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INSTANTANEOUS EROSIONAL PROCESSES IN A TROPICAL, MONSOONAL INFLUENCED MOUNTAIN, WITH EXAMPLES FROM CENTRAL HIMALAYA: TYPES OF DYNAMICS AND INDUCED RISKS.

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ABSTRACT

In tectonically active mountains such as the Himalaya, valleys are cut by rapidly incising rivers that keep pace with uplift rates. Typically, river valleys display narrow floors beneath steep rocky or unstable debris-covered hillslopes that are prone to mass wasting. Also, the seasonally contrasting (monsoonal) climate controls soil saturation, slope instability and river regime. In this geomorphic context, instantaneous erosional processes such as debris slides, earth flow, debris flow and rock slides are quite common. Their occurrence results frequently in ephemeral (less than 24 hours) natural dams across river valleys that ensure, after breaching, efficient hillslope-channel coupling. We present selected examples of these dams and their hydro-geomorphic effects both upvalley and downvalley. Repeated observations at the same sites suggest ephemeral dams and their subsequent failure are the most common and efficient mode of erosion and sediment transfer that control sediment fluxes outward the mountain; the potential impact on human settlements of such failures represent a major threat to local populations along the full length of the river system.

INTRODUCTION

In tectonically active mountains such as the Himalaya, valleys are cut by rapidly incising rivers that keep pace with uplift rates. Typically, river valleys display narrow floors with discontinuous patches of aggradational terraces beneath steep rocky or unstable debris-covered hillslopes that are prone to mass wasting. Since the last two decades, large rock-slope failures have been documented in the Himalaya-Karakoram Range, interpreted as a direct response to relief uplift and sismo-tectonic activity (Hewitt, 1999; 2002; Fort 1987, 1993, 2000; Fort and Peulvast, 1997; Schramm et al., 1997). They are considered as formative events that have imprinted a marked and long lasting response on the present fluvial systems, as expressed by their characteristic features such as prominent steps in the long profile, together with the segmentation and specific assemblages of hill-slope, fluvial and lacustrine landforms and sediments (Hewitt, 2002).

In contrast, and despite their immediate impact on human settlements, less attention has been paid to relatively “small” and instantaneous hillslope instabilities that commonly develop as a function of seasonally contrasting (monsoonal) climate, soil saturation, and river regime. These space-limited, yet recurrent events are susceptible to temporary dam river valleys and generate catastrophic outburst floods downstream (Derbyshire et al., 2001; Fort 2001). On the basis of field experience gained during the last twenty-five years in West Central Nepal (fig. 1A; box for location), we present selected examples of ephemeral (less than 24 hours) natural dams related to debris slides, earth flow and rock slides, together with one example of repeated damming by a tributary river behaving occasionally as a debris flow. We show that these dams are common at all scales and that they may affect powerful rivers such as the Kali Gandaki, a major tributary of the Ganga draining the central part of the Nepal Himalaya.

Geomorphic setting of the Nepal Himalaya

The location of any single hillslope failure is usually a function of combined tectonic, lithological and climatic conditions. The Himalayan range is a continent-continent collision range (Eurasian and Asian plates), characterized by a series of imbricated, northward dipping crustal thrust sheets, with an uplift rate exceeding 10 mm/year (Bilham et al., 1997). The Precambrian metasediments and crystalline nappes of the Lesser Himalaya are overthrust by the crystalline nappe (mostly gneisses) of the Higher Himalaya. In this area, different types of slope failures and landslides may occur in various geological contexts, yet the presence of chlorito-schists and micaceous gneisses on the one hand, the vicinity of mylonitic, thrust related zones on the other hand, are strong predisposing factors to slope instabilities.

The highly seasonal southwest monsoon, bringing precipitation more than 5 m/year, favours soil saturation and high pore pressure in densely shattered rock material, all the more efficient along the steep flanks of river valleys. More often, the monsoon season is preceded by a humid period characterized by localized, orographic precipitation in the form of rain or hail storms. Vegetation (namely trees) plays a minor role, if any, in slope failures since most of these failures develop with depths exceeding 10 m, well below the root level. Consequently, deforestation, which may be the cause of localized top soil erosion, cannot be invoked as an explanation for the landslides that scar the landscape from the foothills up to the High Himalaya.

METHODS

Our approach relies on extensive field investigations and geomorphic mapping, and repeated observations at the same sites during the last three decades. Discussions with local people helped assessing the frequency of described features and establishing the conditions under which they developed. It appeared that the Himalayan mountain villagers have acquired a good empirical knowledge of slope instabilities - that they call “pahiro” in the Nepali language. Villagers are keen and accurate in identifying premonitory field criteria (i.e. sudden drop in river discharge, odd cattle behaviour, opening of cracks and occurrence of unusual, “specific” noises, etc.) that they interpret as warning signals to prompt them to escape towards safer places; in fact, no human casualties were reported in the following case studies.

Case studies

A first example is provided by the Birethanti debris-slide, a single event that occurred in 1977 to the detriment of platy, highly shattered calcschists of the Lesser Himalaya. The 100 m high slope suddenly failed, and the resulting rubble (5.10^5 m^3) blocked the stream for two hours (fig. 1C). The break through of this dam resulted in a flood that reworked a large part of the material (with boulders exceeding 2 m^3 in size), and eroded each bank of the river alternatively. The village settled downstream (left bank) was severely impacted, since all the houses built along the riverside collapsed into the river channel.

A second example shows how some slopes may be affected by the same, recurrent process. This is the case of the Benighat earth flow, developed in the chlorito-schists of the Lesser Himalaya (fig. 1B). This earth flow is active every 2-3 years during the monsoon season, when the soils are saturated, especially in the crown zone, where it can be observed that the natural “jungle” cover has not enough time to recover between two events. The magnitude of the process varies in time, as displayed by the set of distinctive, fill-in lateral levees indicative of past, older and larger events of the same kind. Some years, the earth tongue may reach the powerful Gandaki river and dam it. In this case however, the fine texture of the runout is rapidly washed away by the mighty flows of the river. Yet, the recent building of a road across the earth flow track is an additional factor of slope instability and of increased vulnerability for the travellers.

The third example deals with the Ghatte khola, an intermittent tributary of the Kali Gandaki (fig. 1 D and E) that behaves occasionally as a debris flow. The debris flow usually is triggered during heavy rainy storms that are typical of the pre-monsoon season. Fig. 1 F, G, and H, represent a sequence of events that developed in less than half an hour in early May 1974. The water started flowing in a formerly dry channel (fig. 1F), then, within fifteen minutes, the flow became very muddy (hyper-concentrated flow) and occupied the entire active channel (fig. 1G), with occasional pulses of muddy waves (fig. 1H) with "floating" boulders distinctive of a debris flow. At the confluence with the Kali Gandaki, a debris (mud, gravels and boulders) fan built up rapidly (fig. 1J, from the left to right foreground), the volume of which was large enough to efficiently slow down the Kali Gandaki, which actually was nearly dammed (note the still waters upstream the fan). The cause of the debris flow is a persistent planar slide (the left background of fig. 1I corresponds to a dip slope, with the white scar of the landslide visible in the upper, central part). This slide is occasionally reactivated during heavy rains falling on the upper watershed; the slide mass may clog the narrow valley hence the Ghatte khola upstream during a few hours or days. Usually, the water slowly percolates throughout the landslide dam. However, when the slide mass is larger, the dam resists longer, the water accumulates upstream until a sudden, outburst flood occurs, causing bank erosion, riverbed widening and occasionally crops and cattle losses downstream. Inhabitants are aware of this ephemeral, yet threatening behaviour of the stream, occurring once or twice a year in association with heavy, localized rainfalls. They reported that the Kali Gandaki may exceptionally be dammed for a few hours, and the level of this mighty river may rise more than 10 m in height, reaching the level of the "terrace" visible on the right of fig. 1J.

The last example is even more complex. Nearby the village of Tatopani, right in a gorge section, the left bank of the Kali Gandaki valley has been subject, during the last thirty years, to a retrogressive, large scale wedge failure (fig. 2D) affecting the quartzites and chloritoschists of the upper Lesser Himalaya. In 1974 (fig. 2A, view upstream), the landscape seemed to be fixed for thousands of years. The gorges, cut across the >5000 m long hillslopes of the Higher Himalaya, are bounded by adjacent 600 m high, steep (70°) slopes, dominating two aggradational terraces (respectively +30 m and +15 m high above the river level), the only flat areas where the village and crop fields were settled. During the 1987 monsoon season (fig. 2B), a first slope collapse took place, the rubble of which buried the two terraces beneath and caused the river diversion on its right bank (left on fig. 2B). The 1998 monsoon season was even more destructive: affecting the same left bank cliff, a large rockslide occurred, resulting in the complete damming of the valley (fig. 2C). The event was very dramatic. On September 28, after at least three months of abundant rainfall, the cliff started to fail early in the morning (8 a.m., fig. 2E, in the far background, view downstream). One hour later (fig. 2F, view downtream), the collapse was still in progress, releasing in the atmosphere a dust cloud of crushed rocks whilst the level of the Kali Gandaki dangerously started rising. Actually, the rockslide runout impeded the Kali River flow, and caused rapid backwater flooding, thus threatening and eventually inundating at 3.30 p.m the nearby Tatopani village settled on the right bank of the 30 m-high terrace (fig. 2G). The volume of the resulting lake was approximately estimated to be $3x10^7$ m^3. Fortunately, at 4 p.m., the landslide dam partly breached out naturally. The generated flood was felt more than 60 km downstream. Yet, a residual lake (> $2x10^5$ m^3, 4-5 m deep) persisted during nine more months (fig. 2H); final drainage occurred at the onset of the next monsoon season, in June 1999, when the Kali Gandaki peak flow was close to its maximum (combined effects of snow melting in the upper catchments and local monsoon rainfall). The enlarged breaching of the dam instantaneously released huge injections of both coarse and fine solid discharge, in turn increasing the density and competence of the flow, hence its morphogenic efficiency. The river was diverted by the rockslide mass against its opposite, right bank, in turn destabilizing the whole slope by bank undercutting, mass-wasting and retrogressive erosion (fig. 2I). The outbreak flood waves favoured and accelerated the removal of sediment stores downstream (constituting material evidence of former, similar events), thus eroding even more the cultivated terraces and settlement sites. Presently, the coarser, locally produced debris still act as a buffer to further erosion of the active channel bed, thus forcing the river to adjust its bed by bank erosion rather than vertical incision (fig. 2J), hence adding more threat on crop land and settlements. Further downstream, these sediment pulses alternatively caused massive aggradation (valley narrowing) and large-scale channel change (valley widening).

DISCUSSION

The above case studies showed that, in a given, geologically favourable context, various mass-wasting features (debris-slide, earth flow, debris flow, rock slide) are commonly triggered by abundant, monsoon related rainfall. Their runout may be the cause of ephemeral dams that play a major role in the overall process of sediment transfer, with manifold hydro-geomorphic effects. Upvalley, these dams force local, temporary aggradation and storage of sediments, and cause rapid backwaters flooding, thus threatening and eventually inundating the nearby settlements. Downvalley, dam failure and/or breaching out instantaneously increases the density and competence of the flow, hence its morphogenic efficiency, leading to severe bank erosion, hence loss of cultivated terraces and villages sites. Where the valley bottom widens, changes in both dynamically active river bed morphology and river channel traces occur at a larger scale, resulting in a complex hillslope-channel coupling, alternating in time and space from one bank to the opposite one, and reducing considerably the residence time of sediments in these temporary, spatially limited traps.

Yet, the amount of sediments generated and delivered by these instantaneous mass-wasting features is not easy to calculate, because of several, potential sources of errors. Measuring the sediment load carried by the Himalayan rivers is a first problem, since the peaks of sediment and water flows caused by these ephemeral outburst floods are most of the time missed by the gauging stations (Carson, 1985). In addition, bed load is not directly measured; yet, during such events, it probably represents much more than commonly assumed (i.e. 10-20% of the suspended load; Milliman and Syvitski, 1992). Finally, the great variability of evolution from one watershed to another would certainly make unreliable any attempt for calculating regional sediment delivery ratios and denudation rates.

CONCLUSION

Repeated observations at the same sites suggest ephemeral dams and their failure are directly related to seasonal (monsoon) rainfall and subsequent soil saturation (high pore pressure). They are the most common and efficient mode of erosion and sediment transfer that control sediment fluxes outward the mountain; the potential impact on human settlements of such failures represent a major threat to local populations along the full length of the river system.

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