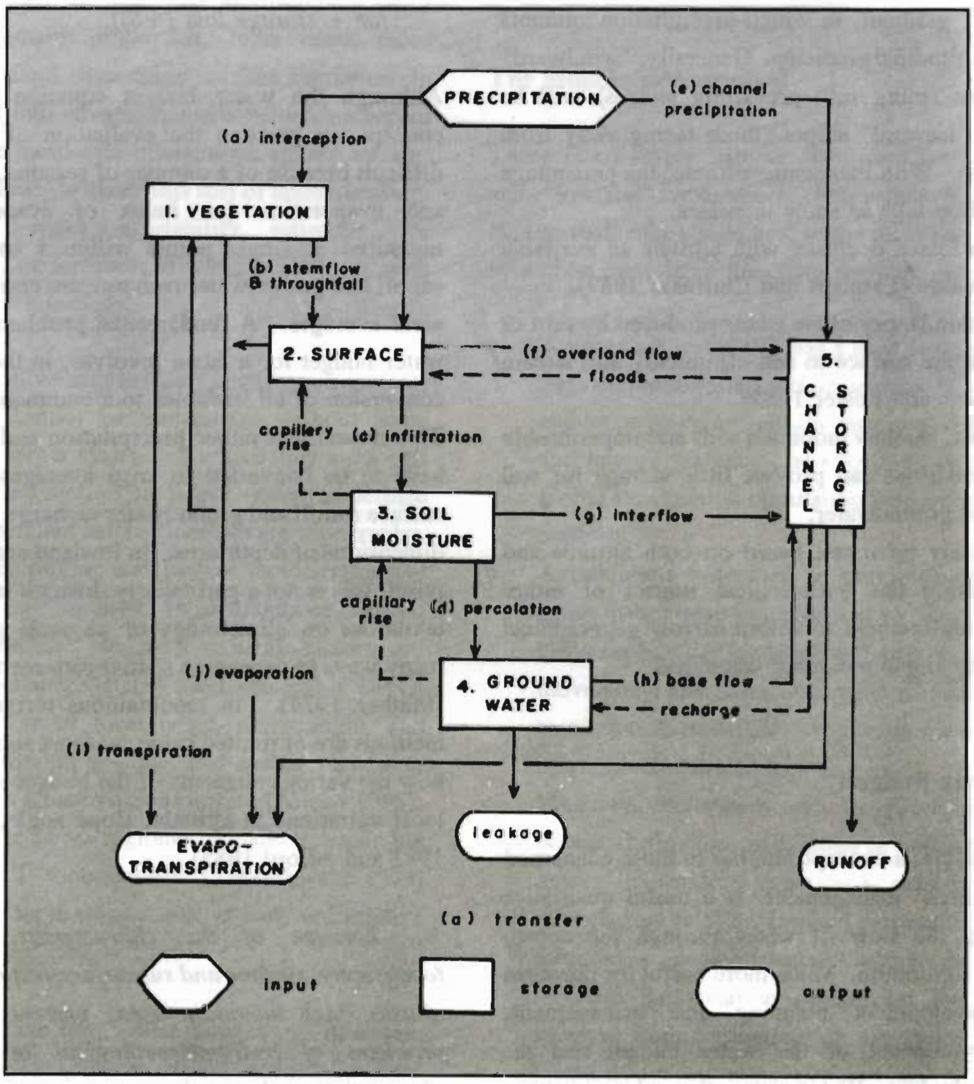


Figure 1: The Relationship among Elements of the Water Budget of a Region or a Catchment Basin

Source: Ward 1975.

Note: If precipitation occurs as snow, there must be an additional term reflecting the seasonal storage of water as snow prior to melt and runoff.

Erosion and Sediment Transport

Erosion includes all processes that result in the physical lowering of the surface of the earth. Surface erosion is the loss of surficial materials, as a result of the action of falling and running water or wind, while mass wasting involves the movement of large masses of fractured bedrock or other unconsolidated materials, including soil, from a slope. Sediment transport is the movement of the products of erosion through a river system (Leopold et al. 1964). It is not possible to consider water resources' management in the Hindu Kush-Himalayas without also considering the sources of the very large volumes of sediment moving annually through the river systems of the region. The limited measurements of sediment for the region are compared with global values in Figure 2. It can be seen that values for the Hindu Kush-Himalayan Region exceed the world average by almost two orders of magnitude. A central concern in the development or management of the water resources of the Hindu Kush-Himalayan Region is the relationship among land use, on-site erosion, and sediment transported through the river systems.

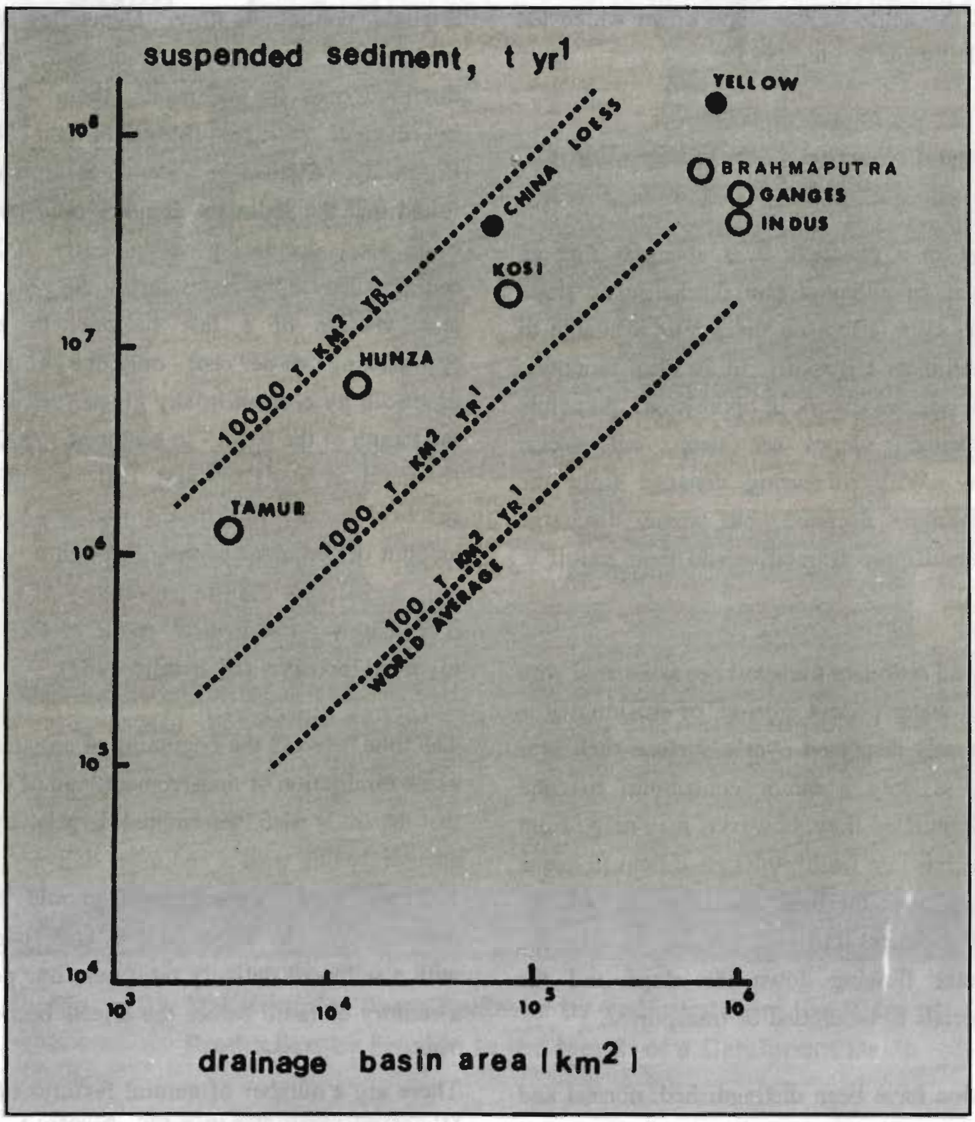


Figure 2: The Sediment Load of Selected South Asian Rivers Compared to the World Average

Source: Ferguson 1984.

Erosion and sediment transport are both processes associated with the work done by water as it moves through the terrestrial portion of the hydrologic cycle. This ability to perform work is defined in terms of power -- the rate at which work is performed. In simple terms, the amount of work that falling or flowing water is capable of is defined by kinetic energy -- the energy of motion. The energy in precipitation is related to droplet size and depth of precipitation during some defined time period -- precipitation intensity. The ability of that precipitation to promote erosion will depend upon a complex interrelationship among surficial properties (e.g., infiltration rate, particle cohesion, coefficient of friction, density of vegetation cover, slope angle). Generally-accepted methods to quantify these interrelationships have yet to be developed, and erosion studies remain highly site-specific and empirical.

The power of flowing water is defined by the depth of flow per unit time and the angle of the slope down which the water is flowing (Petts and Foster 1985):

$$\textit{Power} = \textit{Stream discharge} \times \textit{the gravity slope.}$$

For water flowing in a channel, it is apparent that an increase or decrease in either stream discharge or slope angle will have the same effect on the power available to cause erosion or sediment transport. In an ideal mountain basin, these factors normally work in opposition. At points nearest the headwaters, slopes are steep, but stream discharge is low. With increasing distance from the headwaters, slope angles decrease, but stream discharge increases as more and more tributaries add their runoff to main channels.

Generally erosion and sediment transport are associated with channelled flows of water. Sheet erosion, or erosion that is more or less uniformly dispersed over a surface such as a field or meadow, is only a minor contributor to total sediment yield. Channelled flow, however, may range from small, incipient rivulets in a freshly-ploughed field to major rivers, but, in every case, the basic considerations are the same. Erosion and sediment transport will depend upon the power of the water flowing down the slope and the availability of materials to be eroded or transported.

Two types of erosion have been distinguished: normal and accelerated. Normal erosion is that associated with natural geological, geomorphological, and climatological processes. Accelerated erosion is that associated with human activities. In practice, it is often difficult to distinguish between the two. Particularly in the mountainous headwaters of the rivers originating in the Hindu Kush-Himalayas, it is more realistic to consider all sediment as having resulted from natural processes rather than to assume that it is the result of accelerated erosion (Tejwani 1984 and Haigh 1989). This makes it easier to identify and correct those areas in which accelerated erosion is actually occurring (Carson 1985 and Ramsay 1986).

An important concept linking the processes of erosion at any point within a watershed to the amount of sediment moving through and out of that watershed is that of the "sediment delivery ratio" (Petts and Foster 1985). This is the ratio between the amount of material produced within the basin by erosion annually and the amount leaving the mouth of the basin. Commonly, the products of erosion do not pass directly from their point of origin through the watershed in a single, continuous flow. Depending on the topographic complexity, size of the watershed, and the grain-size distribution of the sediments, there will be a number of intermediate storages (Megahan and Nowlin 1976, see Figure 3). Studies in watersheds around the world have found that the sediment delivery ratio correlates well with basin size, decreasing from nearly 100 per cent -- all sediment leaves the basin during the year it is produced - in small basins of a few hectares in extent, to values approaching one per cent - only one per cent of the sediment produced by erosion in any given year actually moves past the mouth of the basin - in basins of 1,000 sq. km. or larger (Leopold et al. 1964 and Petts and Foster 1985). In practical terms, this means that attempts to control the amount of sediment passing through a watershed annually, e.g., to increase the life expectancy of a reservoir, become increasingly problematical as the surface area of the basin involved increases (Mahmoud 1987).

The time between the beginning of erosion control measures and a diminution of the sediment load of the stream draining that basin is also determined largely by basin size. In smaller basins with a sediment delivery ratio approaching 100 per cent, improvement should be noted almost immediately. In larger basins, and particularly in those with a sediment delivery ratio near one per cent, it may be a century or more before the effects become detectable.

There are a number of natural features of the Hindu Kush-Himalayas ensuring that large quantities of sediment are delivered to the rivers of the region for transport through the river system (Goudie et al. 1982 and Hagen 1980).

These include:

(a) the glaciated nature of the basins,
(b) the limited natural vegetation cover,
(c) the extreme local relief,

(d) the fractured nature of the rock,

(e) the efficacy of freeze-thaw weathering cycles,

(f) the presence of easily-eroded glacier debris, and

(g) the frequency and magnitude of landslides, mudflows, and avalanches that deliver sediment to the tributary channels.

Few of these are amenable to modification using traditional environmental management practices. It is essential that sources of sediment be defined clearly, so that large amounts of time, effort, and money are not invested in attempts to correct what may be normal characteristics of these mountains.

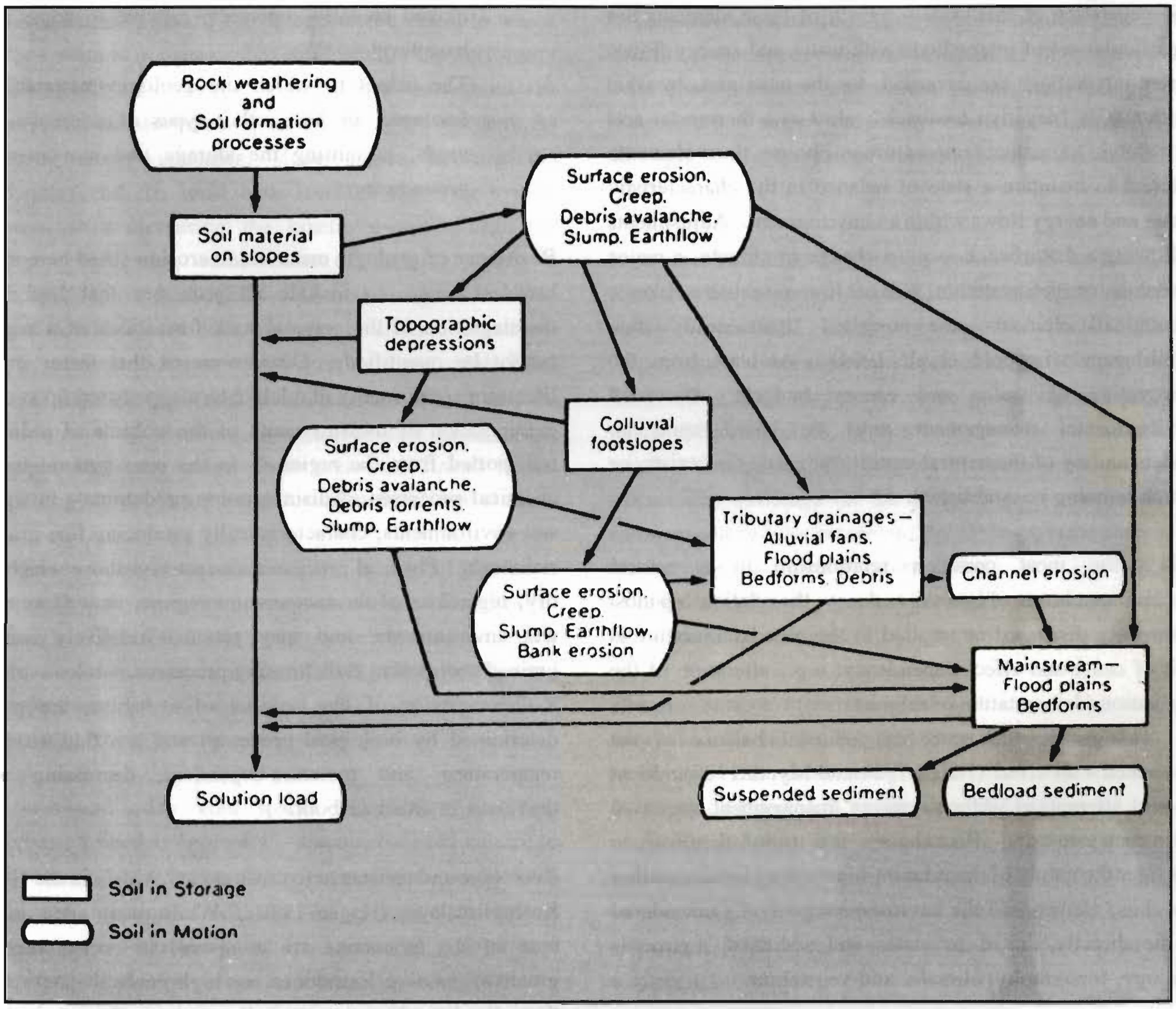


Figure 3: The Complex Paths Followed by Sediment from the Point of Production by Erosion to the Mouth of a Catchment Basin

Source: Megahan and Nowlin 1976.

Note: As the size of the basin increases, the importance of intermediate storage also increases.

III. Environmental Interrelationships

The volume and timing of the flow of water through an ecosystem are related to the climate, geology, topography, and vegetation of that system. Each of these elements has a particular set of interactions with water and energy flows. These interactions are governed, for the most part, by what is known as "negative feedback". Just as a thermostat acts to maintain a constant temperature in a house, these elements interact to maintain a state of balance in the characteristic water and energy flows within an environment. Adjustments following a disturbance, e.g., a change in climate, a major landslide, or deforestation, will act to re-establish a balance among all elements, the so-called "quasi-steady state equilibrium" (Leopold et al. 1964). At least from the perspective of water and energy budgets, successful environmental management must be based upon an understanding of the natural equilibrium state that exists, or which is being re-established.

While the most common relationship in a natural environment is one of interdependency, the relationship most commonly discussed or implied in the popular literature is that of cause-and-effect dependency: e.g., alteration of the vegetation (deforestation or reforestation) -- a cause -- results in changes in the water or sediment balance of the watershed - an effect (Haigh 1984 and Myers 1986). Most current attempts at water resources' management are based upon such cause-and-effect chains. It is useful, therefore, to consider the nature of the relationship existing between water and those elements of the environment generally considered to be directly linked to water and sediment regimes - geology, topography, climate, and vegetation.

Geology

Geology defines the composition and structure of the rocks forming the floor of the watershed. From the standpoint of water resources' management, the following primary geological factors should be taken into consideration.

1) Resistance of the geologic materials to the dominant form(s) of erosion (including soil-forming processes) in the region.

2) The tectonic stability of the region, i.e., whether or not portions of the region are moving, or have moved recently, upwards, relative to some local base level.

3) The extent to which the geologic materials are fractured, or have other types of interconnected voids, permitting the storage and movement of groundwater.

Resistance of geologic materials to erosion (used here in the broadest sense, to include all processes that lead to a disintegration of the original rock formations of a region) cannot be quantified. Discussions of this factor in the literature are normally in relative terms, or based upon areal extrapolation of measurements of the volume of sediment transported from the region. In the most general terms, chemical processes of disintegration predominate in warm, wet environments, characteristically producing fine-grained sediments. Physical processes characterise those which are dry, regardless of the temperature regime, as well as cold-wet environments, and may produce relatively coarse-grained sediments. Soil-forming processes, while involving a disintegration of the bedrock of a region, are partly determined by biological processes and are thus strongly temperature- and moisture-dependent, decreasing with decreases in either or both.

Rock-type and resistance to erosion vary widely in the Hindu Kush-Himalayas (Hagen 1980). While many areas in the core of the mountains are composed of rocks, such as granites, massive limestones, or high-grade metamorphics that are relatively resistant to all processes of erosion, there are also areas underlain by poorly-cemented sedimentary rocks or low-grade metamorphics such as phyllites. These latter rock-types are particularly vulnerable to erosion by running or percolating waters and, in particular, to cycles of freezing and thawing of water contained in fractures or pores. These "freeze-thaw cycles" may occur daily for periods of months throughout an altitudinal range of 1,000s of metres and exert tremendous pressure on rocks as water cycles between the liquid and solid phases. This process rapidly converts the rock to rubble, which is then susceptible to transport by running water or mass-wasting. Soil-forming processes correlate negatively with altitude, decreasing in importance with increasing altitude, as chemical disintegration is replaced by physical weathering processes such as frost-shattering.

Mountains are formed by the uplift and overthrusting of large blocks of the earth's crust. These processes are referred to as "tectonic". The tectonic activity of a region is of importance primarily to determine the extent to which a river system is in geomorphic equilibrium - the uniformity with which kinetic energy is distributed throughout the system from the headwaters to the mouth of a watershed. As tectonic activity increases, slope angles between the headwaters and the local base level of the river system increase, thus increasing the kinetic energy within the system. Following some form of tectonic uplift, a landscape, such as a mountain watershed, readjusts to a new state of equilibrium at differing rates in different locations. This adjustment to a new equilibrium state can create local areas of high energy - and thus, erosion -- which may be misinterpreted as resulting from some other cause, e.g., improper land use, unless these areas are linked to the morphology of the entire basin during water-related studies.

The Hindu Kush-Himalayan Region is one of the most tectonically-active mountain ranges on earth. An analysis of the long profiles of the major meso-scale rivers of the region would disclose numerous discontinuities in long profiles and cross-sections of the river valleys, reflecting past periods of increased tectonic activity.

Fractures and other void spaces within the geologic materials (defined as "porosity" - the ratio of void volume to total volume, - and "permeability" - the degree to which the voids are interconnected) are the primary factors in determining the existence and importance of groundwater resources. Where the rock is neither porous nor permeable at depth, such as in the case of unfractured granite, there is no groundwater, no matter how "wet" the surface environment may be. The best groundwater environments are well-sorted alluvium (deposits formed by running water, which may have a depth of as much as 5,000m over portions of the Indo-Gangetic Plains), cavernous limestones, or sandstones. In the most general terms, mountain watersheds are poor groundwater environments. The rocks forming the core of a mountain range commonly have limited porosity and permeability, limiting groundwater occurrence to local fracture zones or pockets of alluvium. Significant groundwater resources most often begin only at the margin of the mountains - the piedmont zone - and extend downwards into the alluvial valleys of the lowlands. (A detailed discussion of the geology of the Himalayas can be found in Hagen 1980.)

Climate

Climate is the long-term average of meteorological processes as they interact with and influence the surface of the earth. Climate is commonly defined in terms of the processes of mass (precipitation), momentum (wind), and energy (air temperature, solar radiation) transfers between the atmosphere and the earths' surface (Barry 1981 and Flohn 1974).

In areas of extreme topographic relief, such as the Hindu Kush-Himalayas, climatological stations are often located on valley floors that commonly have a much different "topoclimate" from adjacent slopes or ridges (Geiger 1966). Two valley floor stations in close proximity can produce much different values, if one is located at the base of a windward slope and the other is at the base of a leeward slope. The challenge for the climatologist in the mountain environment and, by extension, the environmental planner or manager is to develop interpolation or extrapolation techniques that will represent accurately the spatial patterns of existing topoclimates.

The scale at which hydrological problems are approached may affect the results obtained from the available data. In particular, the relationship(s) between streamflow or sediment transport and environmental factors may change markedly between the micro-scale - the scale of the individual precipitation gauge or erosion plot - the intermediate, or meso-scales, of the individual mountain slope or altitudinal belt - and the macro-scale - the scale of a major river basin.

Meso-scale variations in all elements of the environment, produced by local variations in terrain, are the central issue in understanding and managing any aspect of the mountain environment. At the same time, the meso-scale is the least studied of the three scales in the mountain environment, at least from a perspective relating the processes that determine the mountain environment (e.g., water and energy fluxes) to the properties of that environment (e.g., distribution, type, and density of vegetation). Without this sort of understanding, it is very difficult to assess the probable impacts of any form of environmental management on the water resources of a given basin (Mather 1974).

Topography

Topography, or landform, is a primary factor in determining local patterns of water and energy exchange in mountain watersheds. In turn, these variations in water and energy availability give rise to a spatial mosaic of ecosystems with often widely varying forms of flora and fauna. Geomorphology is the branch of the earth sciences dealing with the study of terrain.

Mountains are often defined as being regions of "extreme local relief". They are also regions of extreme geomorphic complexity and activity. In addition to altitude, the topographic (or geomorphic) factors influencing the surface water and energy budgets are slope angle and aspect. In the lowlands, within the scale of a "normal" resource development project, terrain variables such as altitude, aspect, and slope do not commonly enter into management decisions. In large mountain ranges, if one does not understand the terrain, there can be no basis for understanding the spatial complexity of any other environmental element of interest.

Relief

Relief - elevation above some local base level - is the characteristic topographic element most commonly associated with mountains. The terms "relief", and "altitude" are not synonymous. Altitude is an absolute term, defined with respect to sea level. In a physical sense, relief determines the kinetic energy of the mountain surface, while altitude determines the properties of the air mass surrounding the mountain. The altitudinal interval occupied by the local relief of a given mountain or mountain range is a primary factor in determining differences among mountains. Sagarmatha (Chomo Longma, Mt. Everest), in the Nepalese Himalayas, rises approximately 3,000 m above a local base level, as does Mt. Robson in the Canadian Rockies. The altitudinal interval occupied by Sagarmatha is between approximately 5,000-8,000 m, while that of Mt. Robson is between approximately 1,000-4,000 m. This difference in the altitudinal interval in which the local relief exists produces significant differences in the meteorological environments of the two mountains. To an observer at the base of either, these differences would not be apparent.

In the Hindu Kush-Himalayan Region, both altitude and relief are at a maximum for the earth as a whole, maximising the effects of both altitude and relief.

Slope

Slope is determined by local relief. As slope angles increase, there is a concomitant increase in the importance of all processes linked to gravity, e.g., the kinetic energy of flowing water, mass movements of soil and rock, or the flow of glaciers.

There are a number of areas in the Hindu Kush-Himalayan Region that have been identified as having the greatest local relief of any terrestrial environment on earth. It is probably the Hunza Valley in the Karakoram Range that merits this distinction. In the Karakorams, the Hunza Valley rises from about 1,850 m to the summit of Rakaposhi at 7,788 m, a vertical difference of 5,938 m in 11 km. The other location that has a comparably great vertical height difference over a comparably short horizontal distance is the Kali Gandaki Valley of Central Nepal, rising from around 2,470 m to 8,167 m at the summit of Dhaulagiri I, an elevation difference of 5,697 m over 11 km. Comparable relief exists in the Arun River Valley in Eastern Nepal. These great changes in altitude over relatively short horizontal distances greatly increase the role played by slopes in the processes of erosion and mass wasting (Ferguson 1984).

Slopes and slope-forming processes are central to any understanding of the high volumes of sediment moving through the rivers of the Hindu Kush-Himalayan Region. Slopes and the processes that form them in this region can be divided into the following categories (Hagen 1980, Goudie et al. 1982, and Carson 1985).

(a) <u>Snow- and ice-covered avalanche slopes</u> of the high peaks, usually exceeding 40 degrees in steepness, characterised by sheer faces, overhanging cornices (accumulations of windblown snow), hanging glaciers, and avalanche chutes.

(b) <u>Rock slopes</u>, seasonally snow-covered, subject to severe freeze-thaw and chemical weathering, scarred by rockfalls, avalanches, and mudflows and ranging from 40 degrees to 90 degrees in steepness. In some places, these rock slopes descend to the valley floor, but, more commonly, they terminate up to 1,000 m above the valley bottom because of the accumulation of surface debris.

(c) <u>Scree slopes</u>, composed of rock detritus at the foot of rock faces. They vary in form from simple small rockfall-scree cones to huge compound debris accumulations with slope lengths of up to 1,000 m and relative heights of up to 500-600 m.

(d) Mudflow debris cones and fans occur where fed by discharges of sediment and water from narrow gullies and ravines in the steep rock slopes above. These represent an intermediate member of a continuous series of debris accumulation forms, ranging from high-angle scree slopes to low-angle alluvial fans. Mudflows are probably the most important sculpturing process operating on the lower debris slopes and can occasionally be of such enormous size and destructive force as to create lobes of sufficient volume to dam rivers.

(e) Large, low-angled (2-7 degrees) alluvial fans occur at points where powerful meltwater streams debouch at locations where the main valley is broad enough to allow for their development;

(f) Valley fills. Valleys of the region commonly contain varying thicknesses of unconsolidated sedimentary deposits. The surface of these fills usually slopes gently (less than 7 degrees) towards the centre of the valley, except where overlain by younger moraines (glacier deposits). Some tributaries of the Indus River have become deeply incised into these very young sediments to produce near-vertical cliffs, sometimes as much as 150 m high, which periodically fall into the river as debris falls.

Aspect

Aspect - the compass direction faced by a slope - plays two crucial roles in modifying the surface water and energy budgets. Major air masses follow relatively uniform paths through the region each year, and slopes will either be approximately facing into, or away, from the path followed by the air mass. "Windward" slopes - facing towards the direction from which the air mass is coming - and "leeward" slopes, facing away from this direction, will be respectively wetter and drier than regional average values, as the air mass rises and descends in its path across the mountains. Rising air cools and, as it cools, loses its ability to retain moisture, resulting in increased precipitation. As the air mass descends on the opposite, lee slope, it warms, increasing its moisture-holding capability and producing diminished precipitation (Barry 1981).

The second factor associated with aspect involves the amount of energy received as sunlight. In the northern hemisphere, south-facing slopes receive the maximum amount of sunlight possible during a year, or season, for any given latitude. North-facing slopes receive the least, with east- and west-facing slopes receiving an intermediate value. This difference between north-facing and south-facing slopes increases with distance from the equator and with increasing altitude in any mountain range, as the importance of sunlight in the energy budget becomes increasingly important (Geiger 1966).

In the Hindu Kush-Himalayan Region, it can be expected that windward-leeward relationships will be most important in the eastern portion of the region, at least at the lower altitudes, while orientation with respect to solar angle will be more important in the western portion of the region, approximately 10 degrees further north. This east-west difference should gradually diminish with increasing altitude until, above a certain elevation (approximately 4,000 m), both processes should be roughly uniform throughout the region. This will occur as a result of the decreasing atmospheric moisture with increasing altitude and as a result of the important role this moisture plays in determining both the water and radiation budgets.

Vegetation

Possibly the most emotional positions taken concerning the relationship between an environmental element and water resources have centered around the role played by vegetation in the hydrologic cycle (Bowonder 1982, Haigh 1989, and WRI 1985). This is particularly true of the relationship between changes in forest cover and possible changes in the timing or volume of water availability, both within and downstream from the watershed, as well as erosion within and sediment transport from the affected watershed. Hamilton (1987) has discussed this problem in detail. Vegetation plays three primary roles in the hydrologic cycle: (1) it acts as a buffer between falling or flowing water and the ground surface, (2) it intercepts a percentage of precipitation which is then returned directly to the atmosphere by evaporation, and (3) it returns to the atmosphere a portion of the water which falls as precipitation by the process of transpiration - the flow of water through the roots, stems, and leaves of plants that accompanies photosynthesis.

Vegetation and the surface water and energy environment evolve together. This fact is reflected in concepts of plant succession within ecosystems. In the absence of disturbance, plant communities follow one another in a somewhat predictable sequence and the surface environment is altered by each in turn. In determining the possible impacts of vegetation manipulation, either removal or replacement, it is useful to understand that, at least from the perspective of hydrology, a "forest" is much more than a collection of trees. A forest is a complex assemblage of trees, bushes, and other understory plants, ground litter, soil, and, often in the mountains, bedrock. This assemblage of environmental elements modifies the impact of rain drops on the surface, increases the potential water infiltration into the surface, and alters the nature of energy exchange processes on and near the surface. It is the assemblage of elements, and not the trees alone, that modulate the hydrologic cycle. Removal of the trees, if accompanied by a loss of understory vegetation, litter, and soil as well, may well produce measurable changes in the flow of water and energy into, through, and from the site. Replacement of the trees -- "reforestation" - will not restore the pre-existing conditions until sufficient time has passed for the elements of the mature forest -- the understory, litter, and soil - to have been replaced.

From the perspective of fluvial geomorphology (the branch of science dealing with the role of water in erosion and landscape formation), it is not necessarily the **type** of vegetation that is important but rather the **density** of the ground cover that is critical in determining rates of erosion. All other things being equal, erosion rates in any environment will be highest on bare mineral soil; e.g., soils associated with road-building or seasonal tillage of agricultural lands. It will probably be at a minimum under a dense cover of ungrazed grass, rather than beneath a forest, because of the higher density of ground cover and the near-surface root density of the grass cover relative to the forest (Dunne and Leopold 1978 and Petts and Foster 1985).

There have been many studies demonstrating that changes in the water and sediment budgets of watersheds can be expected as a result of changes in the type or density of the vegetation cover (Dunne and Leopold 1978). For the most part, however, these studies have been conducted in relatively small basins and have involved the removal of a significant percentage of the total vegetation cover. It has generally been found that, in moist climates, unless conscious efforts are made to maintain a devegetated

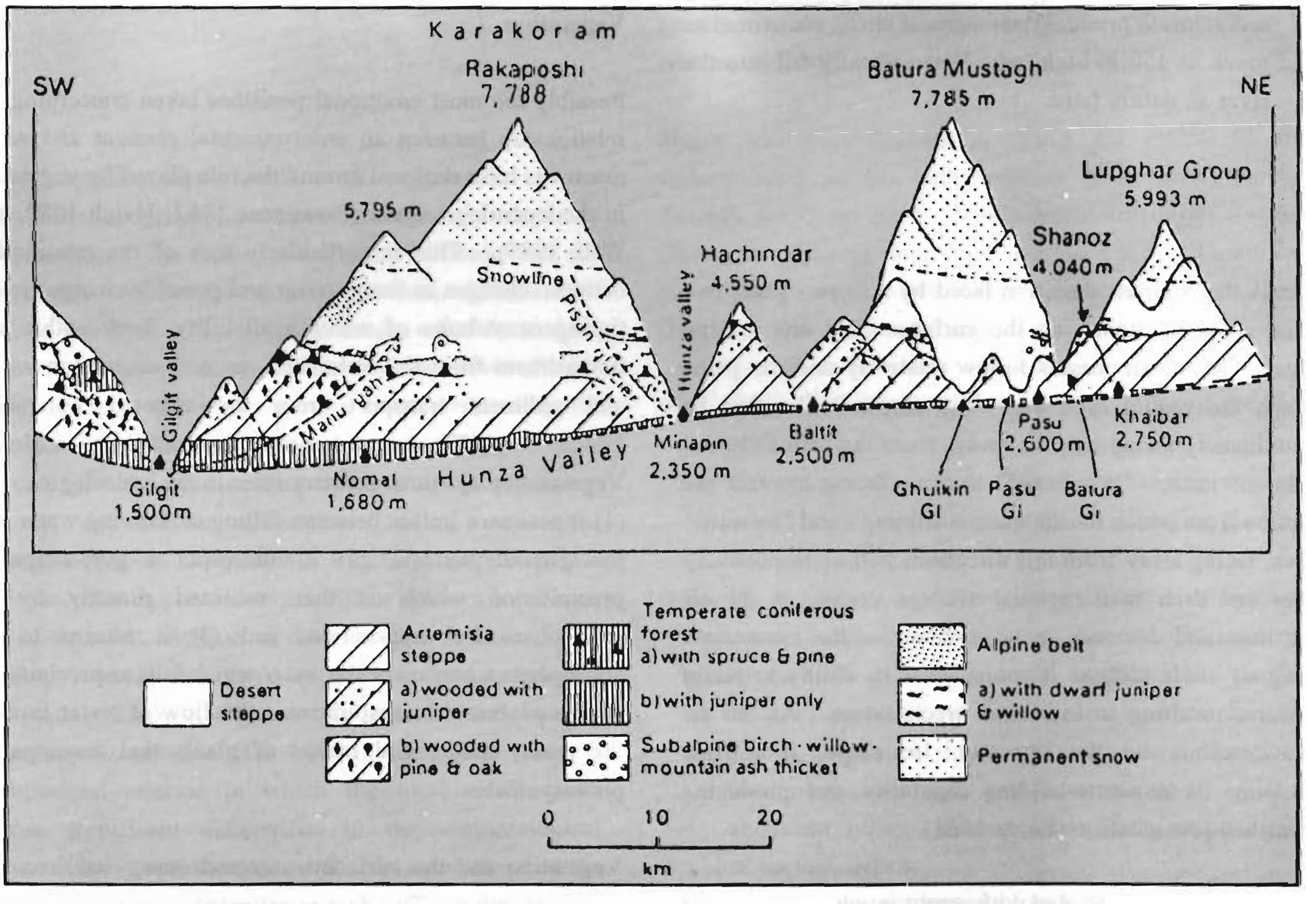


Figure 4: The Altitudinal Zonation of Ecosystems in the Karakoram Range of the Western Hindu Kush-Himalayan Region

Source: Goudie et al. 1982.

condition, e.g., through the use of herbicides, a ground cover is re-established that returns the water and sediment balances to pre-existing conditions. In both the "cold" alpine and dry grasslands, the natural recovery from a disturbance is much slower as a result of a lack of either energy or water. In these climates, therefore, the potential exists for lasting changes to occur. It has been found that the changes in water and sediment discharged from an upstream sub-basin are quickly masked by a "dilution" effect caused by the input from unaffected downstream tributaries, thus making empirical detection increasingly difficult with progression downstream from the affected area.

On the macro-scale, there is an altitudinal zonation of vegetation throughout the mountains of the Hindu Kush-Himalayas (Hagen 1980 and Goudie et al. 1982, see Figures 4 and 5). On the meso-scale, this altitudinal zonation will be complicated by patterns associated with aspect, increasing in importance with altitude and from east to west through the region. Attempts to affect the water or sediment flows from any basin through vegetation manipulation must be based upon an understanding of these zonations, as well as considerations of the total surface area of the basin supporting a natural vegetation cover. If this percentage is low, as a result of altitudinal or aspect constraints on vegetation growth, then changes in water or sediment balances will be difficult to accomplish through the mechanism of vegetation manipulation.

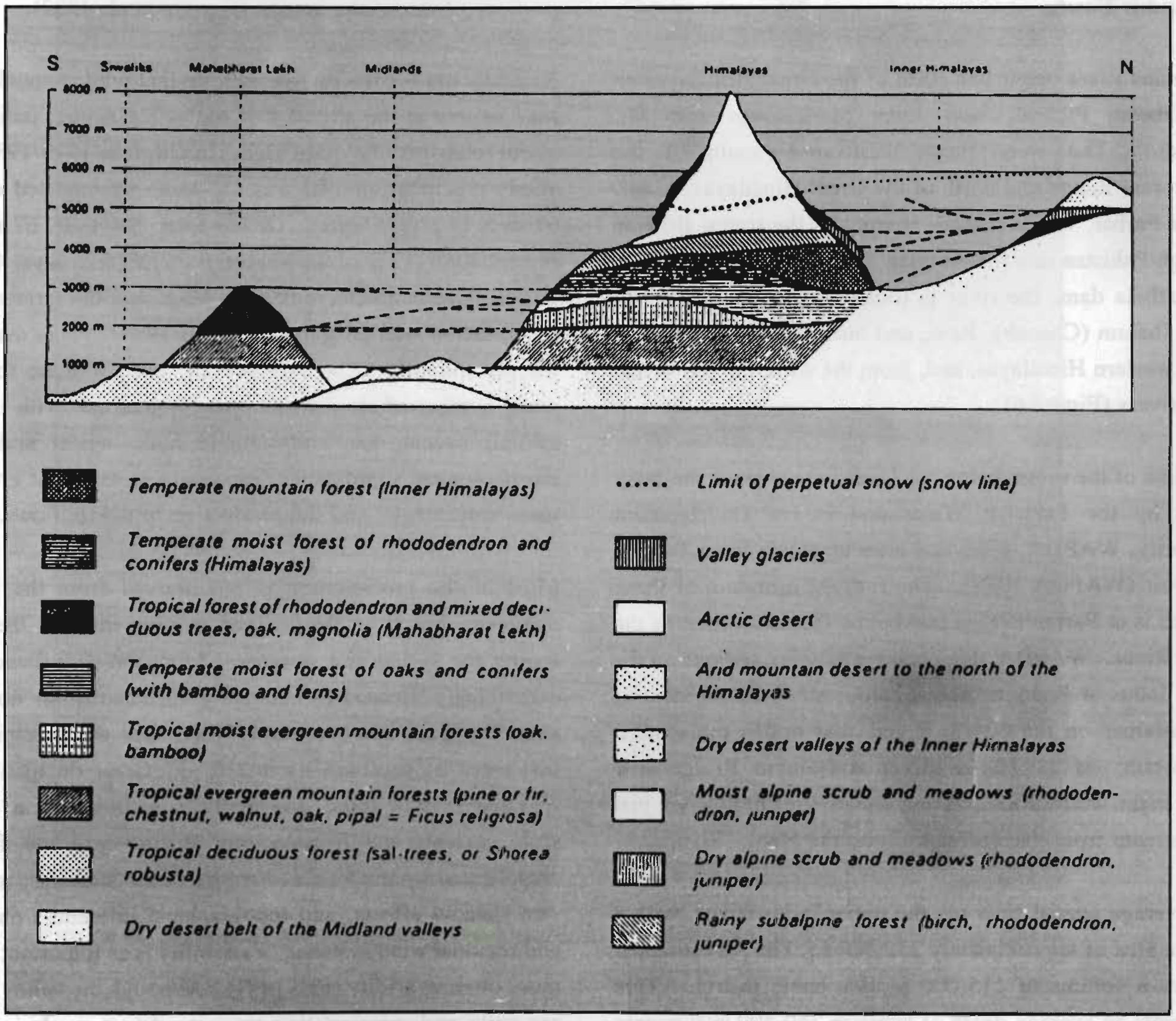


Figure 5: The Altitudinal Zonation of Ecosystems in the Himalayan Mountains of Nepal

Source: Hagen 1980.

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

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

The Indus Basin

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

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

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

Climate

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

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

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

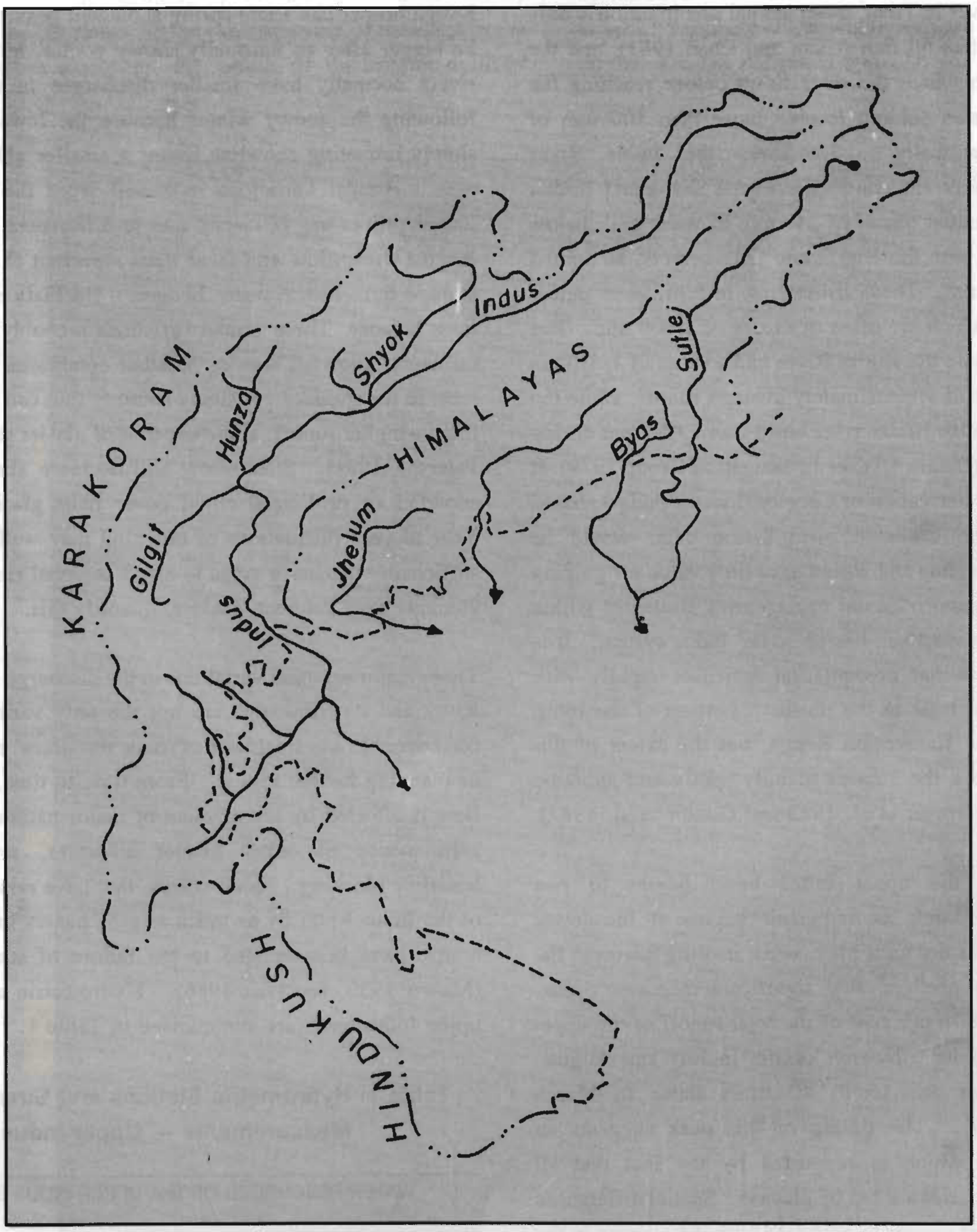


Figure 6: A Sketch Map Showing the Mountain Catchments of the Upper Indus Basin

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

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

Streamflow

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

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

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

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

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

WATER RESOURCES OF THE UPPER INDUS BASIN

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

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

The Ganges Basin

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

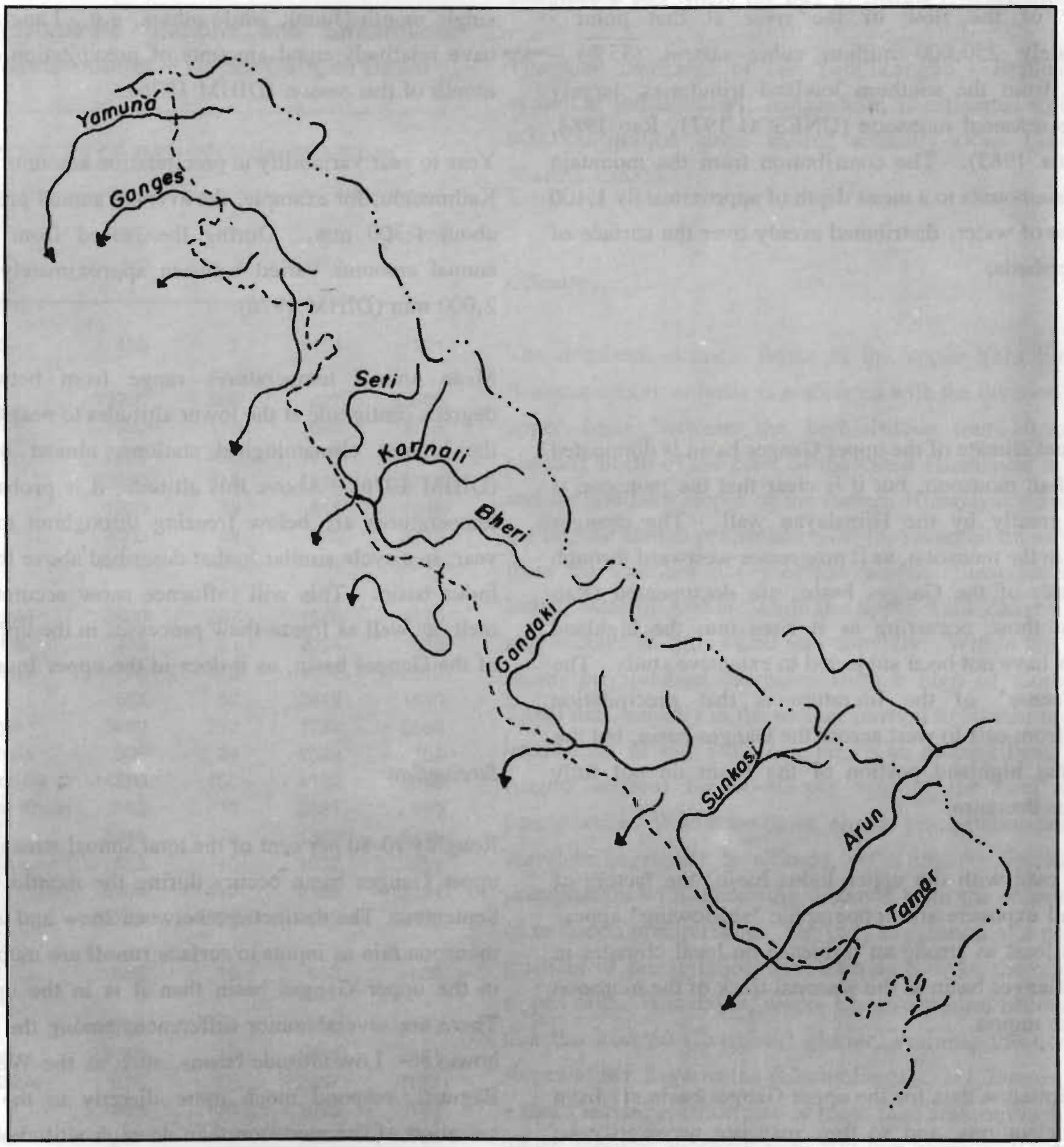


Figure 7: A Sketch Map of the Mountain Catchments of the Ganges River Basin

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

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

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

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

Climate

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

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

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

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

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

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

Streamflow

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

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

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

WATER RESOURCES OF THE UPPER GANGES BASIN

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

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

The Yalu Zangbu-Brahmaputra Basin

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

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

Climate

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

Streamflow

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

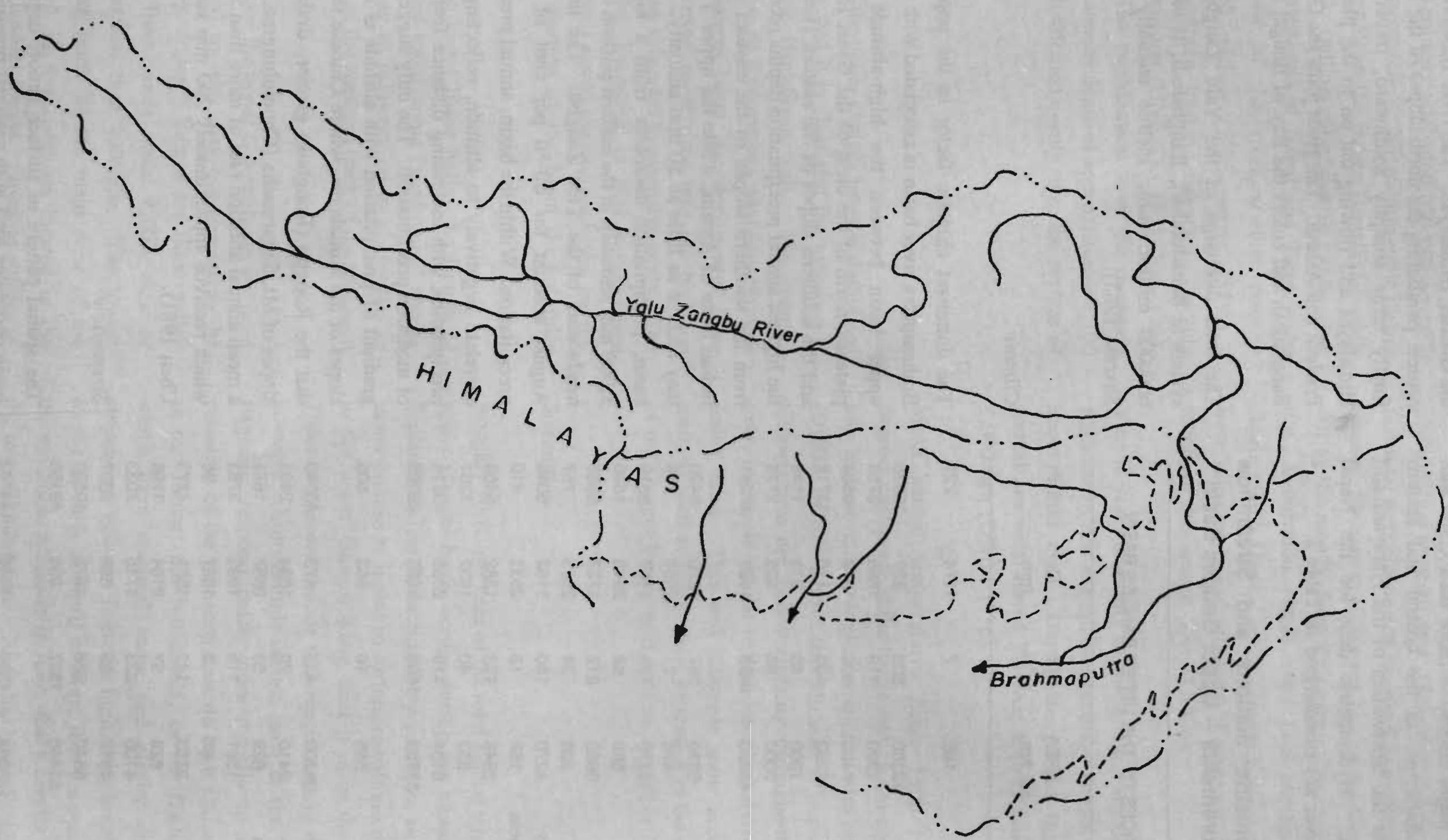


Figure 8: The Yalu Zangbu-Brahmaputra Basin Showing the Lower Limit of the Mountain Portion of the Basin

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

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

WATER RESOURCES OF THE YALU ZANGBU BASIN

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

Source: Guan and Chen 1981

Regional Values of Erosion and Sediment Transport

The Upper Indus Basin

In an average year, the entire Karakoram and Trans-Karakoram region above the Partab gauging station yields 160 million tons of sediment. This is equivalent to approximately 640 tons/km^2/year or 0.15 km^3 of unconsolidated sediment (Ferguson 1982).

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

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

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

The Ganges Basin

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

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

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

The Yalu Zangbu Basin

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

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

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

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

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

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

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

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

Source: Ferguson 1984, Holeman 1968, and Mahmoud 1987

Glaciers of the Hindu Kush-Himalayan Region

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

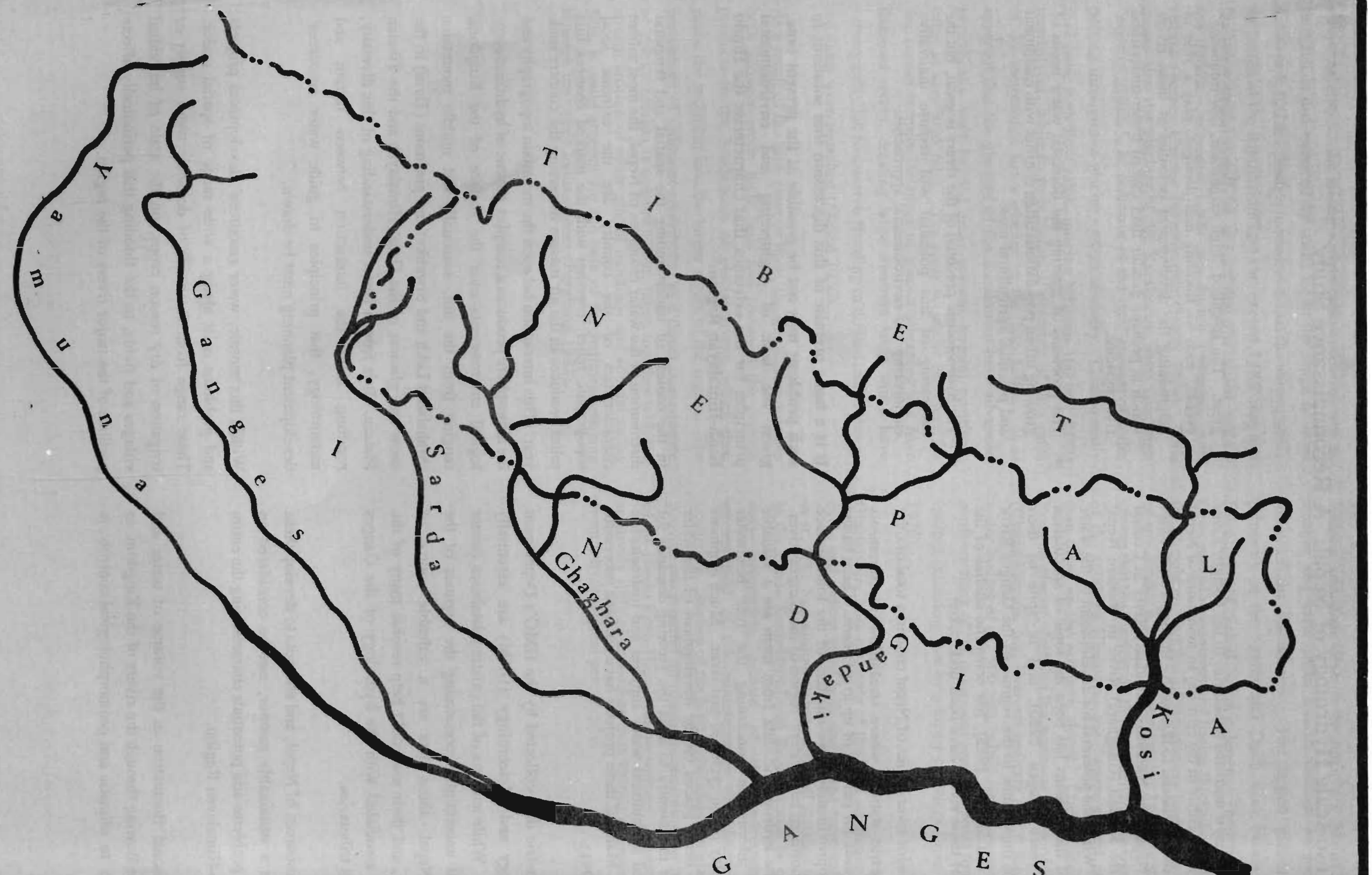


Figure 9: Three of the Major Tributaries to the Ganges River Originate in the Nepalese Himalayas: the Ghaghara (Karnali), the Gandaki (Narayani), and the Kosi

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

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

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

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

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

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

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

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

The Database

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

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

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

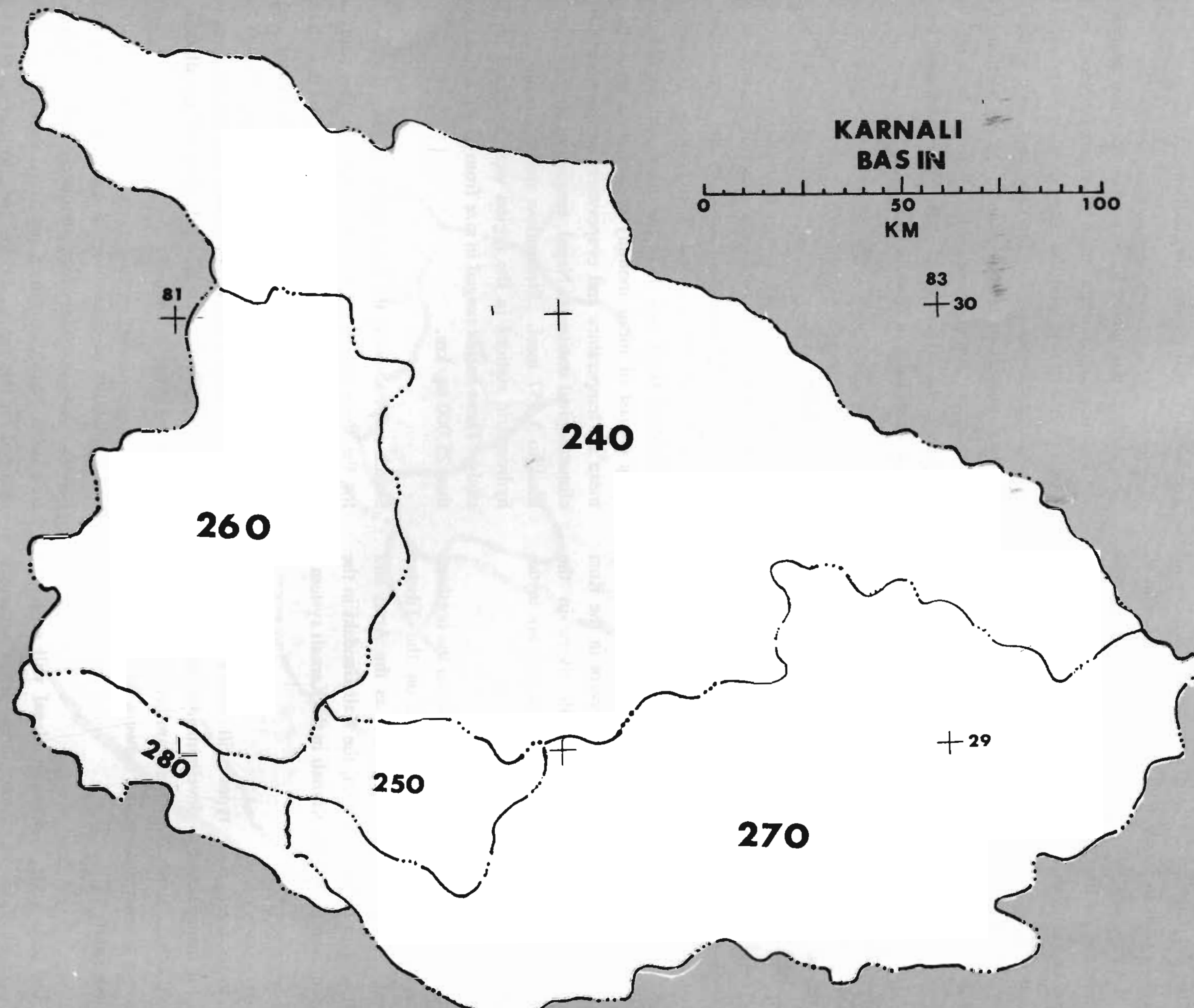


Figure 10: Gauged Sub-basins of the Karnali River for which Data Were Used in This Study

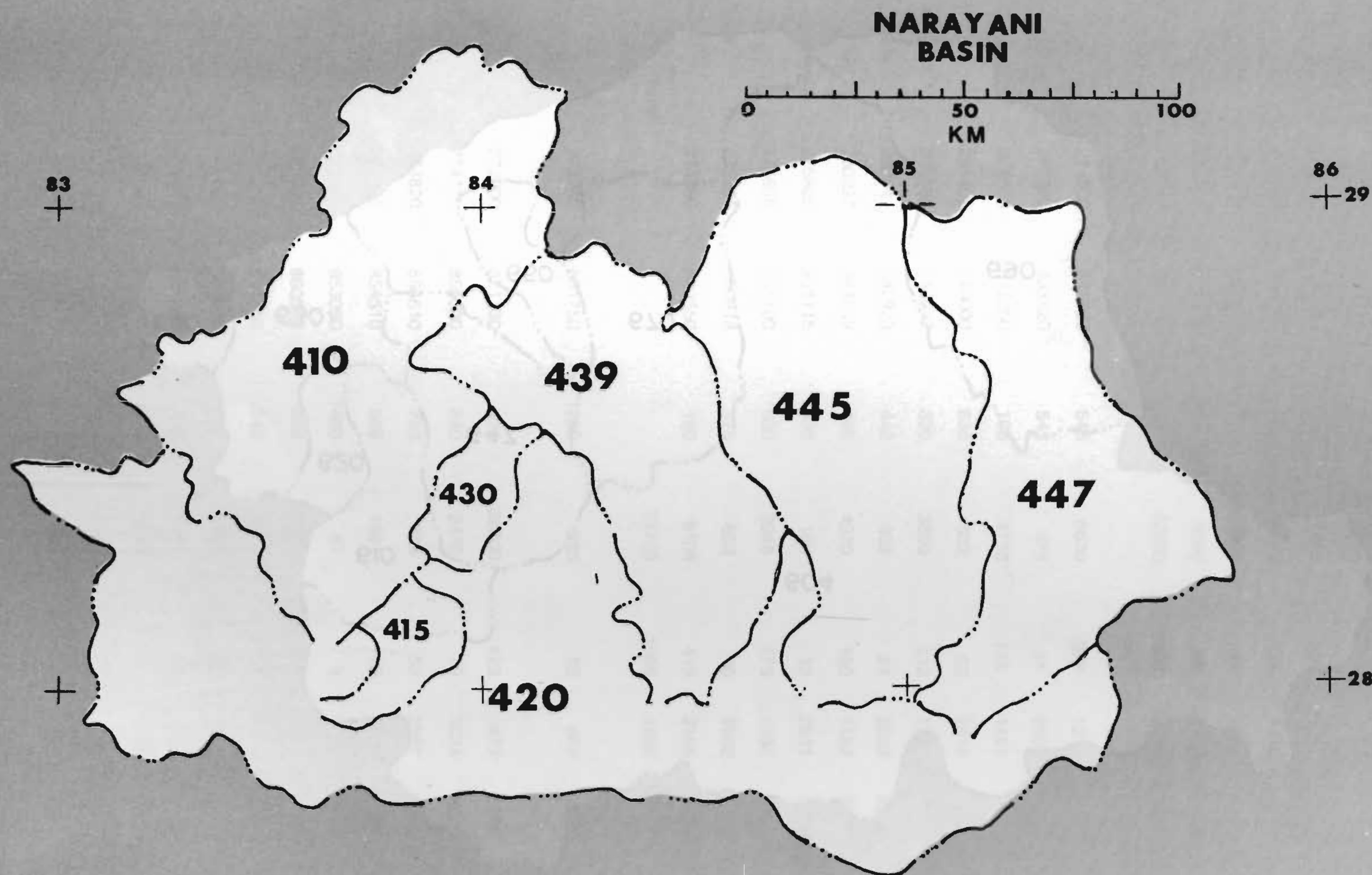


Figure 11: Gauged Sub-basins of the Narayani River for which Data Were Used in This Study

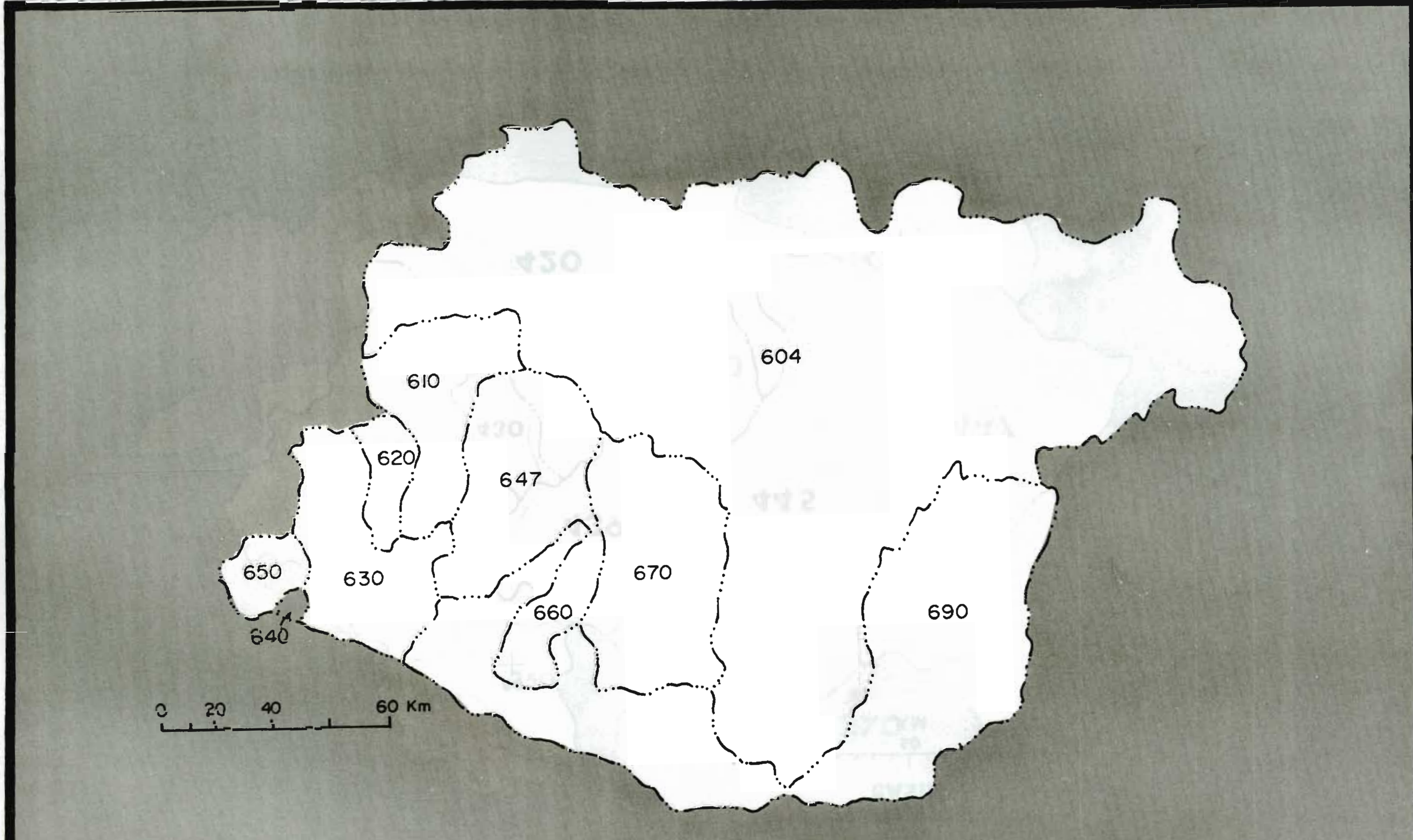


Figure 12: Gauged Sub-basins of the Sapta Kosi River for which Data Were Used in This Study

Table 5: Selected Hydrometric Stations of Nepal

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

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

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

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

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

1. The Sapta Kosi Basin

NO.	NAME	LAT° °N	LONG° °E	ALT (m)	ANNUAL PPT
Bagmati Zone					
1009	Chautara	2747	8543	1660	2007
1011	Kathmandu	2742	8520	1335	1280
1012	Sundarijal	2745	8225	1380	1899
1013	Sundarijal	2746	8525	1576	2057
1014	Kathmandu	2743	8519	1324	1361
1020	Mandan	2741	8539	1370	1737
1021	Kirtipur	2741	8518	1364	1011
1023	Dolal Ghat	2738	8543	710	934
1024	Dhulikhel	2737	8533	1552	1397
1027	Barhabise	2747	8554	1220	2549
1028	Pachuwar	2734	8545	633	795
Janakpur Zone					
1102	Charikot	2740	8603	1940	2160
1103	Jiri	2738	8614	2003	2381
1104	Melung	2731	8603	1536	1827
1106	Ramechhap	2719	8605	1395	1016
1107	Sindhuli	2717	8558	1463	2547
1108	Bahun Tilpung	2711	8610	1417	2189
1109	Pattharkot	2705	8540	275	1954
1110	Tulsi	2702	8555	457	1713
1112	Chisapani	2655	8610	165	1577
1115	Nepalthok	2727	8549	1098	936
1116	Hariharpur	2720	8530	880	2683
Sagarmatha Zone					
1201	Namche Bazar	2749	8643	3450	1007
1202	Chaurikhark	2742	8643	2619	2123
1203	Pakarnas	2726	8634	1982	1769
1204	Aisyalukhark	2721	8645	2143	2604
1206	Okhaldunga	2719	8630	1810	1821
1208	Dwarpa	2713	8651	1829	1494
1209	Bhojpur	2711	8703	1524	1202

NO	NAME	LAT° °N	LONG° °E	ALT (m)	ANNUAL PPT
1210	Kurule Ghat	2708	8625	497	983
1211	Khotang	2702	8650	1295	1089
1213	Udayapur	2656	8631	1175	1978
1215	Lahan	2644	8030	138	1541
1216	Siraha	2639	8613	102	1234
1218	Tengboche	2750	8646	3857	979
1220	Chialsa	2731	8637	2770	1828
1224	Sirwa	2733	8623	1707	582
Kosi Zone					
1301	Num	2733	8717	1497	3079
1303	Chainpur	2717	8720	1329	1350
1305	Leguna Ghat	2708	8717	1680	672
1206	Munga	2702	8714	1317	1288
1307	Dhankuta	2659	8721	1445	912
1308	Mul Ghat	2656	8720	365	1060
1309	Tribeni	2656	8709	143	1851
1312	Haraincha	2637	8723	152	1508
1316	Chatara	2649	8710	183	2177
1317	Chepuwa	2746	8725	2590	2438
1322	Machuwa Ghat	2658	8710	158	1504
Mechi Zone					
1401	Olangchung	2741	8747	3119	1697
1402	Pangthung	2741	8749	2818	1562
1403	Lungthung	2733	8747	1780	2331
1404	Tapelthok	2729	8747	1383	2484
1405	Taplejung	2721	8740	1763	2015
1406	Memeng Jagat	2712	8756	1830	2251
1407	Ilam Tea Est.	2655	8754	1300	1575
1408	Damak	2643	8740	163	2589
1409	Arnamani	2638	8759	122	2242
1418	Angbung	2716	8745	1205	1582
1420	Dovan	2721	8736	1764	1612

2. The Narayani Basin

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

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

3. The Karnali Basin

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

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

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

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

Analytical Procedures

Based upon the available data, spatial and temporal variation in streamflow volume, within and among the sub-basins of Nepal, were determined. These analyses are based upon a comparison of monthly and annual mean values of streamflow volume, in m³/s, and specific runoff, in mm.

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

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

where:

Qs = specific discharge, in mm for time, t;
Qv = measured discharge, in m³/s; and
A = area of gauged watershed, m².

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

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

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

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

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

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

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

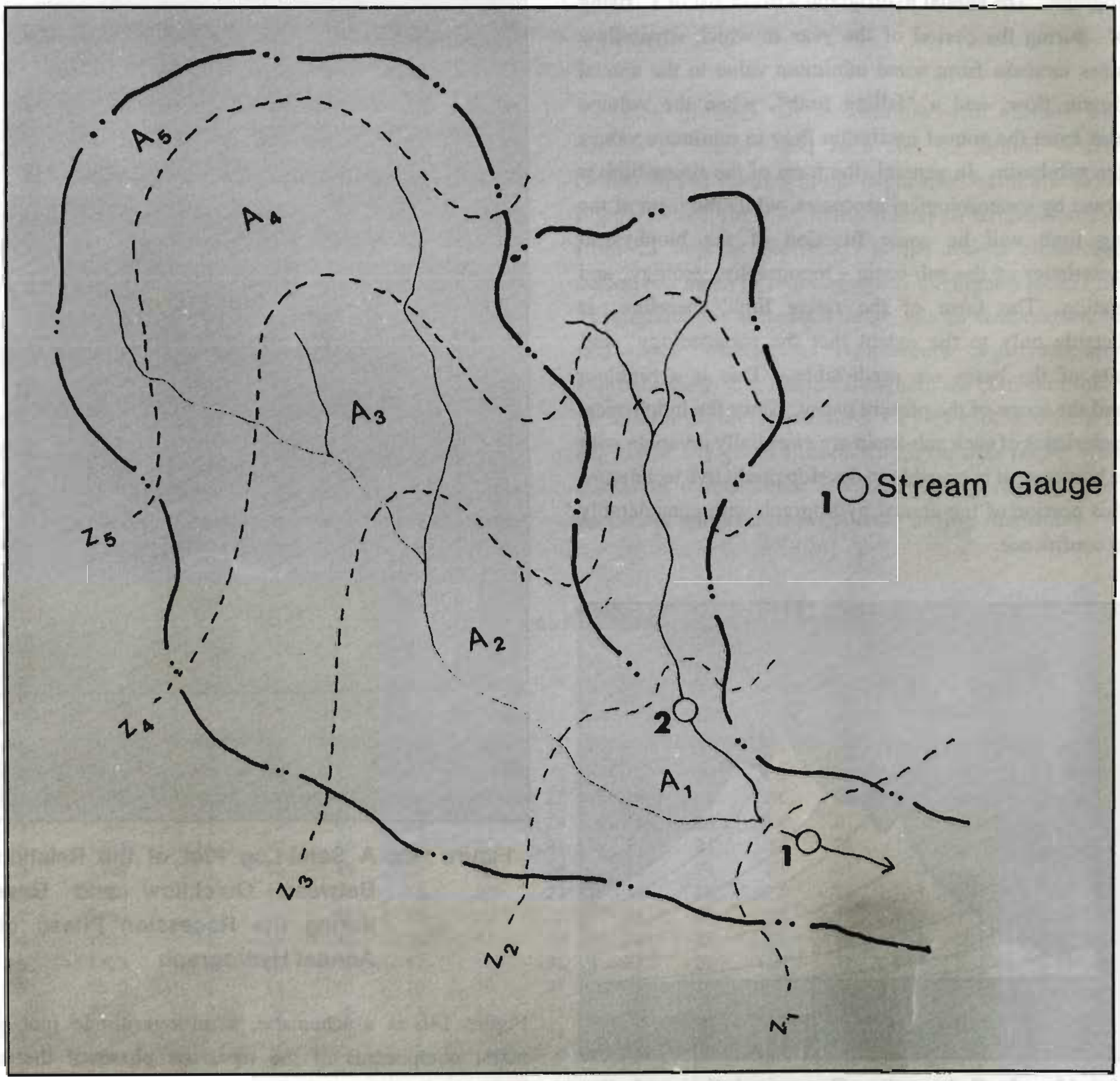


Figure 13: A Schematic Representation of the Altitudinal Zonation Used in this Study to Derive Incremental Volumes of Streamflow

The mean altitude of an altitudinal belt is:

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

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

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

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

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

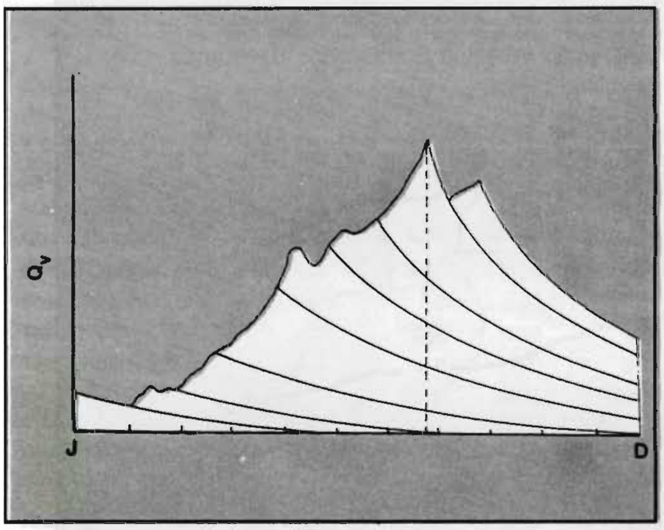


Figure 14a: A Schematic Representation of the Annual Hydrograph, Showing the Composition of the Rising and Falling Limbs

Note: The broken line marks the peak annual flow.

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

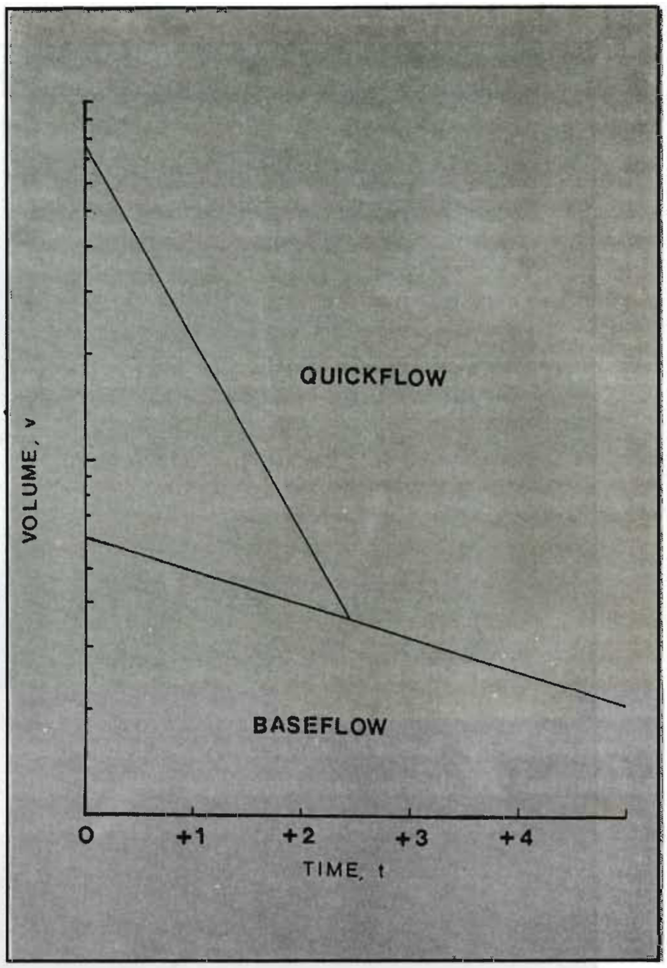


Figure 14b: A Semi-Log Plot of the Relationship Between Quickflow and Baseflow during the Recession Phase of the Annual Hydrograph

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

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

Results

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

Climate

Air Temperature

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

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

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

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

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

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

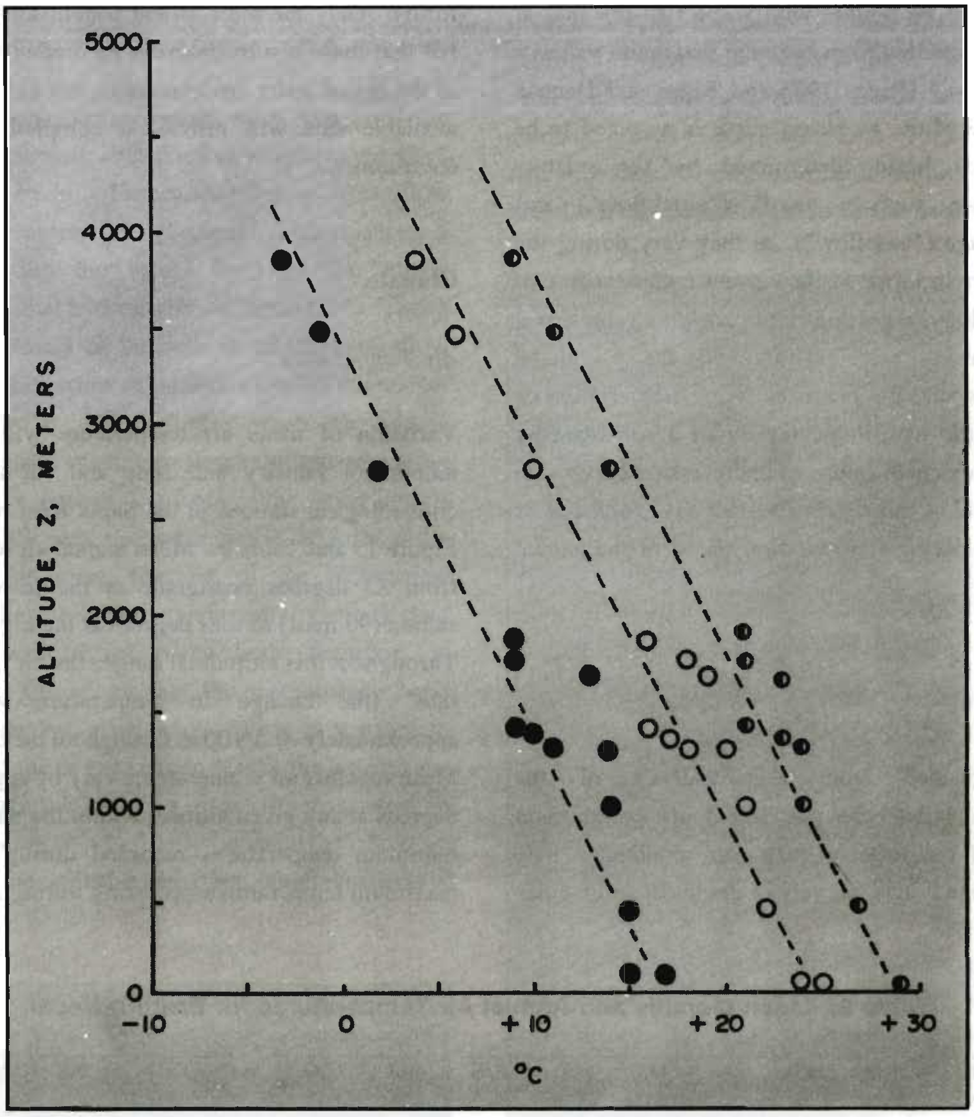


Figure 15: The Relationship between Annual and Seasonal Air Temperatures and Altitude

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

Precipitation

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

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

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

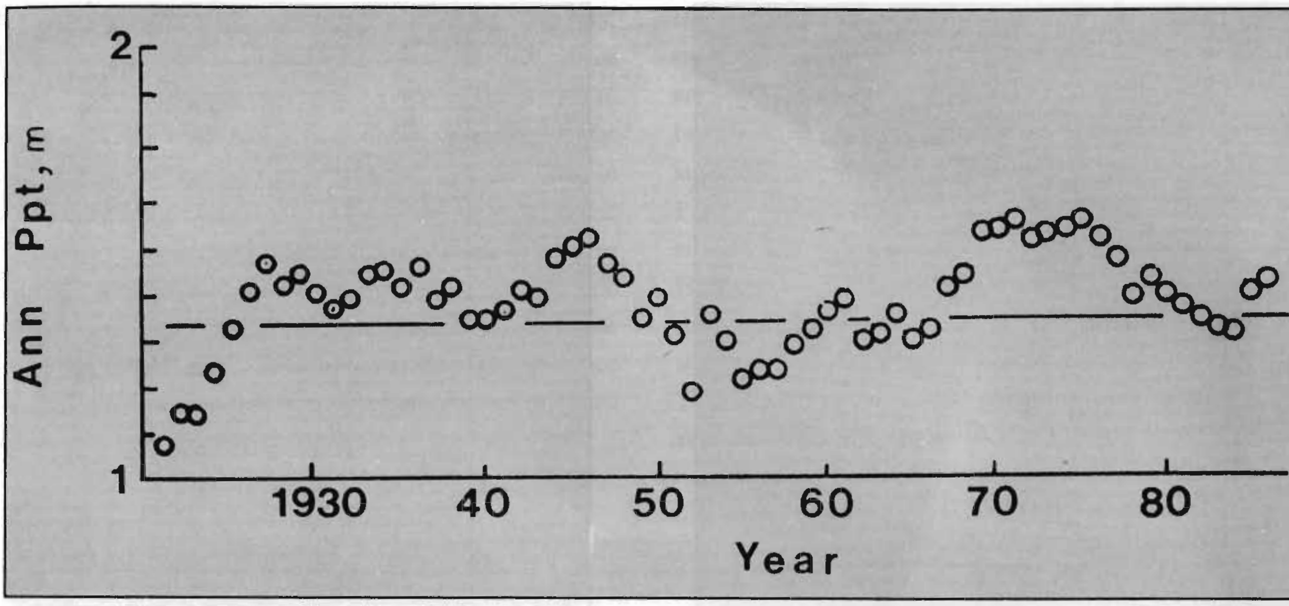


Figure 16: A Five-year Running Mean of Precipitation in Kathmandu for the Period 1921-1985

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

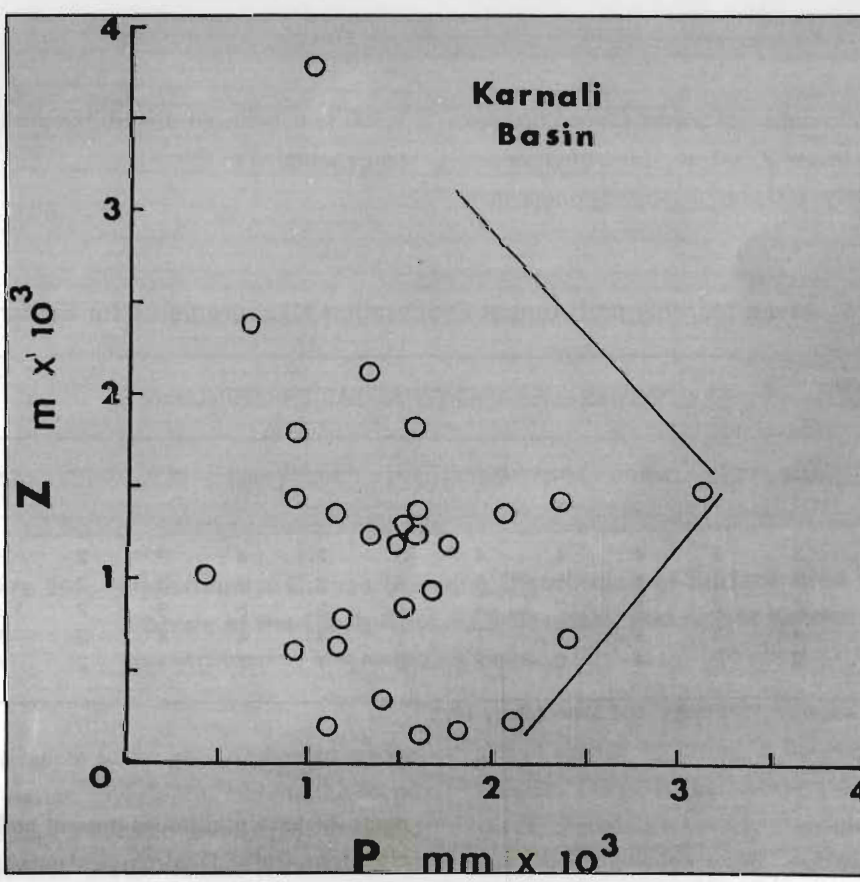


Figure 17: The Distribution of Precipitation with Altitude in the Karnali Basin Shows No Distinct Orographic Trend

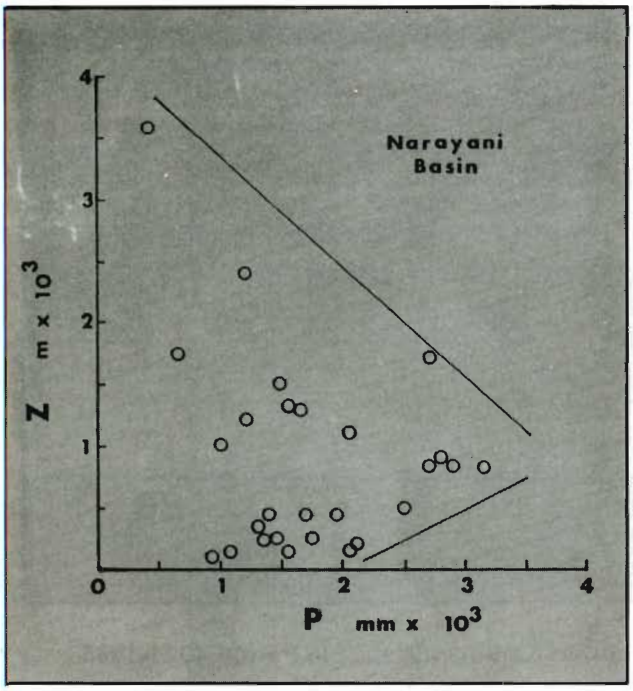


Figure 18: There is Some Suggestion of An Orographic Gradient of Precipitation in the Narayani Basin, Represented by the Formline

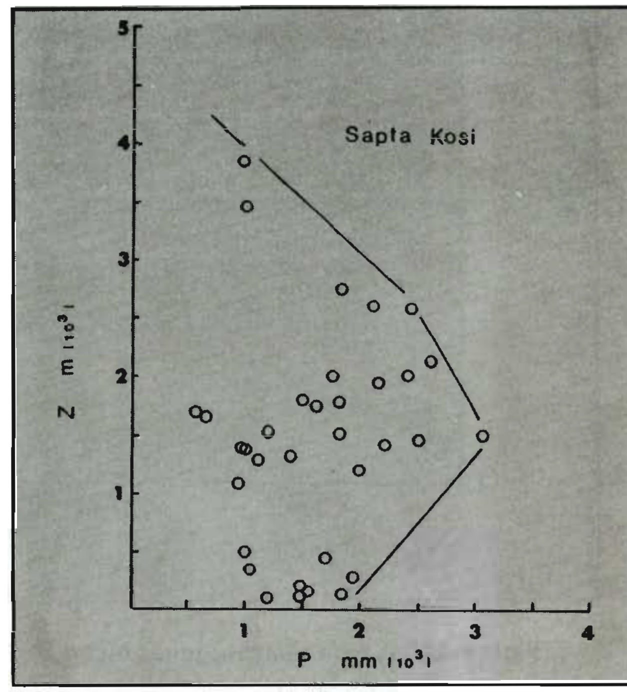


Figure 19: While There is Considerable Scatter, Maximum Values of Precipitation in the Sapta Kosi Basin Occur between 1,500-2,500 m, while Minimum Values are Recorded at the Highest and Lowest Altitudes for which Data are Available

Evaporation

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

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

EVAPORATION MEASUREMENTS -- EASTERN NEPAL(mm/d)

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

Source: Department of Irrigation, Hydrology, and Meteorology 1976

Topography

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

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

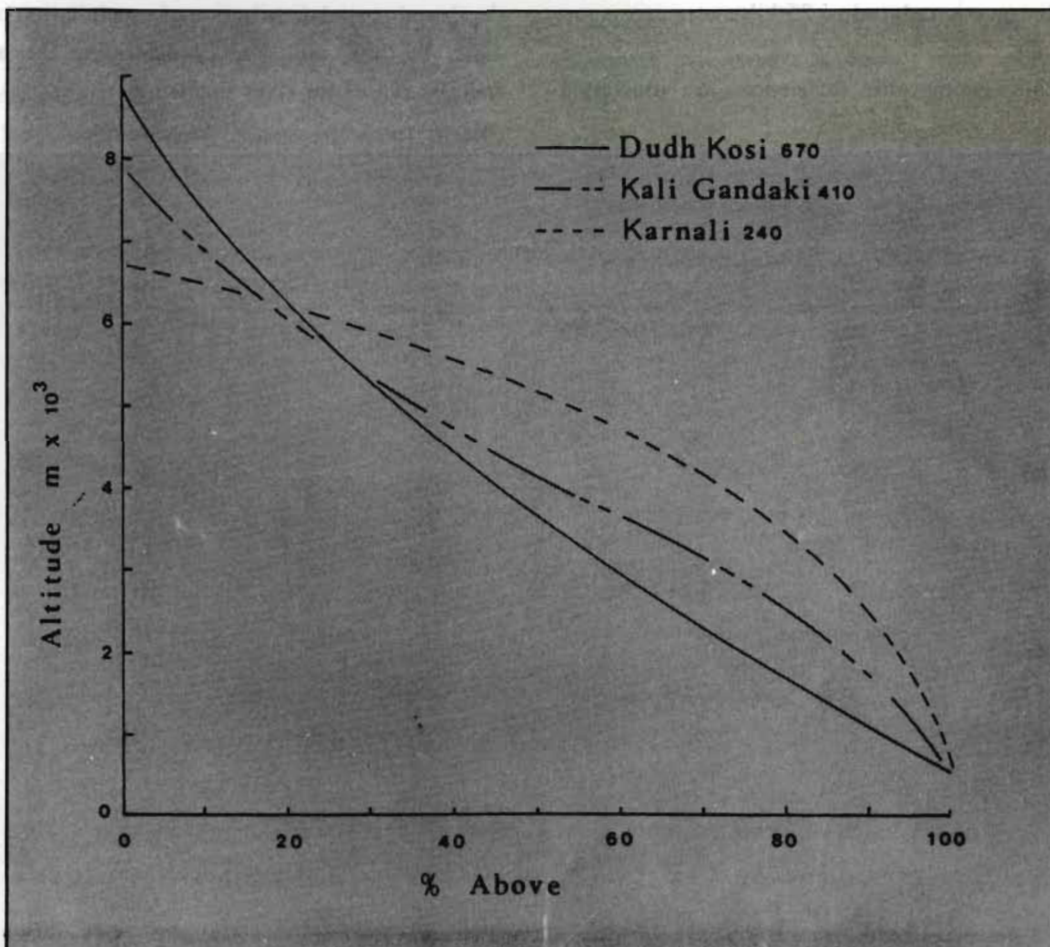


Figure 20: **Hypsometric Curves Showing Distribution of Surface Area with Altitude in the Dudh Kosi, Kali Gandaki, and Upper Karnali Basins**

Note: Distinct differences exist among the basins.

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

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

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

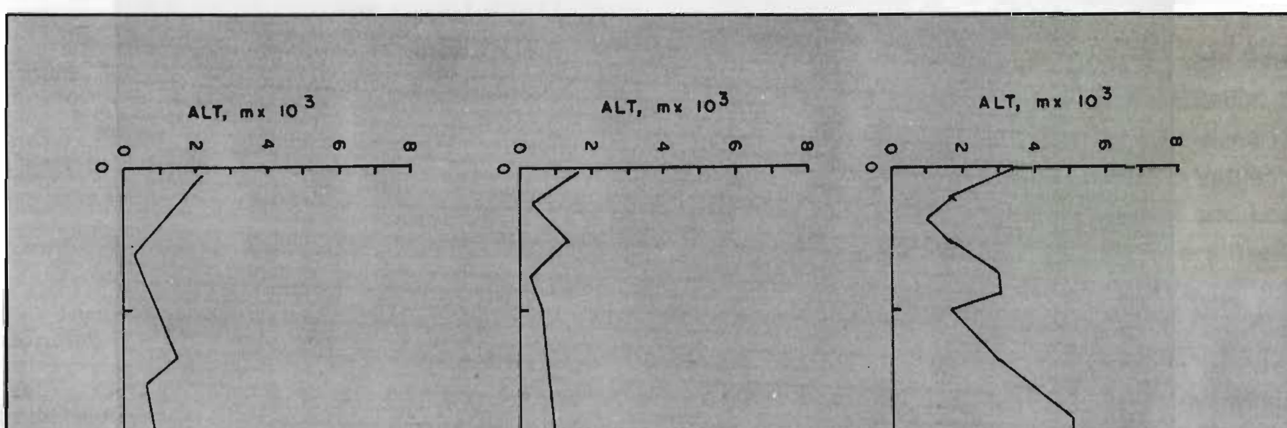


Figure 21: North-south Transects through: a. The Karnali Basin at Long. 83° 10', b. The Narayani Basin at Long. 84° 10', and c. The Sapta Kosi Basin at Long. 87° 20'

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

Streamflow and Specific Runoff

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

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

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

Streamflow and Climate

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

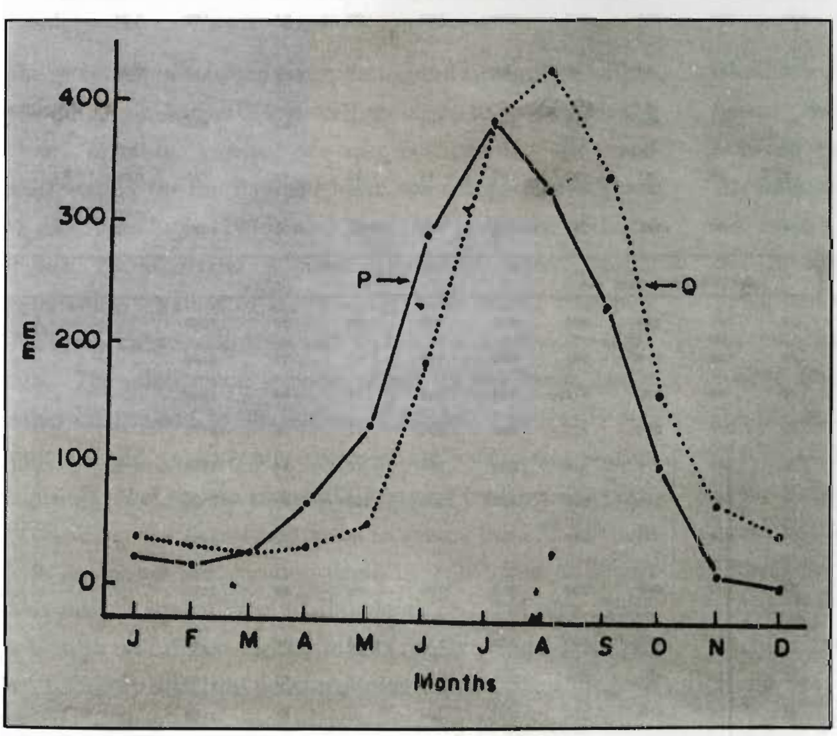


Figure 22: The Annual Distribution of Precipitation and Runoff in the Sapta Kosi Basin Follow Very Similar Trends

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

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

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

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

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

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

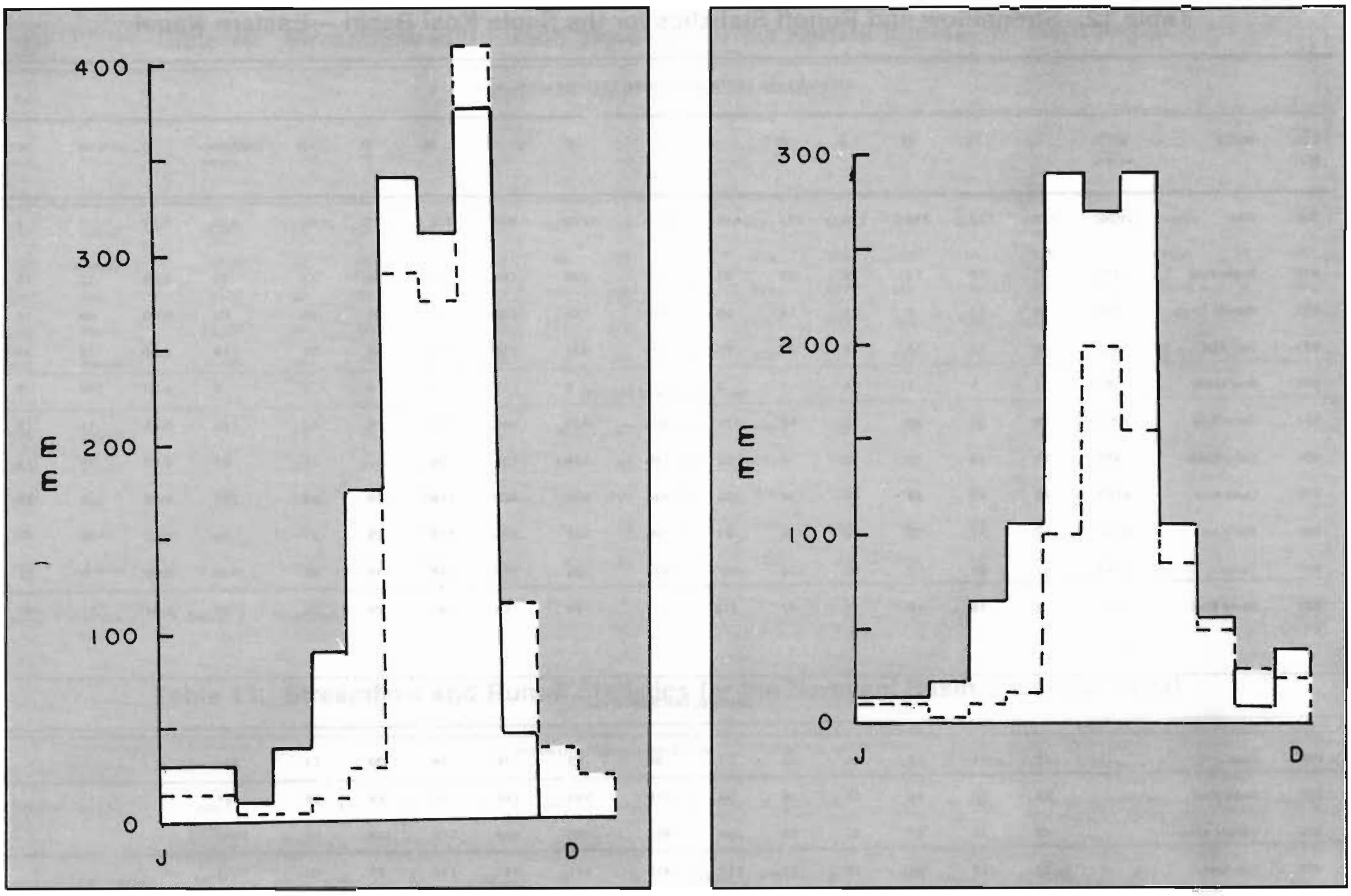
Table 12: Streamflow and Runoff Statistics for the Sapta Kosi Basin -- Eastern Nepal

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

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

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

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



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

b. During 1977, A Year of Below Average Precipitation

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

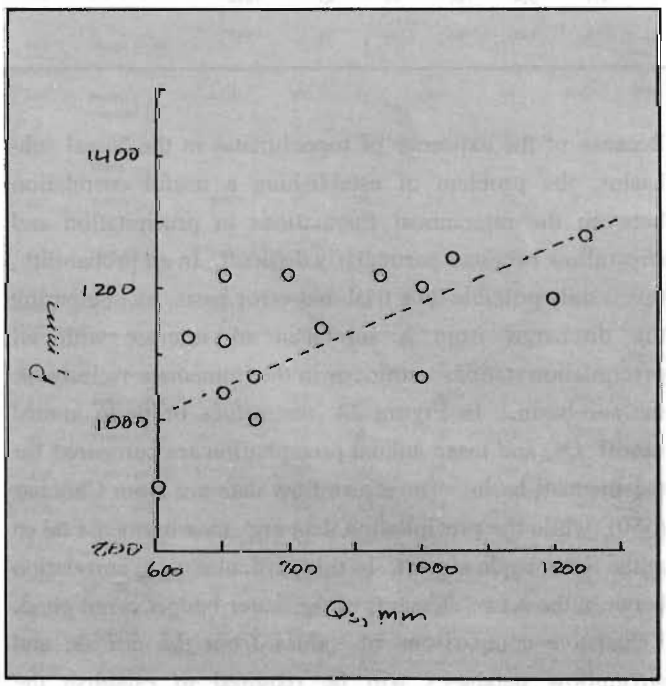


Figure 24: The Relationship between Annual Precipitation and Specific Runoff for the Bagmati Basin for the Period of Record

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

Streamflow and Basin Surface Area

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

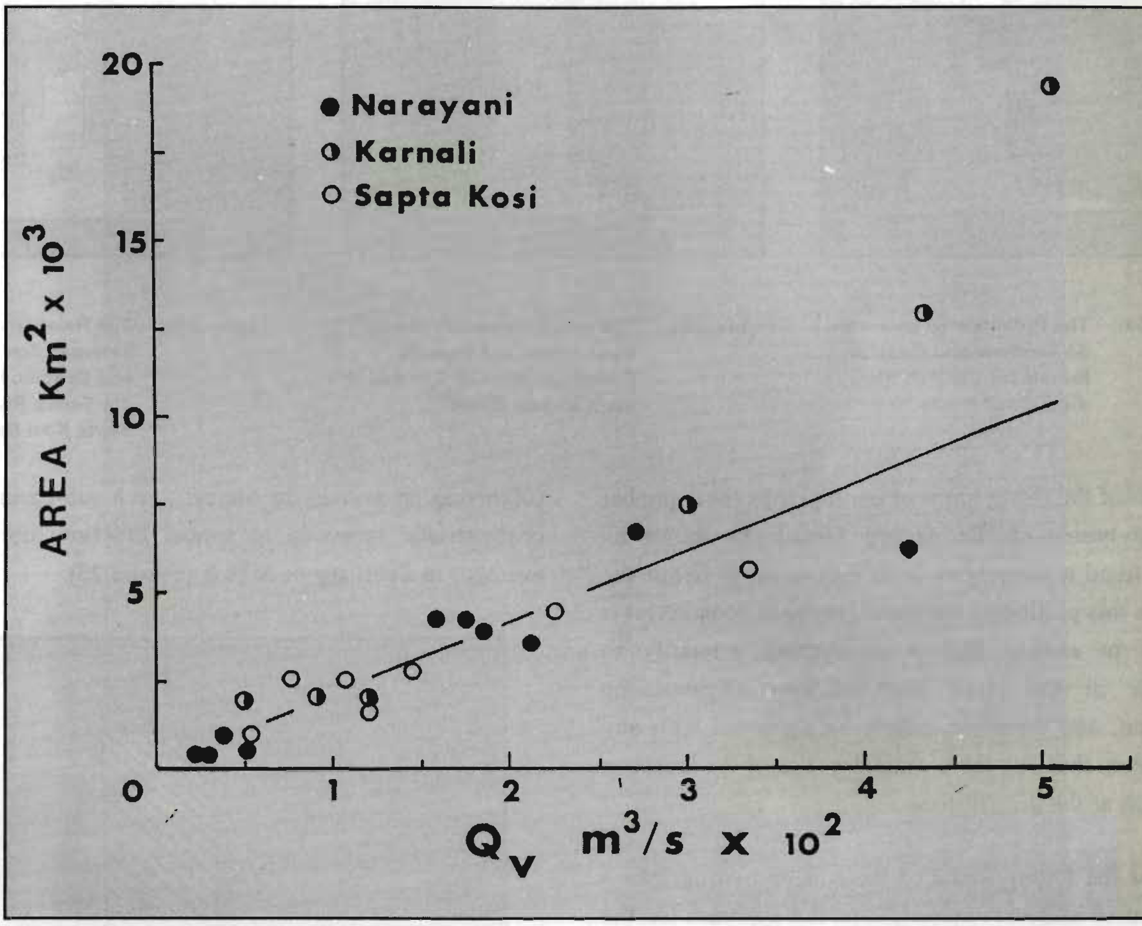


Figure 25: Basin Surface Area is Not a Good Index of Mean Annual Streamflow

The Annual Hydrographs

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

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

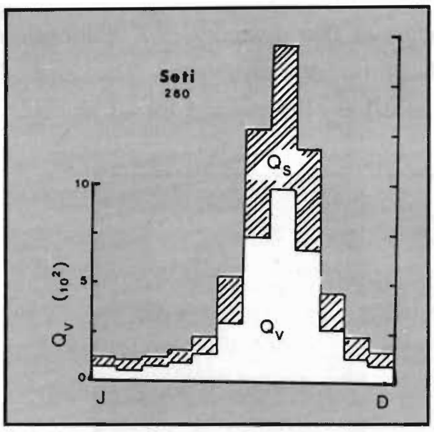


Figure 26a. The Relationship between Streamflow and Specific Runoff for the Seti River in the Karnali Basin

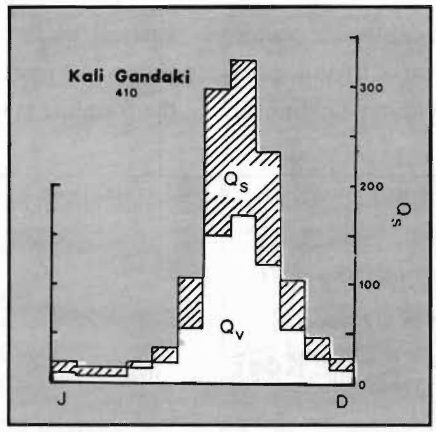


Figure 26b. The Relationship between Streamflow and Specific Runoff for the Kali Gandaki in the Narayani Basin

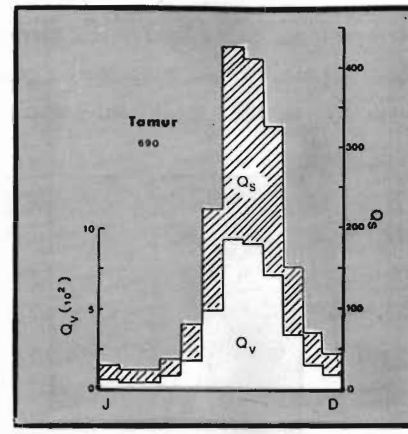
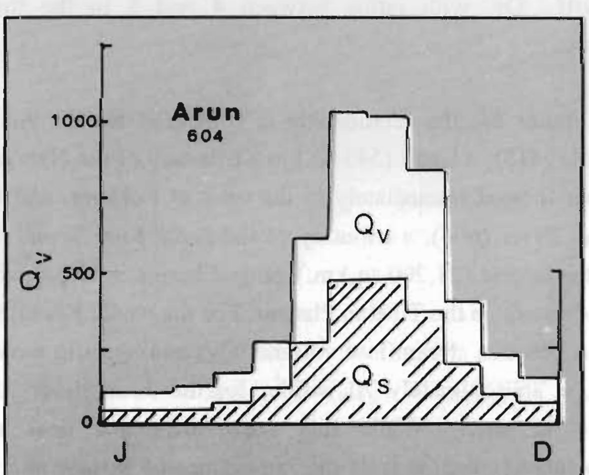


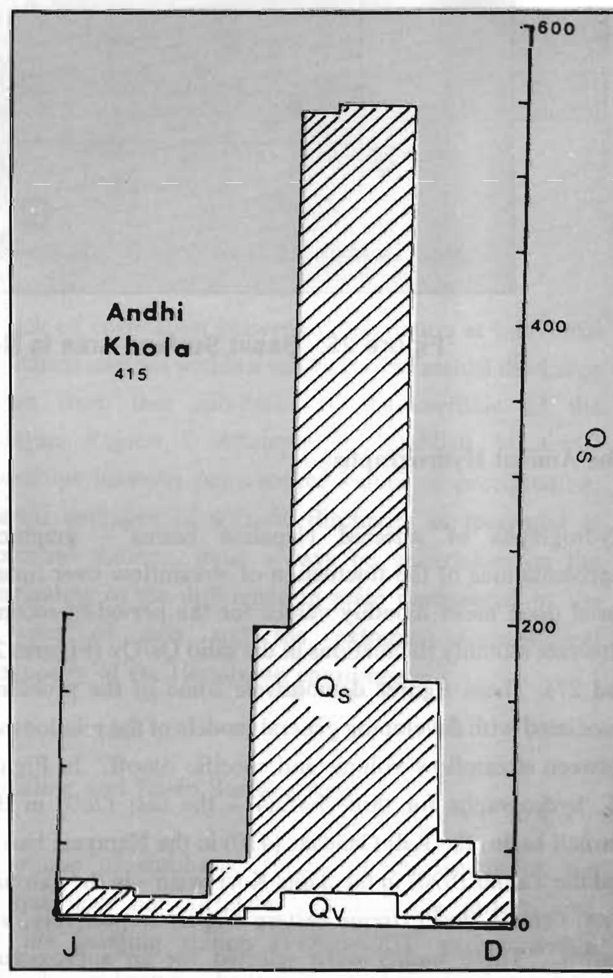
Figure 26c. The Relationship between Streamflow and Specific Runoff for the Tamur River in the Sapta Kosi Basin

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

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



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



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

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

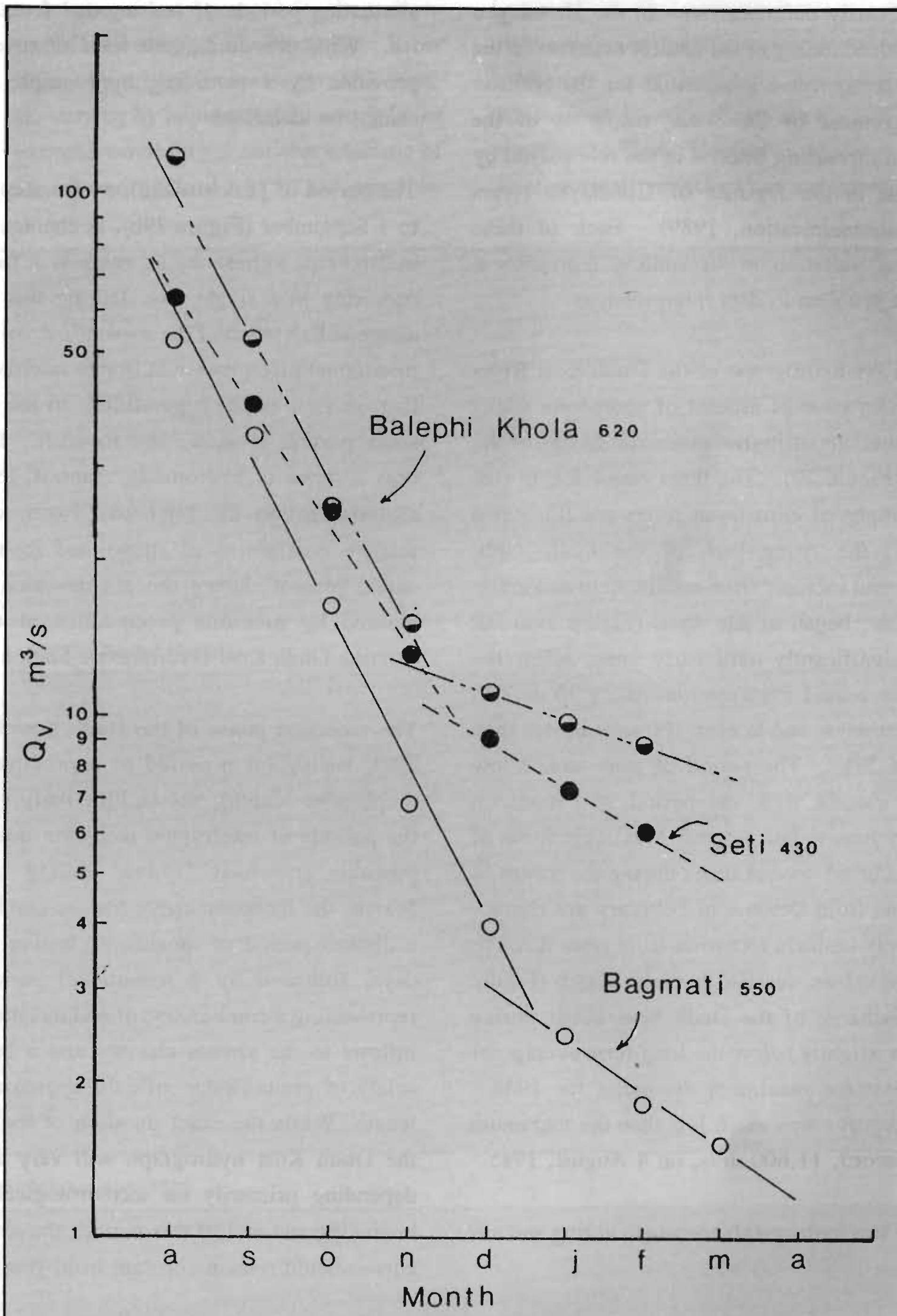


Figure 28: Recession Curves for Representative Basins in the Sapta Kosi, Narayani, and Bagmati Sub-basins

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

Temporal Variations in Streamflow Volume

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

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

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

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

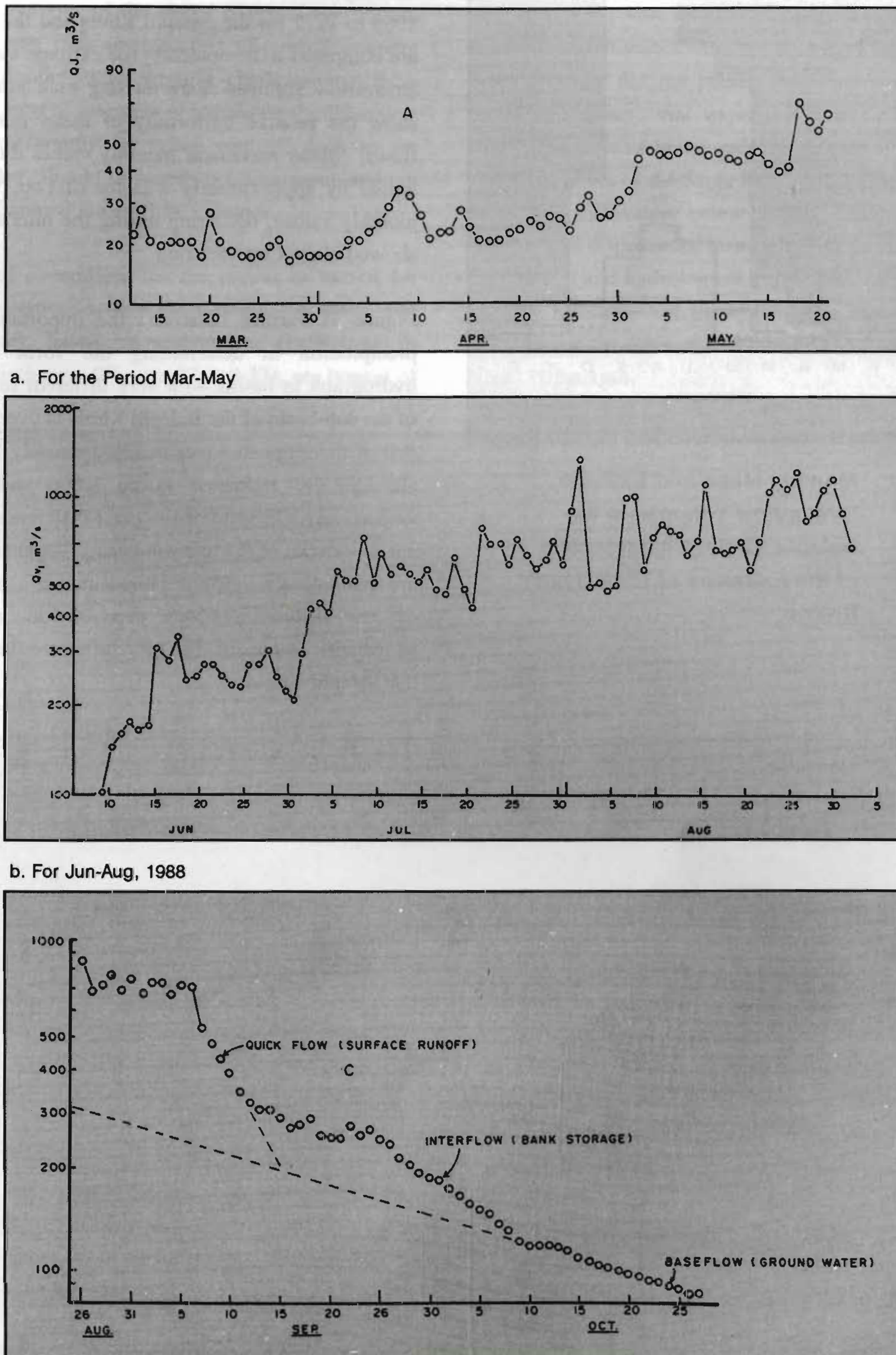
Based solely upon daily mean values of streamflow, it is not possible to separate the snowmelt component of the hydrograph. While it is reasonable to assume that much of the increase in streamflow volume, occurring between 1 April and 1 June (Figure 29a), is the result of this factor, only a continuous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

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

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

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

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



a. For the Period Mar-May

b. For Jun-Aug, 1988

c. For Aug-Oct, 1988

Figure 29: The Hydrograph of the Dudh Kosi River

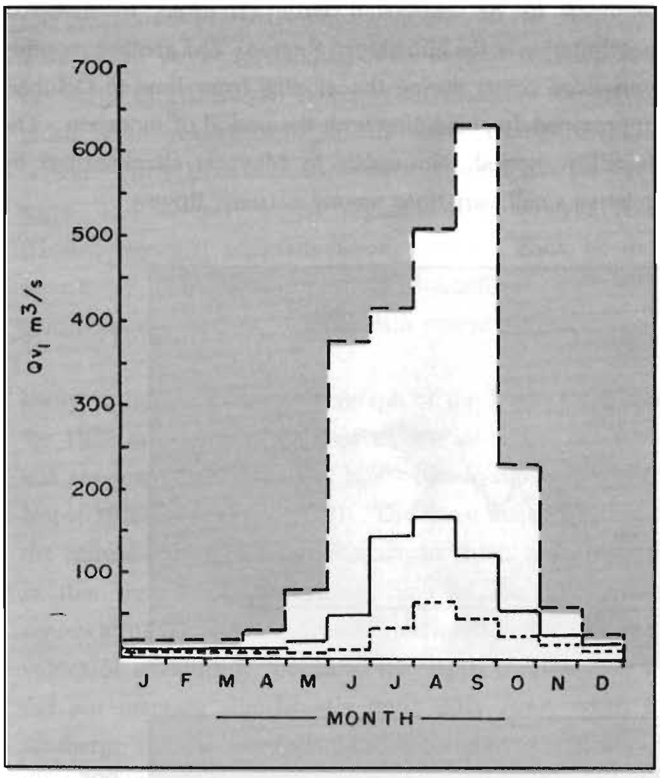


Figure 30: Monthly Mean and Extreme Streamflow Volumes in the Balephi Khola, Characteristic of the Extremes of Himalayan Rivers

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

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

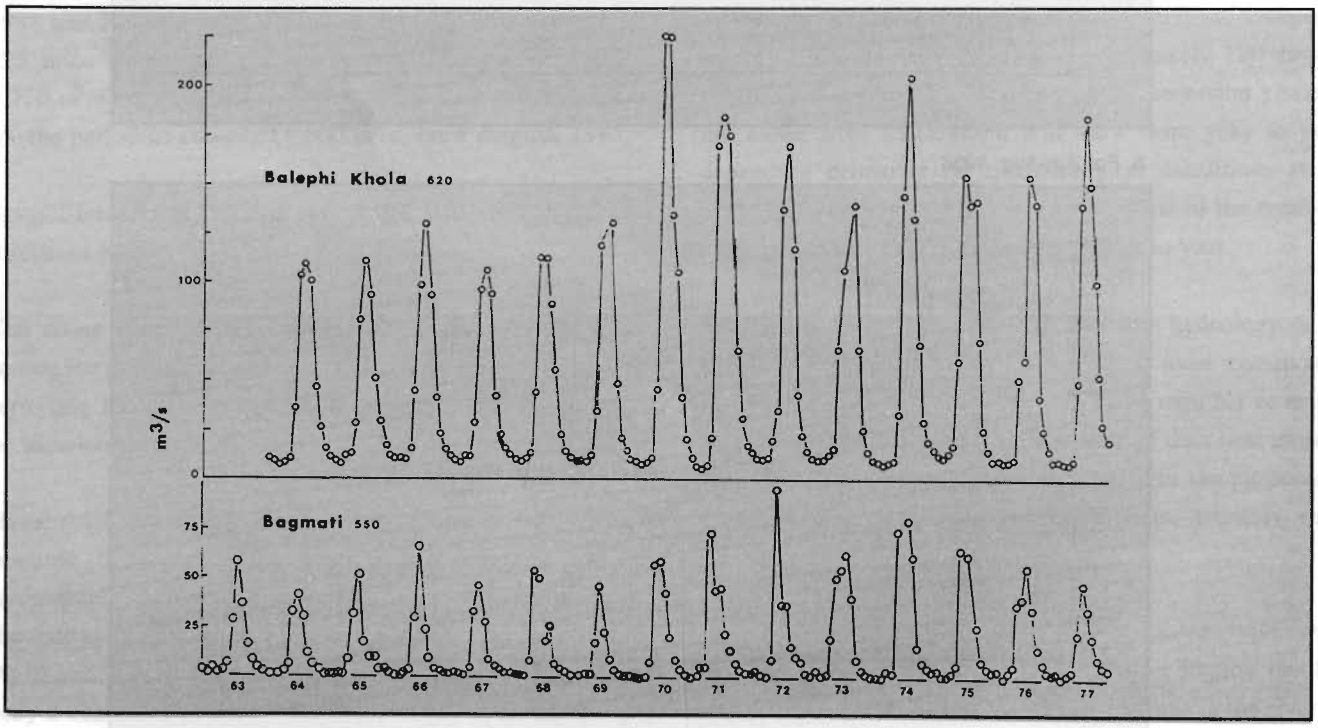


Figure 31: Average Monthly Streamflow Volume for the Balephi Khola and Bagmati River, Showing the Extreme Range of Flows Characterising Individual Years

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

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

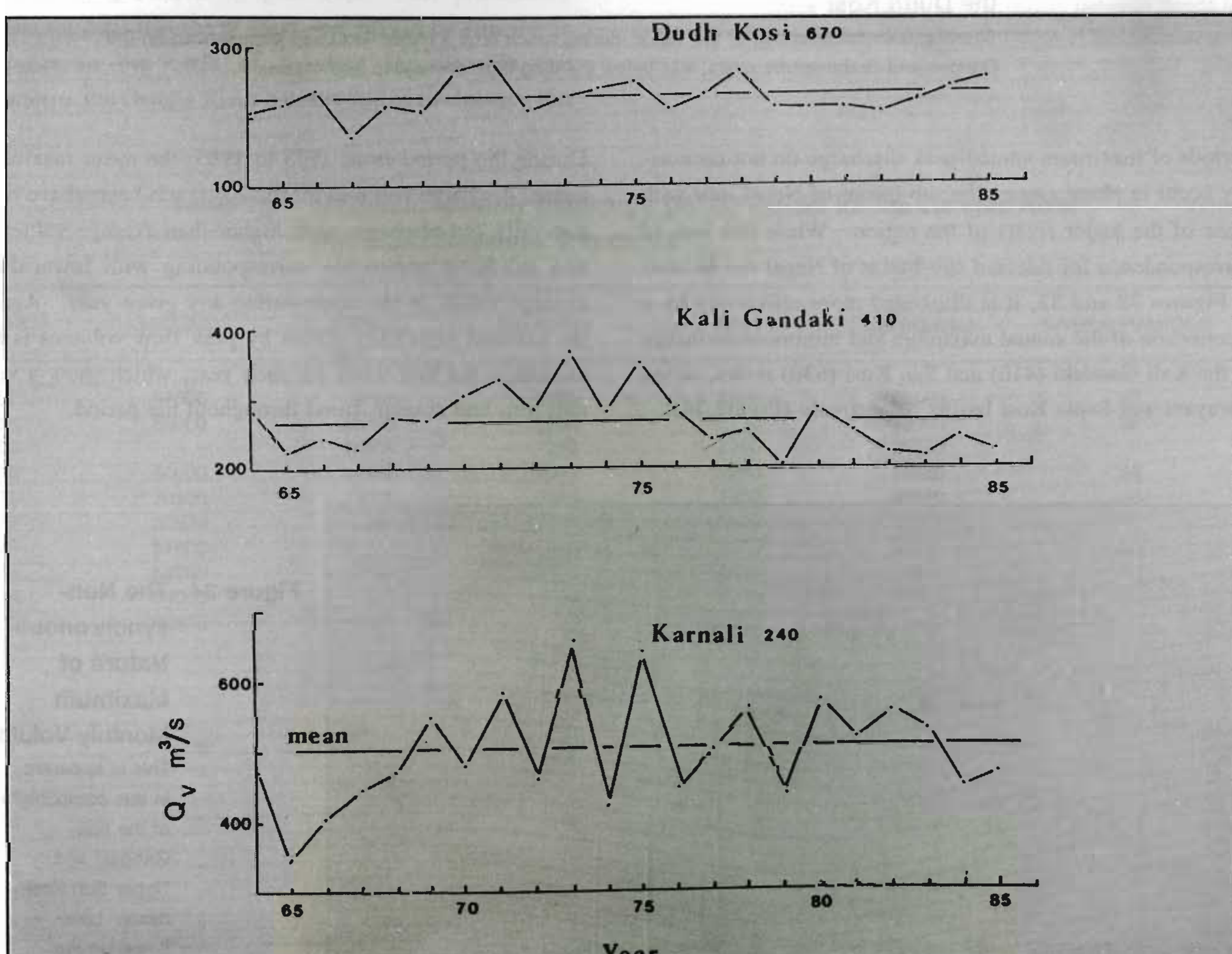


Figure 32: Average Annual Streamflow Volume for Three Representative Basins

Showing: 1) the absence of any long-term trends that might be associated with land use; and 2) the lack of uniformity in high and low streamflow years

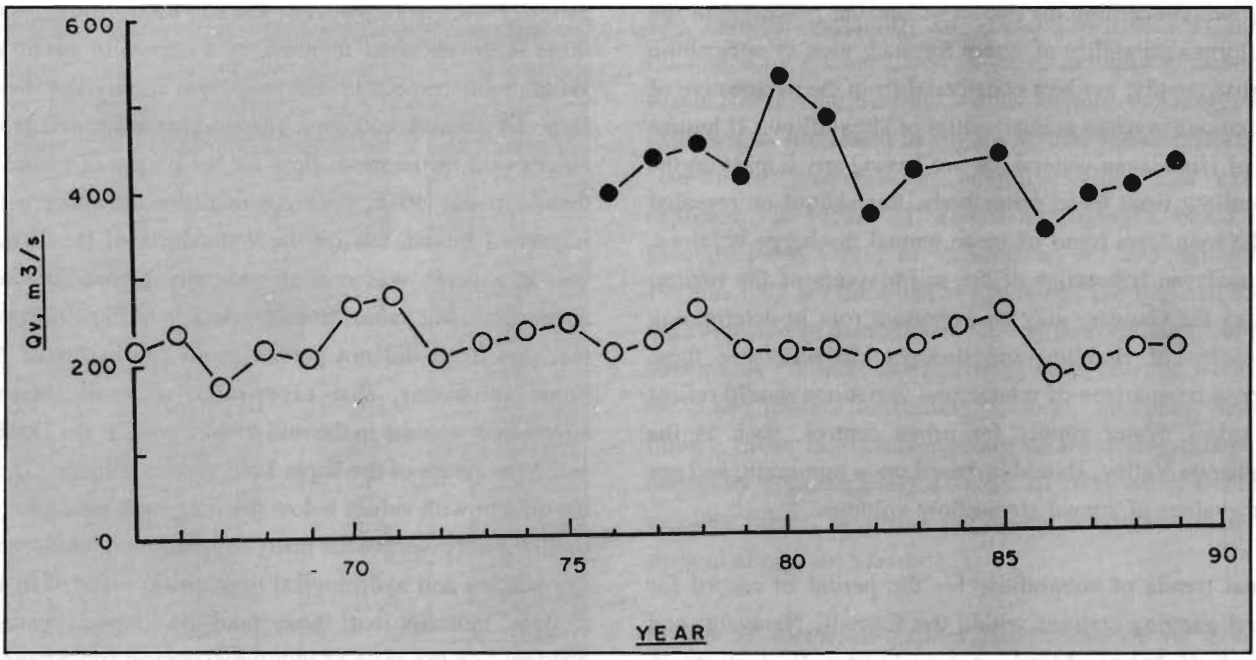


Figure 33: Average Monthly Streamflow Volumes for the Arun River (closed circles) and the Dudh Kosi

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

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

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

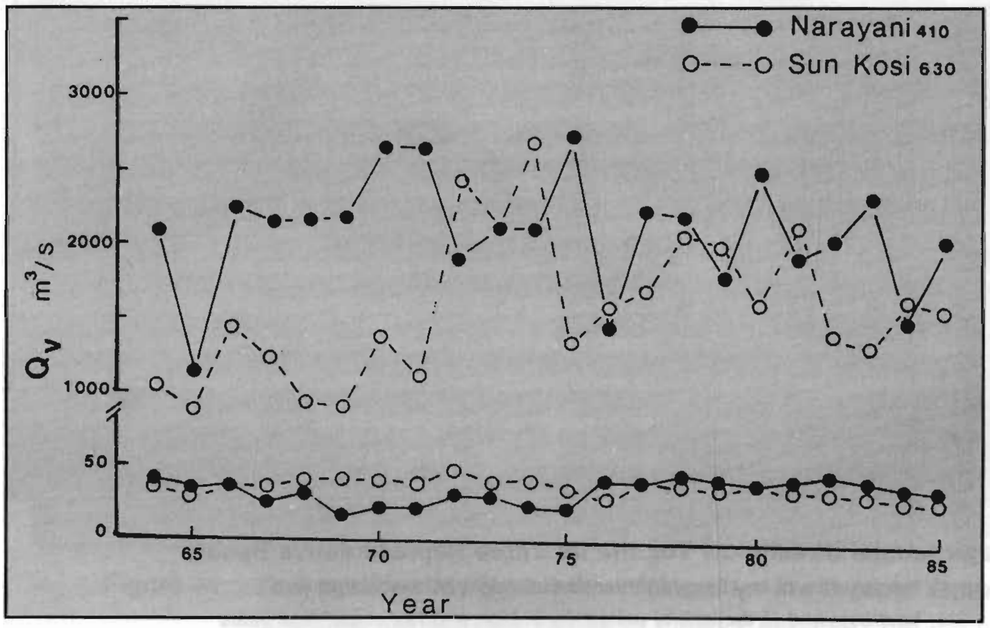


Figure 34: The Non-synchronous Nature of Maximum Monthly Volumes

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

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

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

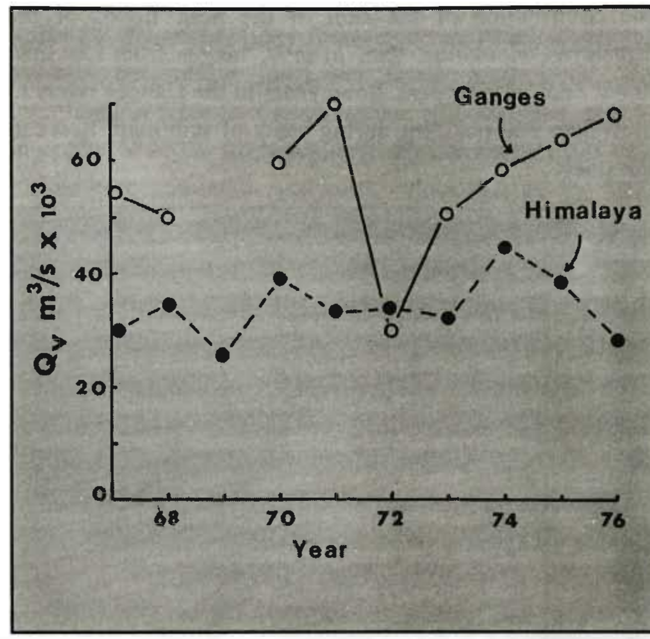


Figure 35: Based Upon the Sum of Peak Annual Flows for the Major Rivers of Nepal
There is no apparent correlation between floods in Himalayan headwaters and those of the main Ganges River

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

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

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

Source: DHM Nepal, unpublished and Rao 1984

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

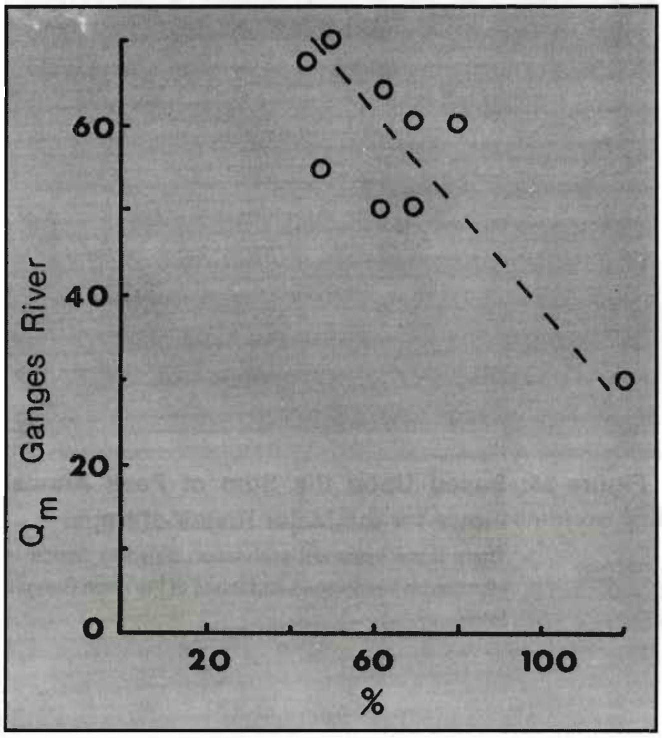


Figure 36: While there is considerable scatter, the correlation between per cent contribution of Nepali tributaries to the peak annual flow of the Ganges River appears to be negative. This suggests that the Nepali rivers modulate, rather than contribute negatively to, the flow of the Ganges

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

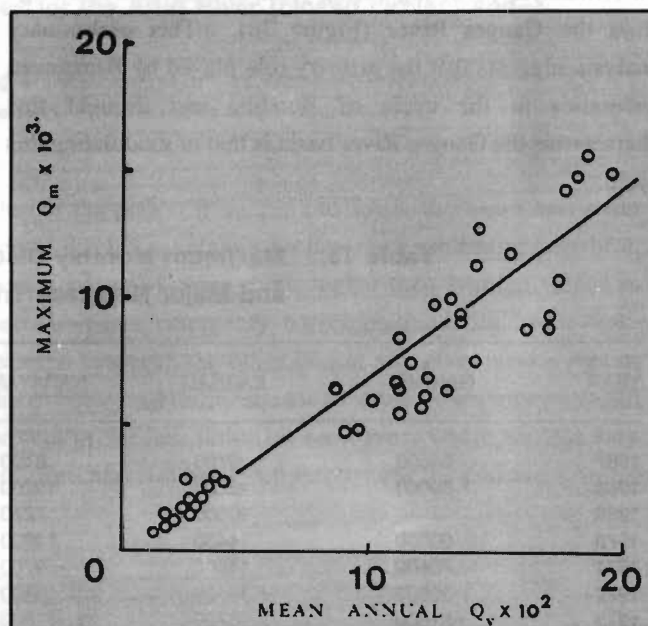


Figure 37: The relationship between peak annual flows and mean annual flows is positive, suggesting that the latter may be used as an index to the contribution of Nepali tributaries to the flood-drought cycles of the Ganges basin

Snow Hydrology

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

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

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

GAUGED WATERSHEDS OF THE DUDH KOSI BASIN -- 1984

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

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

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

Variations in Runoff with Altitude

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

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

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

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

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

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

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

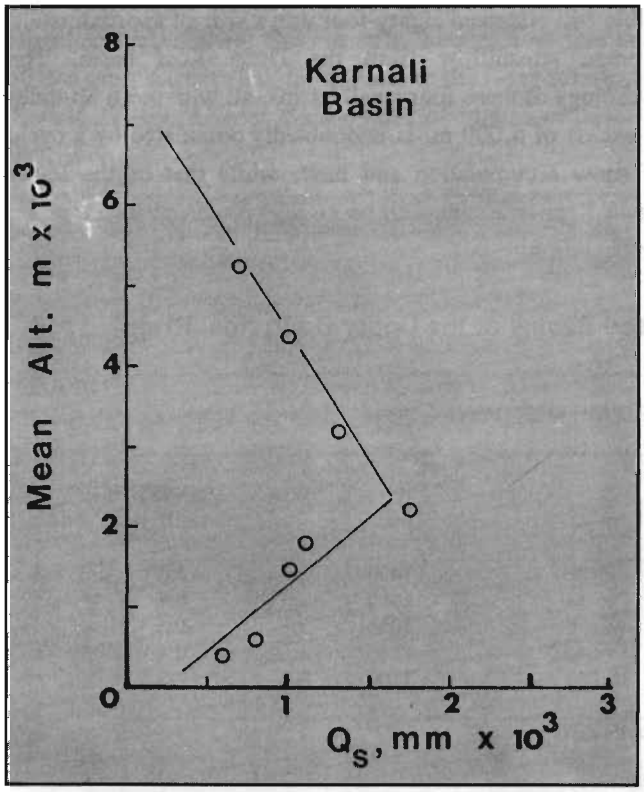


Figure 38: The Relationship between Mean Basin Altitude, Z, m, and Specific Runoff, Qs, mm, for the Sub-basins of the Karnali River

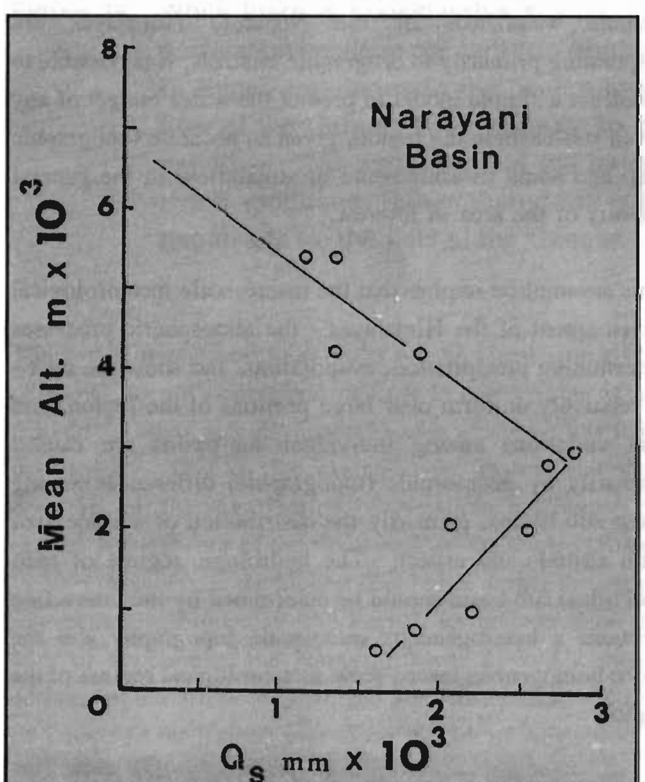


Figure 39: The Relationship between Mean Basin Altitude, Z, m, and Specific Runoff, Qs, mm, for the Sub-basins of the Narayani River

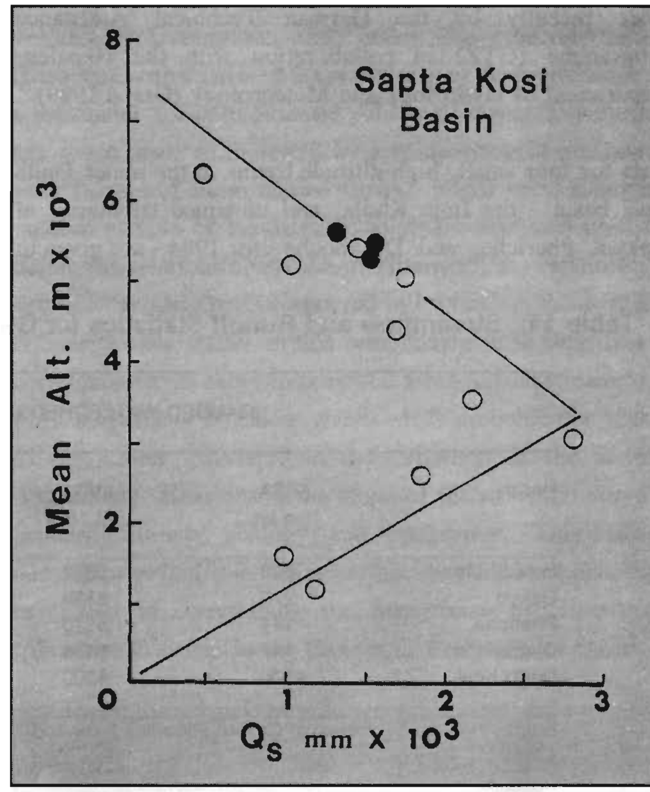


Figure 40: The Relationship between Mean Basin Altitude, Z,m, and Specific Runoff, Qs, mm, for the Sub-basins of the Sapta Kosi River

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

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

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

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

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

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

where,

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

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

for Eastern Nepal -

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

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

for the Tibetan Plateau -

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

for western Nepal -

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

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

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

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

Table 15: Calculated and Measured Values of Streamflow

Selected Sub-basins of the Nepalese Himalayas

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

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

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

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

Altitude Belt (m)	Area sq.km.	%	Q m	Q m^3	%
DUDH KOSI 670					
500	584	0.18	1.75	1.0e+09	0.15
1500	876	0.27	2.20	1.9e+09	0.28
2500	681	0.21	2.60	1.8e+09	0.25
3500	380	0.12	2.75	1.0e+09	0.15
4500	380	0.12	2.00	7.6e+08	0.11
5500	227	0.07	1.50	3.4e+08	0.05
6500	130	0.04	0.75	9.7e+07	0.01
TOTAL	3244	1.00			
	CALCULATED			6.96e+09	0.96
	MEASURED			7.28e+09	
TAMUR RIVER 690					
500	790	0.15	1.75	1.38e+09	0.13
1500	1356	0.26	2.20	2.98e+09	0.27
2500	1243	0.24	2.60	3.23e+09	0.30
3500	565	0.11	2.75	1.55e+09	0.14
4500	518	0.10	2.00	1.04e+09	0.09
5500	340	0.07	1.50	5.1e+08	0.05
6500	340	0.07	0.75	2.6e+08	0.02
TOTAL	5152				
	CALCULATED			1.10e+10	1.01
	MEASURED			1.09e+10	
KALI GANDAKI 410					
500	100	0.02	0.65	6.5e+07	0.01
1500	800	0.12	1.10	8.8e+08	0.12
2500	1750	0.26	1.55	2.7e+09	0.36
3500	1450	0.22	1.30	1.9e+09	0.25
4500	1200	0.18	1.00	1.2e+09	0.16
5500	900	0.14	0.65	5.9e+08	0.08
6500	375	0.06	0.35	1.3e+08	0.02
7500	80	0.01	0.00	0.0e+00	0.00
	6655	1.00	CALCULATED	7.5e+09	0.89
			MEASURED	8.4e+09	
ARUN RIVER 604					
500	850	0.03	1.75	1.49e+09	0.11
1500	1487	0.05	2.20	3.27e+09	0.24
2500	1487	0.05	2.60	3.87e+09	0.28
3500	744	0.03	2.75	2.04e+09	0.15
4500	744	0.03	2.00	1.49e+09	0.11
5500	15244	0.52	0.10	1.52e+09	0.11
6500	9000	0.30	0.00	0	0.00
TOTAL	29555				
	CALCULATED			1.37e+10	1.03
	MEASURED			1.33e+10	
KARNALI RIVER (240)					
500	193	0.01	0.65	1.3e+08	0.01
1500	963	0.05	1.10	1.1e+09	0.07
2500	1540	0.08	1.55	2.4e+09	0.15
3500	2504	0.13	1.30	3.3e+09	0.21
4500	3563	0.19	1.00	3.6e+09	0.23
5500	5008	0.26	0.65	3.3e+09	0.21
6500	5394	0.28	0.35	1.9e+09	0.12
TOTAL	19165	1.00			
		CALCULATED		1.6e+10	0.98
		MEASURED		1.6e+10	

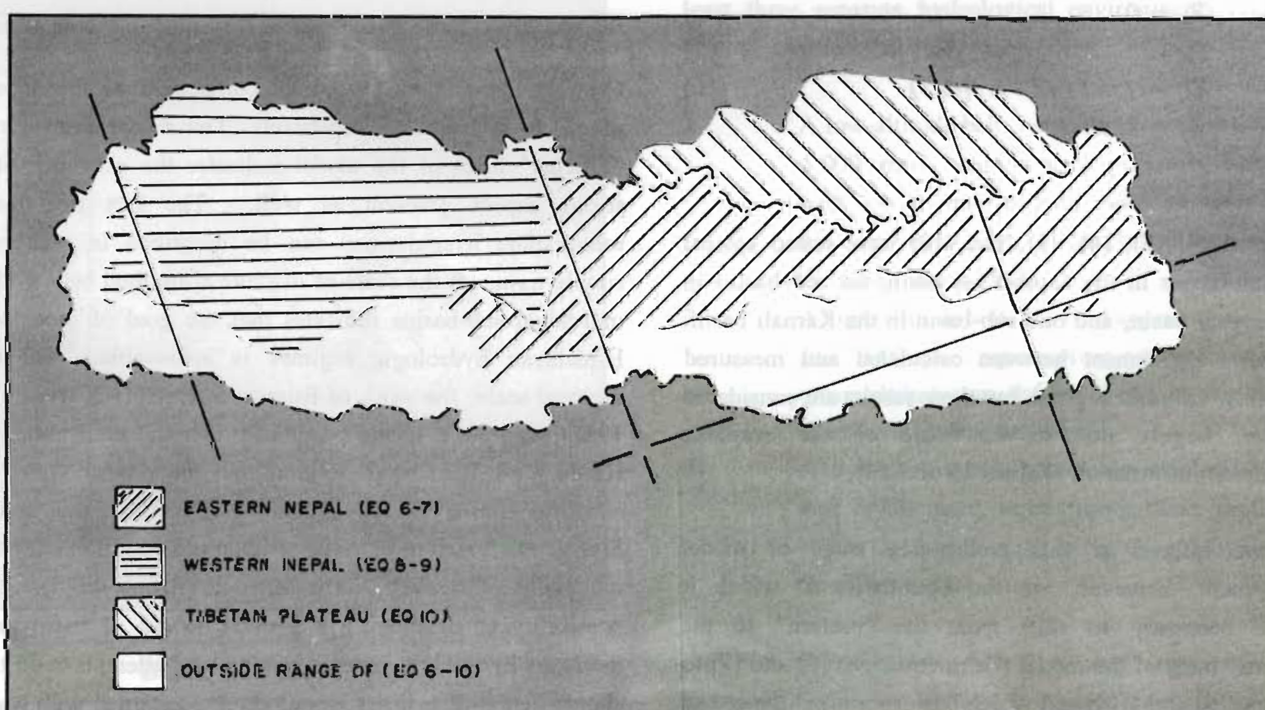


Figure 41: The Three Major Hydrological Environments Described by Equations (6)-(10) in the Text

VI. Summary and Discussion

The interaction between topography and meteorology, as both vary over each of the major river basins of South Asia, and among sub-basins within these major rivers, produces a complex mosaic of "topohydrological" environments, analogous to "topoclimates", or climates determined by topographic characteristics (Thornthwaite 1953). The macro-scale hydrological environments of the three major river basins of South Asia - the Indus, Ganges, and Yalu Zangbu-Brahmaputra rivers - provide only limited insight into the great diversity of such environments present on the meso-scale, within individual mountain tributaries to these rivers. Much of the information on which discussions concerning the hydrological environment of the Himalayas, and the relationships between this environment and past or present land-use practices, has been drawn, or inferred, from analyses of data describing macro-scale phenomena, is based upon measurements from the lowlands to the south of the Himalayas.

It is clear from this study that global models, linking human activities to undesirable changes in the water or sediment output of the Himalayan mountains, overstate the role of these activities. Hydrologic and geomorphic processes operate throughout virtually the entire altitudinal range present in these mountains, while human activities are almost completely confined to the lower 3,000 m. Approximately 50 per cent of the water flowing from the Himalayas and an indeterminate, but presumably high, percentage of the total sediment in the rivers flowing from the Himalayas are produced from portions of the mountains outside the normal range of human habitation or activity - that portion above approximately 3,000-4,000 m. This percentage approaches 100 per cent in the upper Indus and Yalu Zangbu basins.

At the same time, the results of this study indicate that specific runoff in the Himalayas is at a maximum in an altitudinal belt of considerable human activity -- 1,500 to 3,500 m. While the hydrological consequences of environmental disturbances in this belt are unlikely to be detectable on the scale of the major river basins of the region, it is quite reasonable to assume that local problems of increased runoff or erosion could occur as a result of unwise land use.

On the scale of the major river basins of South Asia, the Indus, Ganges, and Brahmaputra rivers do not differ significantly from one another. The total annual discharge of the upper Indus River (including Karakoram and Trans-Himalayan tributaries) is 115,000 million cubic metres, of the Himalayan and Tibetan tributaries to the Ganges River 200,000 million cubic metres, and, of Himalayan and Tibetan tributaries to the Brahmaputra River, 200,000 million cubic metres, a total difference of less than a factor of two. Peak flows occur in all rivers during the summer monsoon, while the intermonsoon period is characterised by receding flows to a base flow reached just prior to the onset of the subsequent monsoon. Each river carries roughly comparable amounts of sediment. This apparent uniformity on the macro-scale masks a very great diversity among the three river systems on the scale of individual sub-basins within each river system.

On the meso-scale - the scale of individual sub-basins or topographic elements within a sub-basin, such as altitudinal belts - hydrological environments range from glaciers or cold-dry deserts to hot-wet, low-altitude subtropical forests. It is not uncommon for these contrasting environments to exist within a few tens of kilometres of one another, often within a single sub-basin. These contrasting environments produce a situation in which the hydrological diversity of a catchment basin cannot be inferred directly from measurements at individual hydrometric stations. Suggestions that additional hydrometric stations be added to the existing network, primarily for research purposes (Ives and Messerli 1987 and ICIMOD 1990), ignore the fact that, in all probability, "representative" basins do not exist.

The following specific points have emerged as a result of this study. On the macro-scale, both the upper Indus and Yalu Zangbu-Brahmaputra are largely snow-fed rivers, while probably not more than 30 per cent of the headwaters of the Ganges River are derived from this source. This fact alone is sufficient to cast doubt on the value of any regional approach to hydrological modelling, planning for water resource development planning/management or land-use evaluation.

An analysis of the hydrometric and climatological databases for the Nepalese portion of the Himalayas, in the mountain headwaters of the Ganges River, illustrates some of these differences in terms of single portions of this complex region.

1 Mean annual discharge, Q_v, m^3/s, ranges from less than ten cubic metres per second to over 400 cubic metres per second in the gauged sub-basins of the Nepalese Himalayas. This range of discharge volumes is a result of differences in both the regional climate and of sub-basin surface area. Based solely upon values of Q_v, no conclusions can be drawn concerning the nature or range of hydrometeorological environments above the gauging station. The highest value for mean annual discharge is from the Arun River, a sub-basin in the Sapta Kosi system, with approximately 80 per cent of its total surface area in the cold-dry desert of the Tibetan Plateau. This river has the lowest value of specific runoff. In contrast, the Balephi Khola, also a tributary to the Sapta Kosi, has a mean annual discharge, Q_v, almost one order of magnitude less than that of the Arun, but the specific runoff, Q_s, is over five times greater, indicating a much more humid environment and a much greater potential for land use-hydrological interactions.

2. Values of mean annual specific runoff, Q_s, mm, range from a low of less than 500 mm (for the Arun River) to nearly 2,800 mm for the Seti Khola, a small tributary to the Narayani River. In terms of specific runoff, the "wettest" major river in Nepal is not the Sapta Kosi, as might be assumed from the east to west climatic gradient often implicitly assumed in the literature, but, rather, the Narayani basin (1,893 mm) in central Nepal. The Sapta Kosi has intermediate values (1,609 mm), while the Karnali basin is considerably "drier" than either (1,203 mm). Differences within each of the major river basins are greater still than the differences among them, varying by a factor of from two to six among the sub-basins in each.

Specific runoff, plotted as a function of mean sub-basin altitude, shows a similar trend for the three major river basins, with maximum values in an altitudinal belt between approximately 2,000 and 3,000 metres and decreasing with altitude both above and below this belt. In contrast, specific runoff increases linearly with altitude in the upper Indus basin to the maximum altitude (approximately 5,000m) for which data are available. In the Yalu Zangbu basin, there is no comparable orographic trend.

3. Variations in the climatic factors influencing hydrological environments vary much more with altitude and with respect to the main crest of the Himalayan mountains than with the east-west position along the long axis of these mountains. Mean monthly air temperatures decline at approximately 0.5 degrees/100m from maximum values of approximately 30 degrees in June at the lowest altitudes to 15 degrees in January. The zero degree isotherm fluctuates seasonally between approximately 3,000 and 6,000 metres, promoting both freeze-thaw cycles in surficial materials, as well as snow accumulation and melt in this altitudinal range. Precipitation trends with altitude are not as well-defined as those of temperature. At any given altitude, within the range for which data are available, the scatter is great. Precipitation data are a poor index of streamflow.

4. For a period of between five and seven months, depending upon the individual sub-basin, rivers of the Nepalese Himalayas are in recession from the peak flows of the preceding monsoon and snowmelt season. Recession curve analysis suggests that relatively accurate short-term (30-90 days) forecasts may be prepared on the basis of the reliability of the recession curves for each sub-basin. Low flows are far less variable from year to year than peak flows; and that may vary by as much as a factor of two.

5. Based upon measurements at the headwaters of the Dudh Kosi River in the Sapta Kosi basin, it is tentatively suggested that snowmelt may contribute approximately 30 per cent of the total annual streamflow volume of this river system.

6. The rivers of Nepal do not respond uniformly to cycles of drought and flooding. During any given year, some rivers may be experiencing a major flood cycle, while others are near long-term minimum volumes of peak flow. This lack of uniformity in the annual peak flows casts doubt on the hypothesis that cycles of flood and drought in the Ganges or Brahmaputra basins are, in some way, a direct result of variations in the runoff from Himalayan tributaries.

A preliminary comparison of the sum of the annual peak flows from the three major Nepalese rivers with the annual peak flow at the Farraka Barrage indicates that the Himalayan tributaries can act as a modulating influence on the Ganges River. During drought years, the volume of the peak annual flow passing the Farraka Barrage is almost completely a result of runoff from the Himalayas. During years with high flow peaks, on the other hand, the Himalayan contribution shrinks to approximately 50 per cent.

A number of specific studies are of some immediate importance.

- A physical geography of Nepal should be produced, relating the factors of geology, geomorphology, climate, and vegetation to hydrologic regimes and land use practices within the Kingdom. This can best be done using the Geographical Information Systems' (GIS) technology.
- An intensive, quantitative analysis of all recession curves of Nepalese rivers should be undertaken to establish the reliability of recession analysis as a forecast methodology.
- A major effort should be directed towards development of a topographic data matrix, for use with the Geographic Information Systems' (GIS) technology. From this study, it is clear that the relationship between water and terrain is more complex than the simple altitude-runoff model developed from existing information. A topographic data matrix would aid considerably in resolving some of this complexity.
- Efforts should be made to maintain the accuracy of rating curves for each station, and funds should be sought to replace all staff gauges with recording hydrographs. Measurement of sediment transport in Nepal sub-basins may not be simply a matter of importing an existing methodology. The relative contributions of suspended and bed load are undefined for Himalayan rivers, but the ratio undoubtedly differs from that of better-studied river systems. Only intensive, scientific studies, rather than a simple monitoring programme, will resolve this question.

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