Himalayan erosion

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Mountain environments are especially susceptible to high rates of erosion relative to regions of modest topography. Steep slopes, present and past glaciation, high rainfall intensities due to orographic effects, and sparse vegetative cover help lead to potentially high erosion rates in these regions. In addition to high erosion rates, the processes of mountain erosion are often catastrophic and, as a result, the downhill or downstream effects of mountain erosion are perceived to be severe. The episodic and large scale nature of such processes, and the ruggedness and inaccessibility of the mountain environment, have meant that relatively few studies have quantified mountain erosion rates. This is especially true for the Himalaya.

Despite the relative lack of data, researchers have long contended that human impact on mountain environments increases or adds to the rate of 'natural' erosion. Human impacts on the Himalayan belt of mountains have been particularly widely condemned as the direct cause of high erosion in the region (Eckholm, 1975; Eckholm, 1976; Myers, 1986; Reiger, 1981; Sterling, 1976; Thapa and Weber, 1990).[1] Environmental degradation in the Himalaya is a very real problem, and the enormous impact of the rapidly growing number of people living in the region gives cause for continued conservation efforts. Attributing the high levels of Himalayan erosion to the human population is, however, not necessarily justified. Conversely, it is not reasonable to suggest that all Himalayan erosion is 'natural' and that there is no need to improve human land use practices.

In this paper, I shall attempt to put both natural and anthropogenic causes of erosion in perspective for the Himalaya through a brief summary of the available knowledge on the topic. In this summary I revisit Ives and Messerli's (1989) theory of Himalayan environmental degradation (referred to here as the *Theory*). They provide a seminal analysis of the range of factors, from the geological to the sociological, that define the environmental state of the Himalaya.

In reviewing their book, Fisher (1990) asserts that the *Theory* has 'become so pervasive that it has obtained the status of a myth, in the anthropological sense that it is a "charter for action", justifying a vast input of foreign aid into reforestation and watershed management projects.'

While other papers question the *Theory* (Byers, 1986; Carson, 1985; Hamilton, 1987; Hofer, 1993; Metz, 1991; Ramsay, 1986), there does not appear to be a significant change in the public perception that human activity is the primary cause behind the landslides and high erosion rates in the Himalaya.[2] The conventional wisdom continues to be that the erosive materials and debris that fill reservoirs, foul hydroelectric turbines, strip soil from potential agricultural land, and pose hazards to villages downstream, are the direct fault of the people living on, farming, and exploiting the mountainous land.

Here, I shall not analyze the public and land use policies that have been affected by this perception, but do place some rough quantitative bounds on both the natural and human-accelerated rates of erosion. I shall suggest that Himalayan erosion rates are high irrespective of what people do, but that human impacts can have serious local consequences. First, I introduce the natural causes of erosion in mountain environments. Next, I place these within the Himalayan region with a review of the limited studies done there. Finally, I address how land management can affect the natural processes.

Within the scope of this paper it is not possible to examine fully the extent and nature of the removal of vegetation, terrace agriculture, and road construction across the Himalaya. These are the primary human impacts in the region that directly affect erosion rates. Instead, I discuss their general impacts on erosional processes. The major goal of this paper is to review Himalayan erosion rates from a process-based perspective and not to assess the very real effects of environmental degradation caused by humans.

Erosion is the removal of material from any landscape and occurs at rates that can be influenced by climatic, tectonic and anthropogenic forces. With the exception of glaciation and periglacial activity, the processes of erosion are similar across landscapes. It is the scale or rate of the erosional process that varies most noticeably as a function of terrain and becomes greater with steeper slopes. Gravity forces material to move downhill and therefore steeper slopes typically lead to more rapid sediment movement. Steep mountain slopes thus usually experience high rates of sediment movement and more rapid and dramatic erosional processes than low-relief environments. Steep slope processes are more likely to be catastrophic because of the large potential energy gradient between the high and low elevations.

These observations are, however, purely qualitative and intuitive. Quantification of erosion rates from different landscapes demonstrates that the rates are significantly, and often dramatically, higher in mountain environments (e.g. see review by Saunders and Young, 1983).[3] While studies such as those that Saunders and Young (1983) cite deserve detailed attention, for the purposes of this discussion it is simply important to note that there are relative magnitudes of erosion rates for the same erosional process and that natural rates are high in mountains.[4]

Landscape form is dependent on the geomorphic process(es) acting upon it and the material of which it is made. Differences in form point toward differences in the processes dominating the evolution of the landscape. Dominant geomorphic processes responsible for the transport of material down hillslopes include soil creep, solifluction, earthflows, landslides, debris flows, rock falls, and glaciation (see good descriptions in Carson and Kirkby, 1972; Selby, 1982; Abrahams, 1986; Summerfield, 1991). Each process has an associated characteristic form that helps to predict how the landscape is likely to respond to changes in climate or land use.[5]

Whatever material is removed from the slopes must be transported out of the catchment system by rivers or accumulate in the valley bottom, leading to reduced relief and slope in the landscape. Rivers therefore play a crucial role in removing the sediment brought down by hillslope erosion. Glaciers can play a similar role in removing sediment from valleys, and they also remove material from hillslopes. Arguably, as evidenced by the deeply incised landscapes carved by glaciation, glacial processes are the most effective erosive agents.

Glaciers only occur where snow persists, and are therefore either at high altitudes or latitudes in the current climate. Because glaciation covered about 30 per cent of the continental surfaces until only about ten thousand years ago, the geomorphic effects are obvious and significant even in areas where there is no hint of glacial activity today. When a landscape is covered with ice that is moving downslope, the intensity of the mechanisms causing erosion increases. The ice is thick and exerts enormous shear stress on the land surface (equal to the density of ice, times its thickness, times the slope), which is transmitted through particles and rocks entrained in the ice mass. Ice erodes the landsurface by directly abrading it with entrained rocks and sediments and by literally plucking pieces of the rock off the ground surface, transporting them and thus removing the material from the hillslopes. In alpine environments the sediments moved by glaciers are typically bedrock boulders that are difficult to erode in a non-glacial regime.

Glaciers erode hillslope materials and deposit them downslope. The high erosion rates from glaciation then deposit boulders and sediment in reservoirs of material that are 'in storage' in parts of the landscape. These deposits can be quite extensive and become a source for high post-glacial erosion rates, as rivers or landslides reactivate and transport the sediment. We can use these deposits to estimate the average denudation rate from a region. Since the deposits can include material transported by different processes, it is difficult to distinguish specific processes from studies on the mean denudation rates. Nonetheless, rough estimates of denudation rates for regions under alpine glaciation range from about 1 to 10 mm/yr.

Periglacial erosion can also be significant in alpine environments as it may result in the removal or movement of large amounts of material. Specifically, when the soil or regolith is saturated with water that freezes and thaws repeatedly throughout the year, it can flow downslope and therefore erode at more rapid rates than would be experienced without the influence of ice. The term 'gelifluction' refers to frozen ground flow and 'solifluction' refers to soil flow under frozen conditions. The material moved under such processes is typically greater than under non-saturated conditions. Rates cluster around 10 to 100 mm/yr, almost an order of magnitude higher than the mean denudation from glacial regions. However, these rates are likely to be biased because they concentrate only on the parts of the landscape where there are active flow processes.

Periglacial processes can also result in block flows, where angular boulders mantle the slopes or accumulate in the valley bottoms. In the high mountains, both glacial and periglacial processes are likely to have played significant roles in shaping the landscape and contributing to the high levels of sediment being mobilized by contemporary processes.

Landslides, debris flows, and rockfalls are perhaps the most commonly associated processes for the mountains and the frequencies and magnitudes of these processes can be increased easily by environmental destruction. Each of these distinct processes typically involves the movement of large volumes of material at high rates. They are distinguished from other processes of mass movement on slopes by their catastrophic nature and are referred to here as slides. While they all have the immediate appearance of causing large amounts of erosion, it is important in any specific instance to assess both the frequency and magnitude of such processes when determining long term erosive effects. All slides occur when the slope material fails. Failure occurs when the driving force, usually gravity, exceeds the resisting force on the material, which is typically the cohesive strength. These are the processes, along with snow avalanches, that we commonly consider mountain hazards.

Researchers have estimated the average rates of erosion by landsliding across a wide variety of climates and topographic forms (see review by Saunders and Young, 1983). Typical methods for estimating the rates involve measuring the volume of debris moved by the slide and estimating the frequency of occurrence. Determining the latter precisely has proven to be challenging. Current methods of analyses are not sufficient and the range of erosion rates from slides of 0.5 to 10 mm/yr have a great deal of interpretive uncertainty in them.

Soil creep and the diffusion of regolith downslope are two processes that continuously transport sediment off soil-mantled hillslopes. While these processes may be imperceptible at any given point in time, their action is likely to be continuous and the cumulative result may become obvious after time. Curved tree trunks (concave uphill), displaced stone walls or pavements constructed on hillslopes, and the accumulation of material upslope of a fence or wall can offer hints to the slow, continuous movement of sediment. This kind of sediment movement is generally done by biogenic activity such as burrowing animals (ants, worms, gophers, rabbits) and vegetative displacement (roots burrow into the bedrock, the plant or tree falls over, and the bedrock is uprooted into the soil column and transported downhill). The cumulative effect of such processes, while not catastrophic, has a significant impact on any alpine environment with sediment-mantled slopes. Estimates of average erosion rates for landscapes dominated by creep processes suggest rates up to two orders of magnitude lower than glacial and landslide dominated regimes: about 0.01 to 0.1 mm/yr.

The above discussion has described processes that erode the hillslopes and bedrock faces of mountainous regions. River incision or erosion, on the other hand, drives the erosion of the surrounding hillslopes by cutting through the uplifted or uplifting landscape. In general, rivers are cut through landscapes at rates roughly in balance with the uplift rate of the mountains.[6] Landscape erosion caused by rivers involves both the incision of channels into bedrock as well as the downslope transport of sediment. Bedrock incision helps set the relief (the difference in elevation between valley floor and ridge crest) of mountainous regions and remains poorly quantified for any landscape. In regions with high sediment delivery to streams (e.g. glacial, landslide dominated, or recently perturbed by human or climatic influences), rivers form alluvial beds of unconsolidated sediments. Sediment sizes reflect the balance between the transporting stress of the water and the resistance of the bed sediments to movement and are therefore good indications of the dominant flow conditions in alluvial channels. Perturbations in flow conditions, or sediment input, are often observable in such channels.[7]

All of the erosional processes I briefly introduce above are applicable and important in the Himalaya. There have been relatively few studies that have quantified erosion rates, either those from natural processes or as a direct result of human activity, in any alpine environment and especially in the Himalayan region. The combination of Himalayan-scale terrain, poor infrastructure, and unpredictable collaboration with local governments, have each contributed to why so little is known about the details of erosion in the Himalaya. However, there is strong and continual interest in knowing more about the balances and differences between natural and human- induced processes of erosion in this region and others.

The Himalayan region is an enormous and complex geographical area that stretches across parts of Pakistan, India, China (Tibet), Nepal, and Bhutan. This area could be extended to include parts of Afghanistan, Burma, Thailand, as well as Bangladesh if we consider the entire catchment area affected by and influencing the hydrological response of the Himalayan region. A typical cross-section, from south to north, divides up the Himalaya into physiographic regions and extends from the Gangetic plains, or Terai, through the foothills, or Siwalik, the Middle Mountains, the Greater Himalaya, the Trans-Himalaya, and the high plateau (Tibetan). Transects across the Himalayan belt yields similar divisions in physiography along its entire length.

Characterizing the Himalaya as a whole is only possible at the most general level. The first-cut division of the region into physiographic zones enables the examination of geomorphic processes across areas that are geographically similar. We could reasonably extrapolate detailed research focusing on landslides in the Middle Hills of Nepal to a similar physiographic region in the Kashmir Himalaya, for example. Conversely, a study of sediment transport in a river flowing through the Terai should not be extrapolated to try to explain the incision of the Indus through the high regions of the Karakoram. While it is likely that the processes of erosion are similar across the physiographic divisions (e.g. landslides are obviously important in the Siwalik, Middle Hills, and the Trans-Himalaya), it is less likely that the magnitude of erosion is similar due to the affects of local relief, climate, land use, and vegetation. Furthermore, studies characterizing the processes of erosion (Bartarya and Valdiya, 1989; Dhakal et al., 1999; Mehrotra et al., 1994) may do nothing to quantify the rates of erosion, and therefore allow no comparison with other regions or processes.

As others (Carson et al., 1986; Hildreth, 1986) have suggested, the Himalayan physiographic regions can be further divided according to their susceptibility to erosion or potential hazard from erosion. Such a secondary division allows us to assign a relative rate to the same erosional process. For example, landsliding may be the dominant erosive force in the Greater Himalaya, but the construction of roads through a particular area increases the susceptibility of that region from 'normal' to 'high'. Dhakal et al. (1999) map the relative hazards in a small, well-studied catchment in Nepal, and show that geology is the factor that contributes most to landsliding. They determined that about four per cent of the Middle Mountains area they focused on was high hazard. They do not, however, determine overall erosion rates from landsliding. It is likely that if researchers conducted a similar study in the Trans-Himalaya or Greater Himalaya (Selby, 1988), the relative proportion of 'high hazard' regions would be significantly higher, as estimated by Carson et al. (1986).

Carson et al. (1986) provided examples of how to make a rough assessment of the net sediment contribution to rivers of the different erosional processes and how to estimate the effect of human land use. They used Laban's (1978) estimates of soil loss for different land uses in their Land System and Utilization mapping for Nepal to divide the landscape according to erosion estimates. Carson et al. estimated that regional denudation rates range from about 1.5 mm/yr for degraded scrub forest, to zero for undisturbed forest and irrigated bench terraces in good condition. Comparison of these rates with basin-wide denudation rates estimated from river sedimentation rates (Williams, 1977; Milliman and Meade, 1983; Upadhaya et al., 1991; Milliman and Syvitski, 1992) suggests that the rates cited by Laban (1978) were especially high (i.e. on the order of 3 to 13 mm/yr) for the degraded range lands. These rates are lower than estimates from the higher regions, but there has been no reliable quantification of erosion rates from the Trans or Greater Himalaya.

Short term studies of erosion rates, especially those carried out on degraded land, can only capture the immediate processes of denudation acting on the landscape. Because the colluvial soil is produced from the underlying bedrock and from any external inputs of organic matter, there is a limit to the amount of material eroding from the landscape. If the short term rates recorded by Laban (1978) and Williams (1977), or observed by Byers (1986), for example, were acting over long time scales and exceeded the rate of soil production, the landscape form would change from a soil-mantled to a bedrock-dominated landscape. Soil fertility studies for the agricultural regions of the Himalaya underscore this point (Nakarmi et al., 1991; Carson, 1992; Schreier et al., 1994).

Human activity often exacerbates and accelerates the natural processes of erosion, and its potential impacts have been the central tenet of the *Theory* of Himalayan degradation. While the deleterious impacts of road building, vegetation removal, and soil compaction through agriculture may be self-evident, there have been few studies to quantify the hypothesized increase in erosion due to such activities.

Studies examining the impacts of humans have tended to be plot studies measuring local erosion rates from small plots of land under different forms of use (see Upadhaya et al., 1991; Carson, 1992; Schreier et al., 1994 for examples and other citations). Increased erosion rates from road building have been well documented in the Pacific Northwest of the United States, and have been implicated as one of the most critical human impacts in the Himalaya (Narayana and Babu, 1983; Haigh, 1984; Validya, 1985; 1987; Tejwani, 1987; Haigh et al., 1989). Despite documentation of the significance of road construction in increasing erosion rates, there is no quantitative estimate of how much more sediment is contributed to the catchment from the increased landsliding caused by road building.

Land use can directly effect the occurrence of sliding by changing either the driving or resisting forces acting on the slope material. Altering the slope by cutting or filling for road construction, for example, changes the driving force on the material by changing the contribution due to gravity and can be done by cutting part of a hillslope away to build a road or a building. Modifying or removing the vegetation can change the resisting force by altering the infiltration capacity and rate of the soils. For example, increased soil water may increase the soil pore water pressure, which decreases the effective normal stress and therefore the shear strength of the material. Soil-water, or water on the potential failure plane of a bedrock landslide, can increase with changes in or removal of vegetation and also with changes in the drainage of a catchment area.[8]

Researchers have given more attention to the impacts of 'deforestation',[9] both real and mythical, than to any other human impact in the Himalaya (Eckholm, 1975; Myers, 1986; Froehlich and Starkel, 1993; Hofer, 1993). Similar to the studies on the impact of road construction, studies on the connection between erosion and deforestation do not offer accurate measures of how much the erosion rate is being increased by 'deforestation'. Such an estimate for a catchment in the Oregon Coast Range shows that the sediment input from landslides increased twenty times over ten years following clear-cut forestry in the region and that producing such an estimate requires large amounts of funding (Heimsath, 1999).

Additionally, as Hamilton (1987) points out, the term 'deforestation' is rife with emotional connotations and does not address the slope stabilizing effects of well maintained terrace agriculture. Ives (1987) and Carson (1992), for example, show how the hill farmer can stabilize the landscape and potentially lower the net rates of erosion from the steep, Middle Hills landscapes they farm. These studies only serve to add balance to the emotional response that most feel about Himalayan deforestation. In reality, the degradation caused by the cutting of wood for timber and fuel is severe in many of the populated regions of the Himalaya, even if the net contribution to regional erosion rates is relatively small. Local soil loss from landsliding caused by the decay of roots following vegetation removal, for example, leads to declining soil fertility and reduces the areal extent of arable land. This causes encroachment on increasingly marginal land, extending the problem to greater areas. These kinds of impacts continue to be documented.

The fundamental question remains unanswered in the literature, however. That is, are increased erosion rates due to human impacts enough to make a noticeable contribution to the already enormous sediment load being transported out of the Himalaya? A rough estimate of the relative contributions of sediment to the major Nepalese rivers suggests that the answer is no (Heimsath, unpublished data).[10]

This paper provides a brief overview of erosional processes in mountain environments, and applies them to the Himalayan context using the findings from the limited number of studies conducted in the region. While more detailed analyses of the erosion rates and processes are required, there are some conclusions we can draw from the limited knowledge we have. The Himalaya are young, rapidly uplifting, and eroding at high rates. If the hillslopes were in a dynamic equilibrium with the uplift rate, the overall denudation rate would be somewhere between 1 and 10 mm/yr. Such rates are widely regarded to be among the highest in the world, along with that of the Southern Alps of New Zealand and the mountains of Taiwan. Because high denudation rates in the Himalaya are likely occurring in the Trans-Himalaya and the Greater Himalaya, physiographic regions sparsely populated at best, it is unlikely that human impacts affect the rates (i.e. have made them significantly higher than 'natural'). These regions have experienced extensive glaciation and are still covered extensively by glaciers that supply downstream regions with large inputs of sediment.

The Middle Hills of Nepal, where much of the quantitative research has been conducted, are comparable geographically and geologically to large areas of the Indian (Garhwal) and Bhutanese Himalaya. These are the regions where the greatest number of people live and can provide evidence for resolving the relative contributions of humans and natural processes on the rate of erosion. While the local effects of degradation and the stabilizing effects of good land management are relatively well understood, the age-old conventional 'wisdom' that farmers do not necessarily mean higher erosion rates does not seem to be widely accepted by policy makers and land managers. Because studies that have sought to resolve the question of whether humans significantly increase erosion rates have produced uncertain results, acceptance of the now outdated conventional wisdom continues. Scientists have modified their use of drastic terms such as 'supercrisis', 'catastrophic soil erosion', and 'extensive degradation' to describe the state of the Himalayan environment. Ideally the shift in rhetoric will help shift conventional wisdom. It is critical, however, that the shift does not mean shifting attention away from the ever-important efforts of improving land management and conservation practices.

Footnotes

1. Papers like these may be partly responsible for the widely held belief that humans are the root of environmental degradation in the Himalaya. However, due to a paucity of empirical evidence, scientists are increasingly cautious in their claims of supercrisis in the Himalaya.

2. Recent articles in *The Hindustan Times* covering the 18 August 1998 landslide in the Kumaon hills that killed over 200 people, as well as other landslides in the region provide examples of conflicting reports. At least three news articles (21, 24, 27 August), one editorial (20 August), and one opinion article (6 September) presented the landslides as being caused by a combination of the natural processes of the Himalaya and the environmental destruction caused by human habitation of the mountainous region. When the Geological Survey report on the disaster was released, *The Hindustan Times* covered the story (30 November) and reported that the geologists 'have ruled out human interference'. Importantly, however, opinion articles (e.g. 17 November 1997), editorials (e.g. 9 February 1998), and news articles (e.g. 4 January 1999, 7 April 1999) stress the impact of humans on the Himalayan forests and environment without drawing conclusions on the causality between human impacts and mountain erosion.

3. I discuss all rates in terms of landscape lowering, or length per unit time. I use the units millimeters per year, mm/yr, which is the same as 1000 meters per million year, m/Ma, the commonly used units for regional denudation rates. I convert the findings from studies that cite erosion as a some unit mass per land area per time (e.g. tons/hectare/year) to mm/yr by dividing by the bulk density of soil (mass/volume), using the appropriate conversion factors, and the catchment area to get the erosion rate per unit area.

4. I will discuss neither the tectonic and isostatic roles in mountain formation, nor the causes of the Himalayan orogeny. Himalayan tectonics and the geodynamic structures that underlie the region justify longer discussion, such as in Searle (1991). Searle does a clear job of summarizing and quantifying the tectonic forces behind the building of the Karakoram and much of the Himalaya.

5. For example, a well-vegetated, gently-rounded, soil-mantled landscape might be stripped of its soil mantle and turned into a gullied, badland landscape if the climate changed from humid to arid, killing the vegetation, or conversely, if an increase in rainfall were concurrent with human removal of vegetation. The dominant geomorphic process under such changes may shift from biogenic creep to overland flow or shallow landsliding.

6. Fluvial erosion and bedrock incision will not be covered in detail here and deserve a separate discussion paper.

7. For example, if removal of vegetation by humans or fire from the surround hillslopes leads to an increase in the erosion of fine sediments, then a rocky mountainous channel may show layers of silt deposition on the boulders and cobbles.

8. Roads are the primary cause of human induced landslide initiation. A typically constructed mountain road concentrates water into the convergent regions of the landscape. Because these areas are concave upward they have also accumulated sediment from the surrounding hillslopes over time. The increase in water discharged into the area can therefore reduce the shear strength of the material and help initiate a landslide. Concurrently, vegetation removal can lead to root decay, reducing the effective shear strength of the soil mantle (the roots may literally be holding the soil in place on steep slopes) and helping to initiate failure on an otherwise stable slope.

9. See Hamilton (1987, 1992) for a discussion of the ambiguity of the term 'deforestation' and a good summary of the role of forests in protecting the hillslopes from erosion.

10. The rough sediment budget that I constructed for Nepal was based, however, on studies with enormous uncertainties, rough physiographic divisions similar to those cited in Ives and Messerli (1989), and on the hazards assessment of Carson et al. (1986). I therefore do not regard my answer as definitive in any way, although the process of arriving at the conclusion is sound. Constructing a sediment budget for a region involves estimating sources, sinks, and transport mechanisms of sediment across the catchment area. Erosion, deposition, and transport rates must be known and the relative areas of the different dominant erosion types must be estimated. An accurate sediment budget must include detailed field verification of the geomorphic processes and accurate measures of erosion rates. The conclusion I reached for Nepal was based on a first order budget done entirely from literature review with limited field verification. However, my first order estimate of under ten per cent for the contribution from accelerated rates of erosion due to human impacts strongly suggests that human contributions are minimal. Again, this is simply an overall sediment budget and says nothing about local degradation.

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