Interactions between unstable mountain slope and Kali Gandaki River, Nepal Himalayas: a sedimentary budget approach

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ABSTRACT: In the Himalayas, landslides interact with rivers, causing channel diversions or short-lived dams and lakes that threaten human assets. We assessed the volume of large (10^6 m^3) debris-avalanche dams, of sedimentary wedges resulting from dam breakout, of landslide debris eroded and exported by the Kali Gandaki river. Landsliding appears as a major denudational process controlling fluxes and residence time of sediments.

1 INTRODUCTION

In tectonically active contexts such as the Himalayas, mass-wasting features are common features. Because of the confinement of valleys, landslides interact with rivers, causing channel diversions or short-lived dams and lakes that may threaten trails, roads and human settlements (Paul et al. 2002; Fort 2006). Their impacts may occur successively in time, depending on the magnitude of the landslides and their capacity to act or not as a barrier; they may affect randomly the functioning of the sediment fluxes. We present interaction patterns between unstable mountain slopes and the Kali Gandaki river (Nepal Himalayas), and try to assess a first sedimentary budget as an example of cascading sequence of temporary, intramontane storage units.

2 GEOMORPHIC SETTING

1.1 Regional context

The Himalayan range is a continent-continent collision range, characterized by a series of imbricated, northward dipping crustal thrust sheets, and an uplift rate (7-10 mm yr^{-1}) matched by river incision.

The Kali Gandaki river originates from the southern edge of the Tibetan Plateau. It cuts across the >8000 m high peaks of Dhaulagiri and Annapurna, forming the deepest gorges in the world carved into the gneisses of the Greater Himalaya, then into the metasediments (mostly quartzites and schists) of the Lesser Himalaya.

The valley displays narrow floor with discontinuous patches of aggradational terraces beneath steep rocky unstable debris-covered hillslopes.

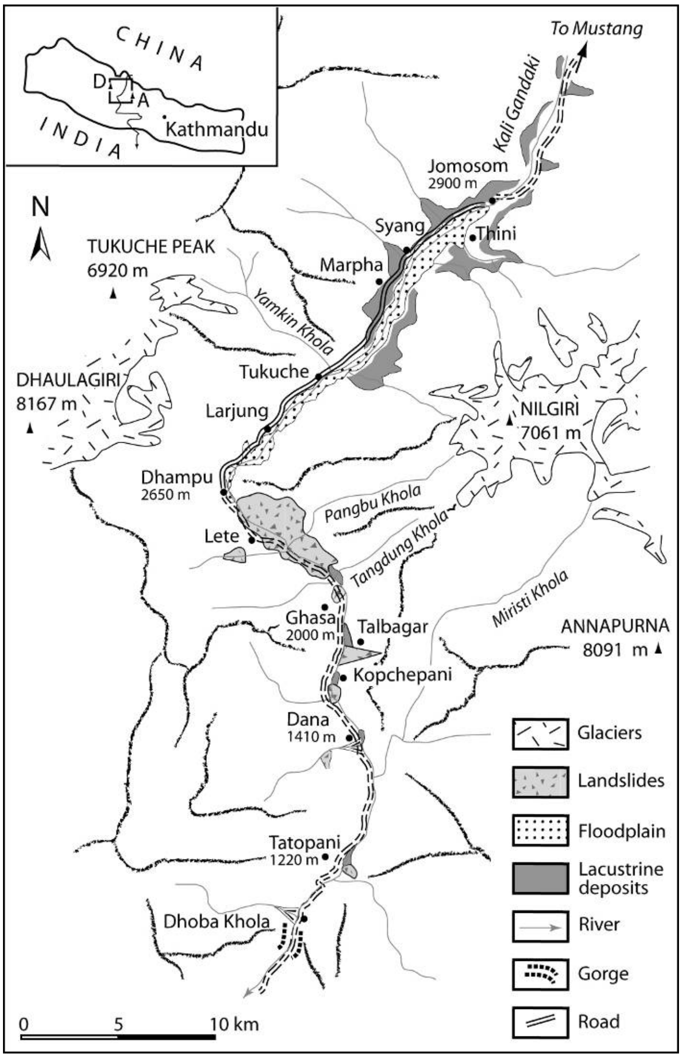

Figure 1. The Kali Gandaki valley system. Several landslides barriers interrupt the longitudinal profile of the valley, with upstream and downstream aggradational complexes.

The highly seasonal southwest monsoon, bringing precipitation more than 5m yr^{-1}, favours soil saturation and high pore pressure in densely shattered rock material, all the more efficient along the steep flanks of the river valley. Vegetation plays a minor role in slope stability control since most of slope failures develop with depth exceeding 10 m, well below the root level.

The present Kali Gandaki valley appears as a fragmented river system, interrupted by a series of landslides and/or large debris flow fans that temporary blocked the sediment conveyance of solid discharge to the downstream reaches (Fig. 1). From north to south, landslide barriers are as follows. The prehistoric, giant (10^9 m^3) Dhumpu-Kalopani rock avalanche dammed the upper Kali Gandaki and created a lake about 25 km long (Fort 2000). Further down, the valley again is interrupted by the undated Talbagar and Kopchepani landslides dams. Other modern features are intermittently impounding the valley (Fort 2006): the two debris cone of Dana and Dhoba khola, both supplied by the right bank tributaries of the Kali Gandaki, and the Tatopani landslide. We present here two sites, the Talbagar and the Tatopani landslides.

1.2 Study cases

Both Talbagar and Tatopani landslides dammed the Kali valley and caused upstream water and sediment ponding.

Figure 2. The Talbagar debris slide/avalanche failure, and associated sedimentary wedge downstream (right), viewed from the right bank of the Kali Gandaki river. Note the track of a new road completed in March 2008 (MF.07-02-473).

The Talbagar (= the boulders of the lake, *Nep.*) debris slide developed on the left bank of the valley along a 2000 m high mountainslope. The age of the event is unknown, but the lack of any soil suggests it probably occurred less than one century ago. The landslide runout buried the narrow gorges and forced the sedimentation upstream (mostly lacustrine, alluvial and slope sediment). After the river break through the blockage, an aggradation wedge of coarse debris built up downstream, that is nowadays dissected and perched >40 m above the Kali Gandaki river.

The Tatopani (= hot waters, *Nep.*) site has been subject, during the last thirty years, to a retrogressive, large scale failure affecting the quartzites and chloritoschists of the Lesser Himalaya. The gorges, cut across >5000 m long hillslopes, are bound by adjacent, 600 m high, steep (70°) slopes, overlooking two aggradational fluvial terraces, respectively +25m and +15 m above the river level. In 1987, during the monsoon season, a first collapse took place, the rubble of which buried the two terraces beneath and caused river diversion on the opposite, right bank. The 1998 monsoon was even more destructive: at the same site, a large wedge rockfall occurred on September 28, after three months of abundant precipitation (Fig. 3). The cliff started failing at 7 a.m. One hour later, 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, causing progressive back water flooding that eventually inundated the Tatopani village settled upon the higher gravel terrace. At 4 p.m., the lake drained out naturally, and released both coarse and fine solid discharge.

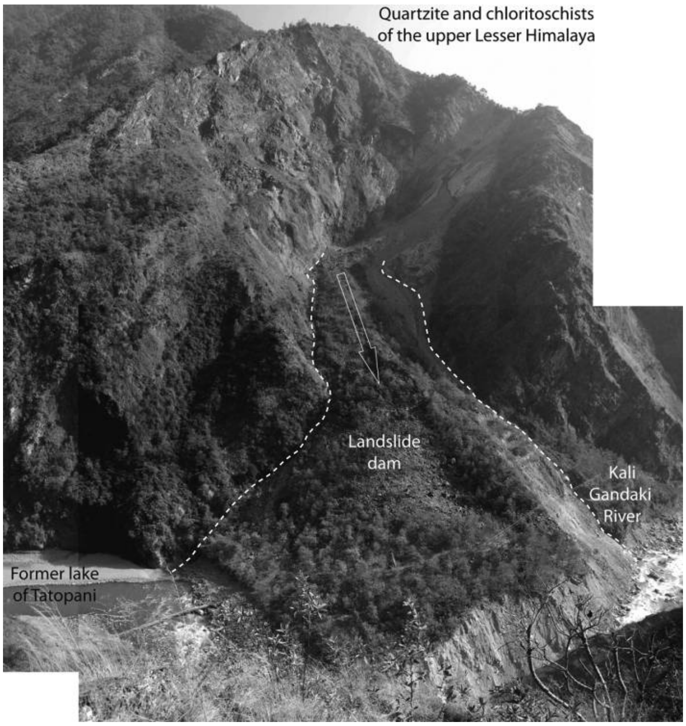

Figure 3. The Tatopani wedge rockfall/rockslide failure, viewed from the right bank of the Kali Gandaki river (MF.07-02-839-840-841).

3 METHODS

A sediment budget approach is appropriate for assessing the impacts of landslide-derived material and understanding the links between sediment mobilisation, transport, storage and yield (Slaymaker 2003); it also helps assessing the importance of storage *vs* sediment outputs. Sediment is routed through storage reservoirs: sediment fluxes are inferred from the variation of the volume of the reservoirs. On the basis of diachronic (1974-2000-2008) geomorphic surveys and mapping, and with the help of DEM facilities, we reconstructed the extent of the landslide deposits, the volume of the resulting lake and/or sedimentary trap, and the evolution of the landslide mass. We established the cross section of the landslide mass in its valley and characterized the material (size, sorting). The volume of sediments released by the mountain slope was assessed, including the debris cones (the very dam), and the sedimentary wedges resulting from superficial reworking and redistribution of debris. We also estimated the volume of debris eroded and exported by the Kali Gandaki since the failure. All sediment export calculations were based upon simple geometric landforms (Campbell and Church 2005). Basic measurements (height, width, etc.) were adapted to this kind of remote area, and surveyed with a Leica laser telemeter. We reconstructed hydraulic geometry and estimated hydraulic parameters in applying the equations of Bagnold (specific stream power), Rotnicki (discharge) and Jarrett (Manning's resistance coefficient).

4 RESULTS

4.1 Tatopani site

We tried to reconstruct the geomorphic impacts of the 1998 landslide dam and its failing. We first assessed the landslide and lake volumes (Fig. 4). We also estimated the inflow discharge responsible for the lake filling, i.e. 54 m^3 s^{-1}, a quite low value compared to other data collected in Nepal. In contrast, the discharge reconstructed downstream of the dam amounts to an average of 389 m^3 s^{-1}, a value that would indicate a little more than an hour for the complete draining of the lake. However, reports by the local population say the draining of the lake lasted between 2-to-3 hours. This suggests that the discharge was much lower during most of the draining stage hence the breaching of the landslide dam was not instantaneous but progressive. In fact, when the lake level reached the landslide crest the water spilled over, and a breach progressively developed, causing a huge injection of both coarse and fine solid discharge, that partly aggraded downstream in the form of a sedimentary wedge. This accumulation, less than 1 km-long, represents no more than 10% of the debris removed from the breach. The landslide diverted the Kali Gandaki on its right bank, and caused the undercutting of the Holocene terrace deposits and the partial removal of colluvium. The largest blocks (> 4 m^3) are clustered near the landslide dam and eroded banks, suggesting their transport on short distances; they are now armoring the river channel. Yet, the morphology of the Kali Gandaki flood plain is still changing, while sediments are removed from both sides of the valley, threatening villages, cultivated lands and infrastructures. Observations of this slope during the last 30 years have shown that rock falls continuously supply the foot of the slope, hence reducing the cohesion and buttress effects of the rock mass, and maintaining the slope in an unstable state. In fact, the slope is affected in depth by slow rock creep, as expressed by almost vertical shear planes that bend into a listric shape in the lower part of the slope (Voelk 2000).

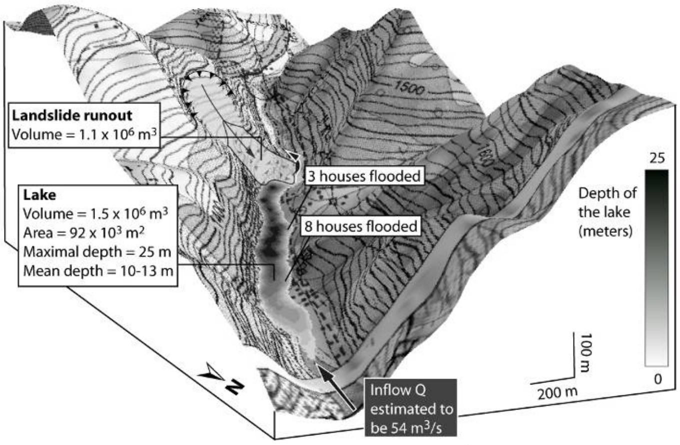

Figure 4. DEM and volume assessment of Tatopani landslide dam and lake (1:25,000 sheet, Nepal Topographical Survey).

4.2 Talbagar site

This example is quite complex and also reflects a continuous instability of the mountain slopes on both sides of the valley. The Talbagar debris avalanche cone (16 x 10^6 m^3) dammed efficiently the valley, and created a lake (1.5 x 10^6 m^3) that persisted long enough to be entirely filled in. The subsequent landslide dam breach favored the aggradation of a 4 x 10^6 m^3 sedimentary wedge, the thickness of which was also controlled downstream by the Kopchepani landslide dam.

Figure 5. The Talbagar debris avalanche cone (right) facing a rockfall cone on the opposite right bank of the Kali Gandaki. The river channel is clogged by very large boulders that slow down the incision rate of the bedrock. Note the successive positions of the major trail in the background. View northwards (upstream) (MF-00-05-26).

When this latter was by-passed by the Kali Gandaki that entrenched its course into the bedrock (*i.e.* epigenetic gorge), retrogressive erosion caused active gullying of the Talbagar debris avalanche cone upstream. This erosion, together with modern debris flows pulses continuously supplied to the Talbagar cone, still forces the diversion of the Kali Gandaki river on its right bank (gneisses). The resulting steepening of the valley walls acts as a trigger for recurrent rock falls, as expressed by the many realignments or abandons of the main trail track cut into the bedrock (Fig. 5). For the last 30 years, the flux of sediment out of the gorge seems approximately balanced by new inputs from adjacent slopes.

4.3 Preliminary sediment budget

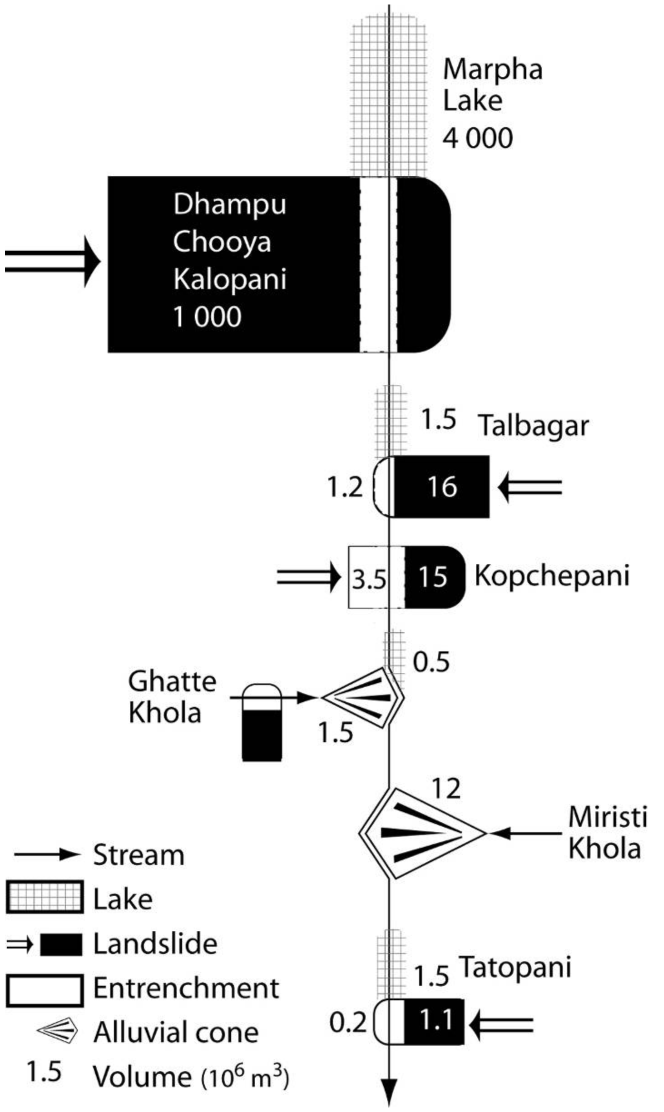

Figure 6. Sedimentary budget along the middle Kali Gandaki river (volumes in 10^6 unit; storage boxes not at scale).

Our results are summarized on Figure 6. This tentative sediment budget shows how a large amount of sediment is trapped upstream of the landslide and/or within debris flow dams, the duration of which is related to their size and stability. Here, the shape of the runout (constrained by the topography), the percentage of fine material (dependant on bedrock lithology, *i.e.* gneisses *vs* schists/flyschs), and the potential undermining and dam material removal counteracted by bed armoring by the largest boulders are control factors of the duration of the dams. Interactions with hydraulic parameters (channel long profile, river discharge, regime and stream power), control potential dam breach, hence sediment export from upstream. In fact, observations of recent events (*i.e.* Tatopani) indicate that a large amount of debris is released as soon as the dam breaks, hence activating the sediment cascade efficiently.

5 DISCUSSION

5.1 Understanding the complexity of the processes

Our results show the rapidity with which geomorphic processes are acting in the Himalayas. The sediment storages created by landslides of moderate magnitude (10^4 to 10^6 m^3) are temporary features that are partly reworked and exported by the rivers during the monsoon high flows. However, these “regular” flows are insufficient to remove the larger boulder lags armoring the channel bed. Only higher magnitude events would remobilize them, most often related to an off-normal supply of debris, *i.e.* caused by new landslides and/or debris flows occurring upstream, events that in turn increase the density and the transport capacity of the flow downstream. Our studies also point out the fact that once disequilibrium affects a mountain slope, various processes are acting towards a new equilibrium that in fact can barely be reached in a context of continuous river incision and persistent rock uplift. Deep rock flow (or creep) is certainly more generalized than usually said, and is a direct response to the rate of river downcutting, as other examples in the Himalayan Range illustrate it (Paul et al. 2002).

More specifically, complex assemblages of sediment preserved in temporary stores reflect better the varying modes of erosion/reworking/deposition of landslide material, both in space and time (Fort 2006, Pratt-Sitaula et al. 2007), independently of any mid- or long term climate change, contrary to some interpretations (Monecke et al. 2001).

5.2 Tectonics vs climate trigger with regards to time scale

In most cases we observed efficient (i.e. fast) sediment trapping upstream of the dam, a good evidence for large mechanical erosion rate related to steep topography, again demonstrating that uplift/downcutting forcing is more efficient than climate forcing. Despite this however, monsoon climate together with seismic activity appear as the main triggers for landsliding. More specifically, seasonal monsoon rains are an efficient and repeated trigger. As shown by Carson (1985), landslide occurrence reaches a peak in September, when the pore pressure is at its maximum.

Over a short term period (a few decades), the density of the landslides and the residence period of the landslides in the landscape vary according to precipitation frequency, rock/soil type and landuse, as observed in the Tatopani case. This is of particular importance when assessing landslide risks in rural areas and along new infrastructures (Paul et al. 2000; Petley et al. 2004; Fort et al. 2008).

On a larger time scale, earthquakes are the most efficient to trigger massive landslides that are persistent in the landscapes and impact durably sediment fluxes. In the Pokhara valley drained by the Seti khola, the seismically triggered, giant collapse of the Annapurna IV that occurred 500 years ago brought *c.* 4×10^9 m^3 of debris, half of which is still stored in the tectonically ponded basin; the calculated annual contribution of this rockslide-derived sediment is in the order of 4×10^6 m^3 a^{-1} (Fort 1987). In the narrow Marsyangdi valley, quite similar to the Kali Gandaki valley, Pratt-Sitaula et al. (2004) showed that the stored material along the valley reaches represent <2-8% of the material eroded during a 350-800 years of gross sediment flux, hence suggesting the majority of the sediment is not stored but passed downstream.

If we now consider very large landslides such as the Dhumpu-Chooya-Kalopani rock avalanche (Fort 2000 and Fig. 1), their formation is most often related to the combined effects of large scale seismo-tectonic features (North Himalayan Detachment Fault, in the Dhumpu case) and postglacial debuttressing and paraglacial reajustment (Hewitt 2002, Hewitt 2006, Fort et al. in press). These giant landslides create a disturbance regime that may be persistent for tens of millenia after their occurrence (Hewitt 2002, 2006). The efficiency of high-magnitude/low-frequency events *vs* low magnitude/high frequency events to foster sediment fluxes and/or to create sediment storages is again questioned, particularly when dealing with landslide risk assessment.

6 CONCLUSION

Comparison with other features observed along the middle Kali Gandaki and other adjacent valleys suggests that landsliding plays a major role in the overall process of denudation and sediment transfer. When coupled with high fluvial activity, it considerably reduces the residence time of sediments in the temporary, spatially limited traps of the valley bottom and highly influences sediment fluxes outward from the mountain zone.

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