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

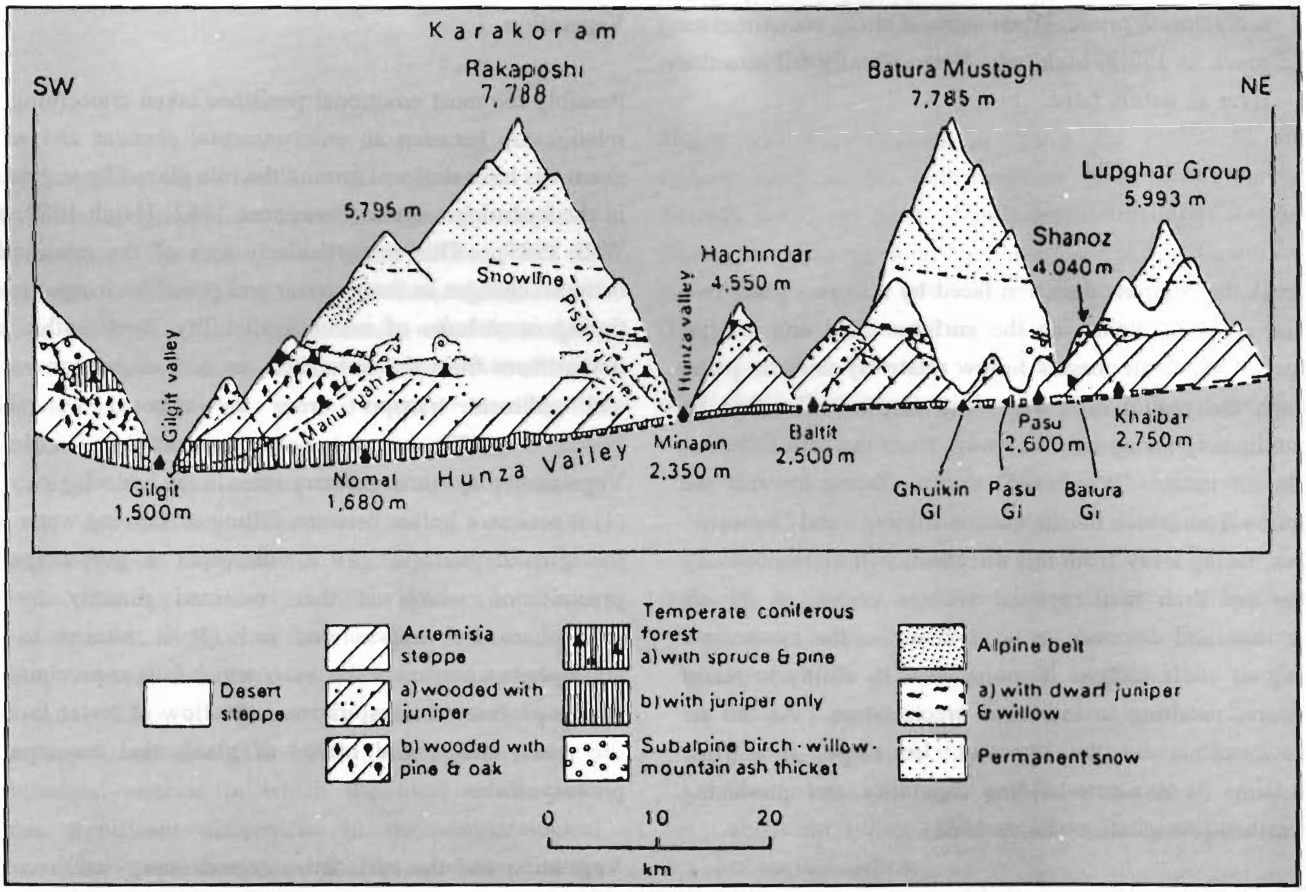

Figure 4: The Altitudinal Zonation of Ecosystems in the Karakoram Range of the Western Hindu Kush-Himalayan Region

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.

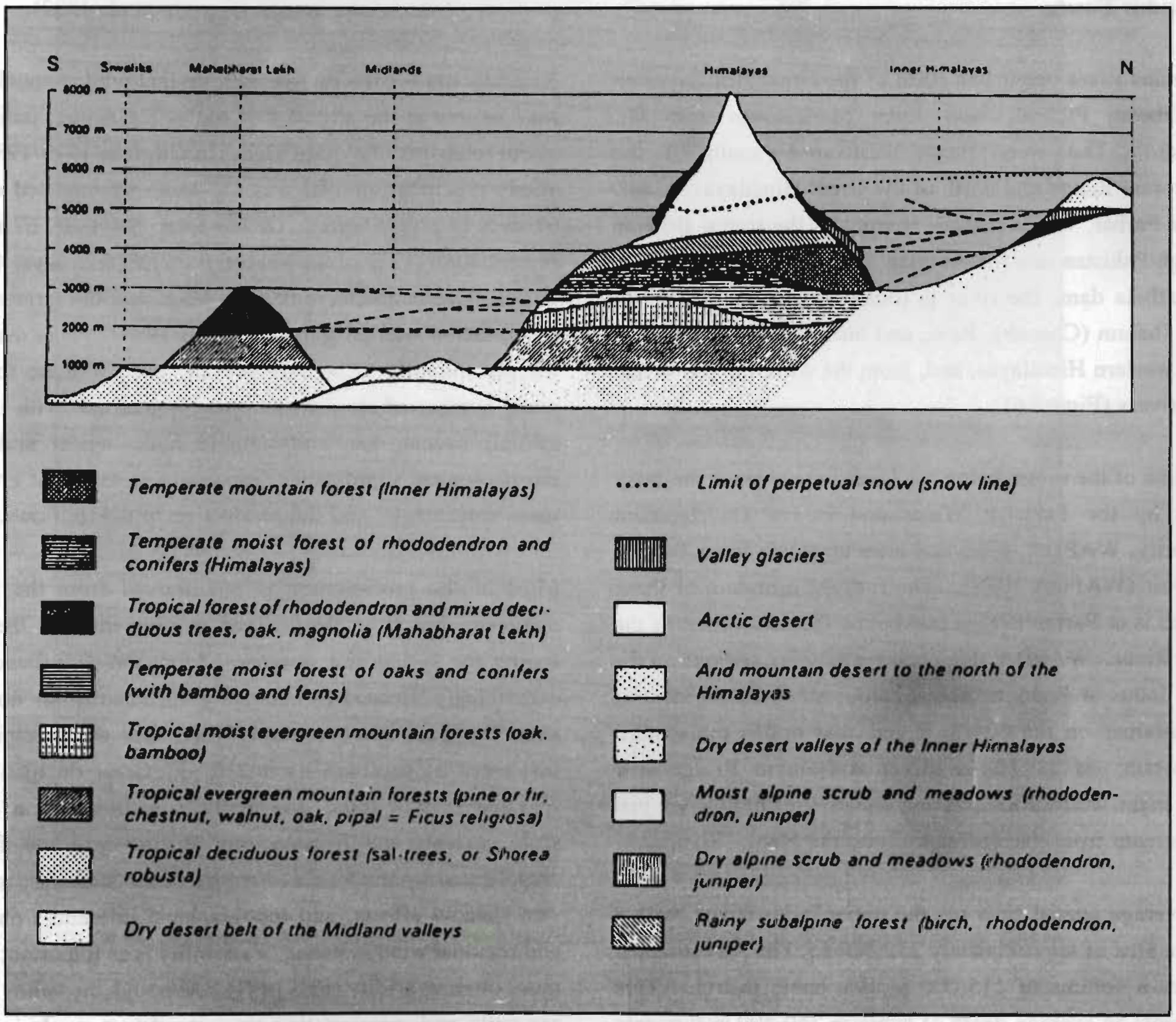

Figure 5: The Altitudinal Zonation of Ecosystems in the Himalayan Mountains of Nepal

Source: Hagen 1980.