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, Crol and Bailey 1964, Baker 1944, and Alford 1985).

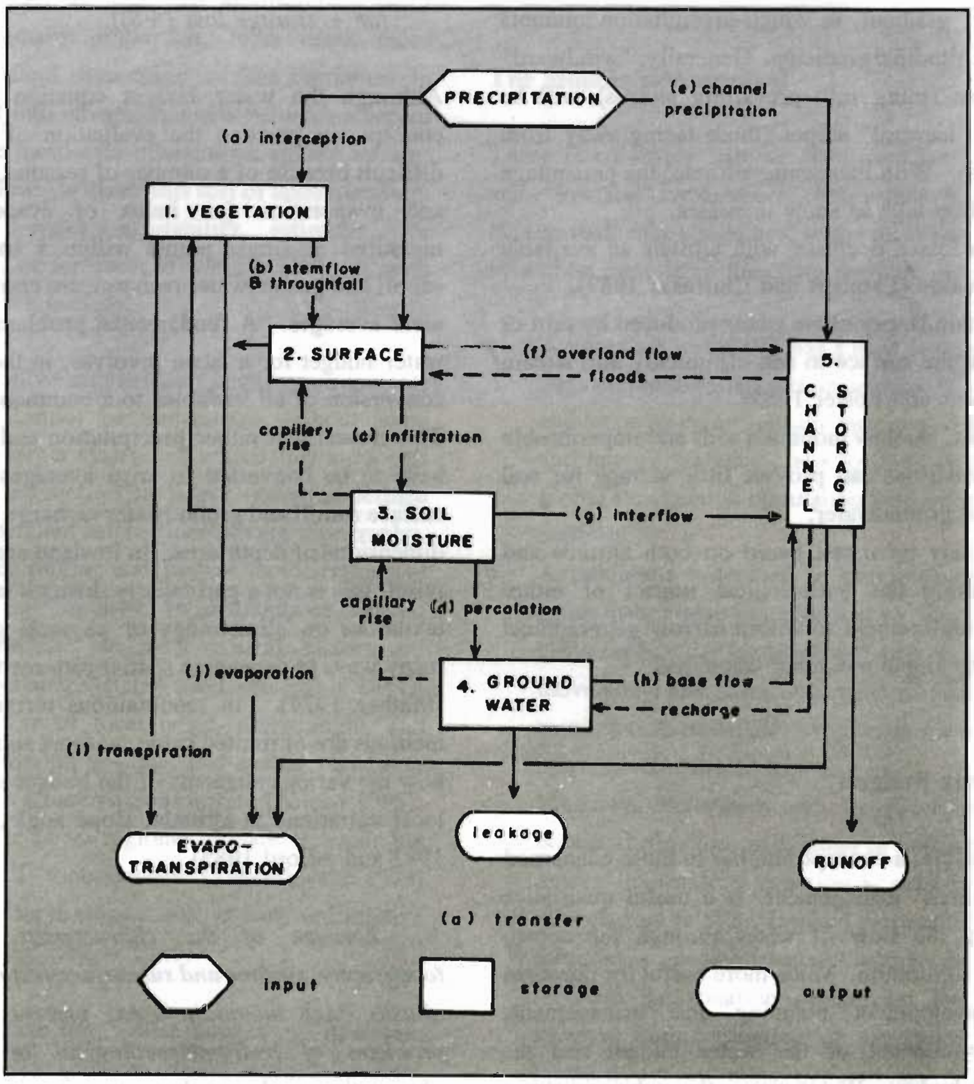

Figure 1: **The Relationship among Elements of the Water Budget of a Region or a Catchment Basin**

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.

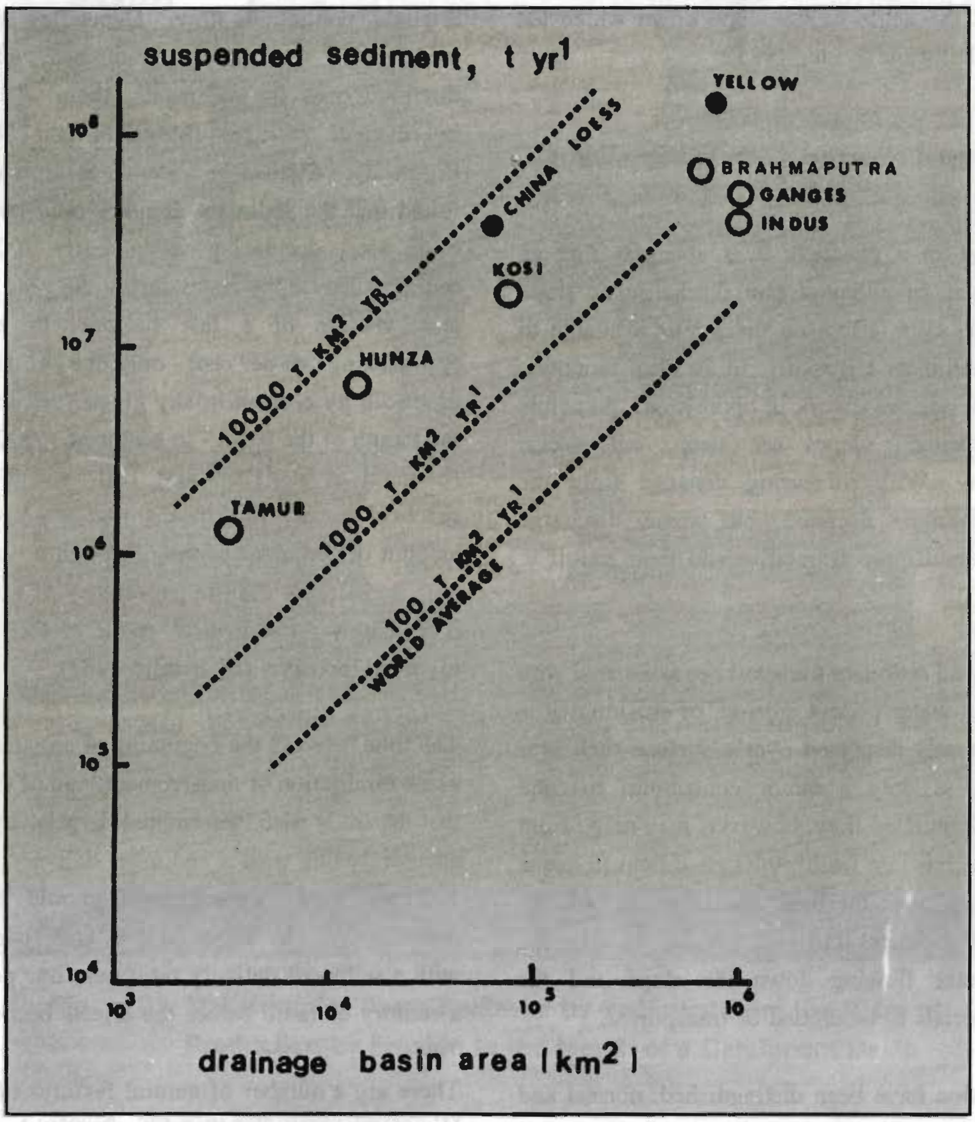

Figure 2: The Sediment Load of Selected South Asian Rivers Compared to the World Average

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):

$$Power = Stream\ discharge \times the\ gravity\ slope.$$

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.

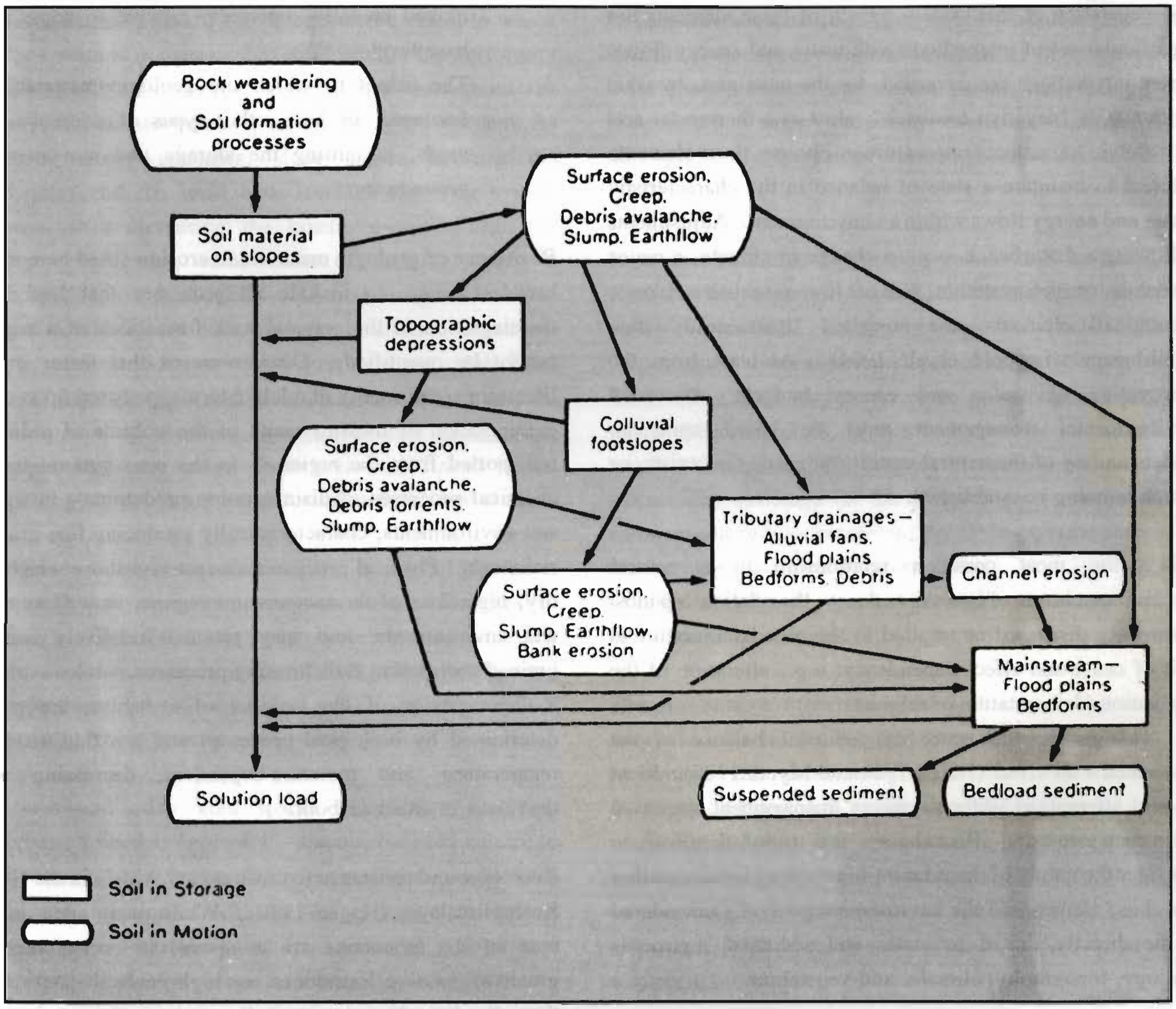

Figure 3: The Complex Paths Followed by Sediment from the Point of Production by Erosion to the Mouth of a Catchment Basin

Source: Megahan and Nowlin 1976.

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