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MONIQUE FORT (PARIS)

REPEAT PHOTOGRAPHY: A USEFUL TOOL FOR UNDERSTANDING SHORT-TERM GEOMORPHOLOGICAL DYNAMICS IN NEPAL HIMALAYAS

Abstract: The Himalayan Range is subject to both tectonic forces and climatic variations, each operating on different time scales, as observed in Nepal. Through the use of repeated photos, we try to illustrate some examples of very rapid geomorphological evolution, especially over the last 10 years, showing both the intensity of the processes in action (landslides, floods) and their potential impacts on inhabited areas and infrastructures under construction. We selected four sites from the middle Kali Gandaki valley (Annapurna–Dhaulagiri Himal) where frequent natural hazards are threatening the two-lane highway under construction, and two more sites in the south of the Everest massif to illustrate the changes brought about by the last 2015 earthquake.

Key words: repeat photography, landslides, hyper-concentrated floods, earthquake, landscape changes, Nepal Himalayas

INTRODUCTION

For a researcher in geomorphology, who has a specific commitment with field work, the passing years are a privilege because they enable him or her to gain experience in areas that are revisited several times during a career and thus to gain a better understanding of the processes that transform – gradually or abruptly – landscapes and landforms. Natural processes are obviously a major component of these transformations, but human activities, whether land use or infrastructure development, can also cause changes in landscape dynamics, unless they suffer their adverse consequences.

This is particularly true in a country like Nepal, one of the less developed countries in the world, which has undergone significant transformations in recent decades. The population has grown from 13.13 million (M) inhabitants in 1974, to 15 M (1980) then 19 M (1990), 24 M (2000) and 27 M (2010), to exceed 30 M inhabitants in 2020. This demographic growth has been accompanied by a strong migration from remote rural areas to urban areas, or even abroad, and by a rapid development of roads to provide access to the most economically dynamic regions.

Another characteristic of Nepal is its location in the heart of the Himalayas, a very active mountain range that is subject to both tectonic forces and climatic variations, each operating on different time scales and acting as triggering factors for sudden events (earthquakes, landslides, floods), difficult to control, with potentially catastrophic consequences for the development of the country.

We do not want here to repeat our contribution on the Nepal Himalayas "From mountain building to landform evolution in a changing world" (Fort 2011), but to present a few detailed examples of this evolution at a rather short time-scale, through a series of repeated photographs over a 45-year period, and especially over the last ten years or so. Our aim is to show the rapidity of morphological and hydrological changes under the influence of hydro-climatic events that may trigger chain reactions that affect inhabited areas or the communication axes. Most examples are selected in the middle Kali Gandaki valley, but we added two final examples to quickly illustrate the changes brought about by the last 2015 earthquake in an area (south of the Everest massif) rather marginal in relation to the seismic event.

STUDY AREA

The section of the Kali Gandaki (KG) valley studied here is located in the Central Western part of Nepal, on the southern part of the Greater Himalaya, dominated by the Dhaulagiri (8,167 m a.s.l.) and Annapurna (8,091 m a.s.l.) Peaks. It belongs to the subtropical side of the mountain, affected by a 4-month rainy monsoon season, alternating with a rather dry season, that may be interrupted by orographic, stormy rainfall events. The river cuts across three main Himalayan structural units (the Tethyan sedimentary series, the Higher Himalayan Crystalline and the Lesser Himalayan units) in a deep and narrow gorge, considered as "the deepest in the world". As shown on Fig. 1, the valley is locally obstructed by mass wasting features of different ages (Fort et al. 2010), the material of which is a permanent threat to the new road, which was opened in 2008 and is now being upgraded to a 2-way black-top highway as a project under the China's Belt and Road Initiative (BRI), an annex of the New Silk Road.

The four selected study sites (Myagdi District) have been documented over my different visits, the first two sites in relation to landslides activity, the third

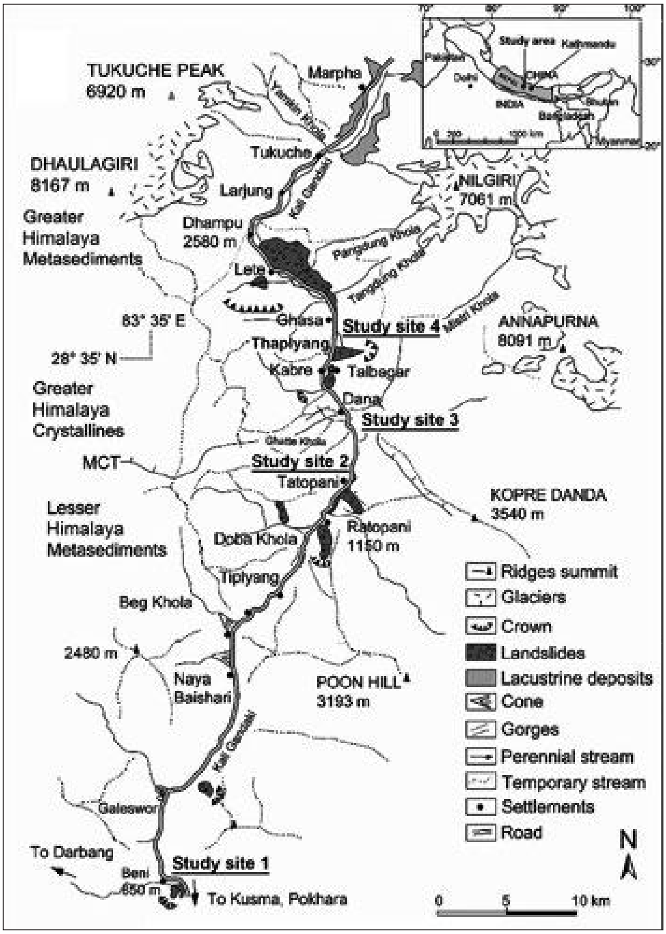

Fig. 1. Location map of the middle Kali Gandaki (KG) valley, with four study sites. Adapted from M. Fort et al. (2010)

and fourth ones in relation to torrential and gully activity, all of big concern for the new road.

The first landslide site, Beni, is a rapid update of what was presented in M. Fort (2011), with a rather dramatic expansion of the city. The second site, the Tatopani landslide (1,000 m a.s.l.), was extensively studied in M. Fort et al. (2010), but the full story over the last 40 years, shows a progressive stabilization and readjustments that occurred since the dramatic 1998 failure. The third study site, the junction fan of the Ghatte khola stream with the KG River, appears as the most active area at a short-time scale and, in the meantime has become a key site for infrastructure development (Gurung et al. 2020). The fourth study site, the Thaplyang, active gully, represents a new hazard that appeared a few years after, and in connection with, the opening of the road.

The last two (5th and 6th) sites are located in the Solukhumbu District (Eastern Nepal) (Fig. 2), along the Dudh Koshi valley which drains the higher Khumbu area, with glaciated peaks >5,500 m a.s.l., dominated by Everest Peak (8,848 m a.s.l.). The climate is strongly influenced by the monsoon, and the Dudh Koshi section considered here is cut across Himalayan metamorphic terrane. Yet many high terraces of the valley are the legacies of major rockslide collapses regraded by alluvial deposits (Goetz et al. 2015; Posch et al. 2015; Fort et al. 2019). We focus on two sites quite closed from the river side, that we visited before and after the earthquake sequence, hence allowing us to assess the geomorphic changes caused by the earthquakes and the subsequent monsoon.

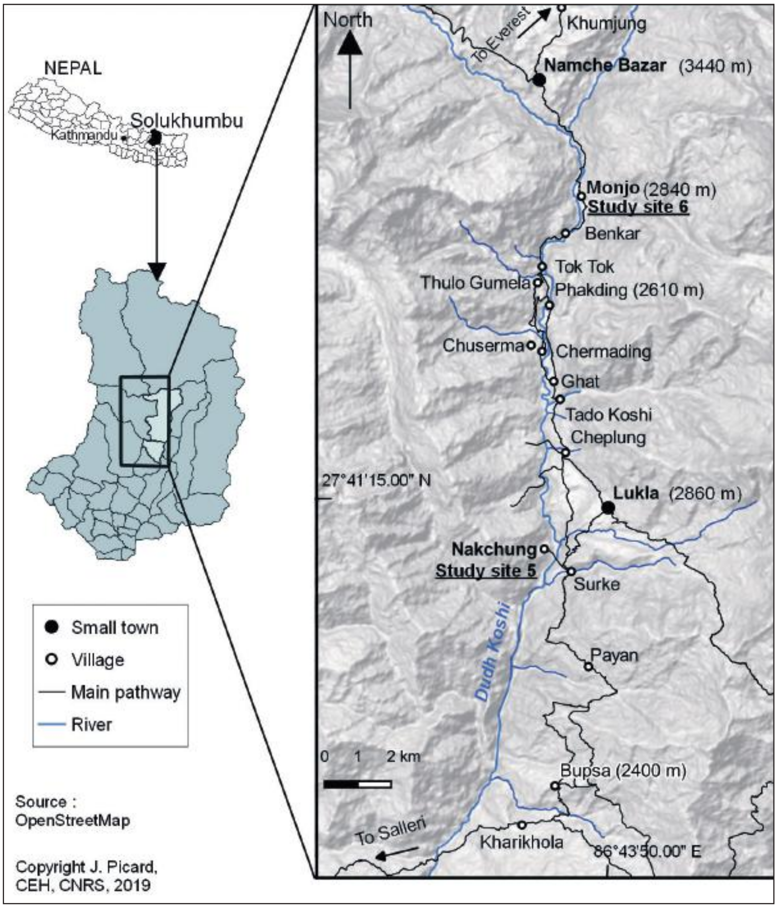

Fig. 2. Location map of the Dudh Koshi (DK) valley, with two study sites. Adapted from M. Fort et al. (2019)

METHODOLOGY

This contribution mostly focuses on photographical records taken during field investigations in Nepal. During my earliest visits (from 1974 onwards), photographs were a support of my notebooks and drawings. When passing by the same itinerary some years later, then I realized that locally some changes did occur, and this is why, for a few selected places, I started repeating my photographs. According to AC. Byers (1987), "repeat photography, or precise replication and interpretation of historic landscape scenes, is an analytical tool capable of broadly clarifying the patterns and possible causes of contemporary landscape/land-use changes within a given region". It is an efficient, cheap and rapid research tool which has been used in Nepal Himalayas by different researchers in various fields (biogeography, geomorphology, glaciology, ethnography, natural resource…), in conjunction with local interviews and possibly with literature reviews (Byers 1997, 2017; Garrard et al. 2012a, b). Most of the photographs presented here were taken with different digital cameras and different lenses, except for the oldest ones (before 2000).

RESULTS

BENI

This first example intends to complete the narrative reported in M. Fort (2011). Beni (899 m a.s.l.), the district Headquarter of the Myagdi District, is located at the confluence between the KG river and the Mayangdi khola (Beni means "the place where two rivers meet" in Nepalese) and it is set on narrow river terraces (Fig. 1). In the early days, Beni was an important stop along the Tibet–Nepal–India trading road, and it also used to be the winter capital of the Malla rulers of Parbat (17th–18th centuries). But this flourishing town declined rapidly after the collapse of the Gorkha Kingdom in 1786 (Gurung 1980). However, when the maoist insurgency started developing in the Dhorpatan area (upper Mayangdi catchment) in the late 1990's, with many killing of "enemies of people", many people left their home and fled to district headquarters for their security (Gurung 2003; Hachhethu 2008). A large part of them settled in Beni, which started growing very rapidly, independently from, and with no concern about, the natural environment and its potential hazards. Beni's population has grown from 28,511 inhabitants in 2011 to 33,498 inhabitants in 2014 (http://www.benimun.gov.np/en). In the absence of more recent statistics, and assuming that this growth rate has been maintained, the number of inhabitants has probably exceeded 40,000 in 2018.

The old photograph of the southern hillslope facing Beni (Fig. 3A) shows that the confluence area is potentially a dangerous area, because of its instability, favored by the presence of green, chloritic phyllites of the Lesser Himalaya. In 1973, in response to a heavy rainfall event, a large earthflow moved down to the river and nearly dammed the junction between the two rivers. Four years later, the earth-flow track is still very outstanding. 27 years later (Fig. 3B), the top of the slope is still very active, with even a renewed instability towards the south (left), materialized by head scarps caused by rotational slides. The situation has improved at the lower part of the slope, as evidenced by partial regrowth of vegetation, which no doubt reassured the populations who built a rural road at the foot of this slope, without thinking of potential adverse effects. This hillslope is crossed by a foot trail much frequented by young people whose school is located at the top.

In 2018 (Fig. 3C) the situation is somewhat different. The hillslope is now hidden by an abundant forest (*Alnus Nep.)* whose natural regrowth has been encouraged by the local authorities who have "defended" this area. But the tilting of the trunks shows that this slope can be reactivated at any time, during heavy rains. Moreover, with the opening of the new road (left bank of KG), the situation has become crucial: south and north of Beni, travelers report

Fig. 3. The slope opposite to Beni, on the right bank of the KG river, immediately downstream of the Mayangdi Khola junction. (photo M. Fort). A: In 1977, the 1973 earthflow is still very prominent, with relics of former, larger events, as evidenced by longitudinal levees on both sides of the earthflow tongue; B: In 2000, the head scarp of the earthflow is still active, and expands laterally. The lower part is less active, allowing the vegetation to progressively regrow on both sides. Note the new rural road across the earthflow toe and, the progressive urbanization of Beni Bazaar on the opposite side; C: In 2018, the earthflow seems stabilized, as attested by the dense forest cover

the existence of many landslides (either active or dormant), leading to traffic interruptions of several hours/days.

Looking at the April 2018 panoramic view of the city of Beni (Fig.4) gives an idea of the high urban density, which can be explained by several factors. Apart from the migratory processes linked to the civil war, the city's location as a crossroads has strengthened the city's commercial activities. The widening of the KG road to two lanes has reinforced this trend. The population of the municipality of Beni continues to grow, and as space is very limited and there is no urban zoning scheme, buildings are expanding in dangerous areas, which may be subject to landslides or slope movement. The risk of flooding cannot be ruled out either, and if the 1973 earthflow on the southern slope were to be reactivated, the consequences would be dramatic throughout the lower parts of the town, all the more that most of the inhabitants are new incomers with no knowledge of the former natural hazard events (Fort 2011).

Fig. 4. The Beni city (Myagdi District), settled on the lower terraces at the confluence of KG (foreground) and Mayangdi rivers (830 m a.s.l.). The city is progressively encroaching over the hillslopes. The KG river is now contained by dikes. The new bridge (right) was completed a few years before, as part of the upgrading of the KG Road. The white rectangle corresponds to the frame of Fig. 3C. (Photos taken in April 2018 at 1,100m a.s.l., from the upper terrace overlooking the city and close to Mallaj; photo M. Fort)

TATOPANI

The highly touristic Tatopani ("hotsprings" in Nepalese) village (1,200 m a.s.l.) is settled on the two lower terraces (+12m, +8m) of the KG River (Fig. 1, 5A and 6A). Hillslopes are cut into the Lesser Himalayan Formations (quartzites and phyllites – mostly green chloritoschists; Upreti, Yoshida 2005). They are commonly affected in depth by slow rock creep (vertical shear planes that bend into a listric shape in the lower part of the slope). Yet, south

Fig. 5. More than 40 years of morphological change of the Kali Gandaki valley, downstream from Tatopani village. (All photos were taken from the suspended bridge across the KG, one kilometer south of the village; photo M. Fort). A: The Tatopani village is set on the right bank of the KG, upon Holocene alluvial terraces well developed and visible on both sides of the river (photo: October 1977); B: On 23 August 1988, a first collapse of the left bank partly buried the terraces, causing the shifting of the river on its opposite, right bank (photo: fall 1990); C: On 28 Sept. 1998, a large landslide mass caused the damming of the KG; after breaching, a mass of debris was carried downstream, widening the active river bed (photo: spring 1999); D: In December 2007, the 1998 landslide mass appears as partly revegetated, yet its toe is still under erosion by the KG. 2007 also corresponds to the final completion of the construction of the road, which appears as a new asset in threat. E: In October 2016, the landslide toe is nearly stabilized, except downstream where a gully is still active during the monsoon season. F: No significant change 18 months later (April 2018): most of the river bed morphology remained also quite the same after the 2018 monsoon, despite a higher discharge episode in August 2018 (see Figs 6C and 8F)


C
D
Road
E
Road
F

Fig. 6. Tatopani landslide toe and its impacts, viewed from the road, downstream from Tatopani village. The narrow section of the KG valley, locally controlled by quartzitic outcrops, favored the valley damming by the landslide in 1998 and is still influencing the river response to exceptional discharge events. (photo M. Fort). A: In December 2000, the KG river bed morphology clearly displays the impacts of the 1998 landslide dam after the complete draining of the residual lake in June 1999. The relicts of this lake are still visible, with white sands and gravels upstream from the former landslide dam; B: In April 2018, the 1998 landslide toe is nearly totally revegetated; C: In November 2018, after an intense monsoon season characterized by two exceptional rainfall events, the higher KG flows severely eroded the 1998 landslide toe again, hence illustrating an ongoing hillslope-channel coupling process

of the village, on the left bank of the KG, the mountain slope has experienced a series of retrogressive, large scale, failures during the recent decades (Fort et al. 2010).

A first failure developed on August 22, 1988, as a large debris cone that partly buried the left bank terraces of the KG and caused river diversion on its right bank (Fig. 5B). On September 1998, at the end of a long and abundant rainy monsoon season (1172.5 mm during the three months that preceded the event) (Sikrikar, Piya 1998), a dramatic landslide occurred at 7:00 pm, as a rock wedge in the upper slope, evolving into a rock avalanche downslope. One hour later, the collapse was still in progress, releasing in the atmosphere a dust cloud of crushed rocks whilst in the valley bottom the debris piled up (estimated volume= 1.5 10^6 m^3; M. Fort et al. 2010) and impounded the river flow (Fig. 5C and Fig. 6A). A lake formed (photo in M. Fort 2014). At 4 p.m., the lake drained out naturally, and released both coarse and fine solid discharge. However, the drainage was not complete, and a shallower (5–3 m deep), smaller (90,000–60,000 m^3) lake persisted 9 months more until the next monsoon high flows restored a continuous flow of the KG River (Fort et al. 2010; Fort 2014). In fact, if the collapse did not cause human losses, the consequences on river dynamics were important. More specifically, the landslide mass caused the diversion of the KG river course along its right bank, hence favoring bank undermining and triggering of shallow landslides.

Ten years after the 1998 event (Fig. 5D), these shallow, retrogressive landslides are rapidly expanding upslope (colluvial material) and have become a direct threat to the stability of the under-construction road (2007) built 20 m above the river bottom (Fort et al. 2010). On the opposite left bank, the stabilization of the landslide hillslope is increasing, as evidenced by the progressive regrowth of an *Alnus Nepalensis* groove, a species adapted to instable, wet soils. In October 2016, the new road is operational, still it is locally threatened by small debris slides that may cause traffic interruption for a few hours or days, whereas the left bank hillslope is nearly entirely revegetated (Fig. 6B), except for a small ravine outlet which remains locally active (Fig. 5E). Two years later, in spring time (April 2018), the KG does not display many changes compared to 2016, yet the abrupt rainfall events which affected the areas 20 km upstream from Tatopani created a flood wave which propagated downstream (Bell et al. 2021) and was efficient in eroding again the loose landslide material, as observed in November 2018 (Fig. 6C).

DANA

Dana village (1,440 m a.s.l.) is settled on a large fan built up by the debris brought by the Ghatte khola, a small (7.8 km^2), steep (37%), intermittent

Fig. 7. The Ghatte khola (GK) catchment at Dana (1,450 m a.s.l.), viewed from the opposite Garpar ridge (1,800 m a.s.l.). The KG river flows from right to left. Note the contrast between the dip slope to the south (left), facing the counter-dip, steep slope to the north (right). The width of the torrential stream bed, without any vegetation, is clear evidence for repeated hyper-concentrated flows events. The size of the GK's fan reflects the abundance of sediments brought by this torrent over the decades and, explains the position of the river bed of the KG, pushed back on its left bank. (November 2016) (photo M. Fort)

tributary of the right bank of the KG (Fig. 7). This Ghatte Khola catchment is typically a "landslide catchment" (*sensu* Starkel 1972, 1976), characterized by pulsating, short debris-flows or hyper-concentrated-flows events initiated by landslide outburst floods (LOFs), as witnessed during our very first visit in Nepal in 1974 (Fort 1974, 2014). The pronounced asymmetry of this east-west elongated basin (upper ridges at 3,420 m a.s.l., confluence with the KG River at 1,400 m a.s.l.) is due to the northward general dip of the Himalayan structures, with sharp contrasts in lithology (the Main Central Thrust controls the catchment orientation; Fig. 1). The gentler, north oriented dip slope (micaschists), covered with a widespread mantle of landslide-derived debris is facing the steep, south-exposed counter-dip slope (quartzites and gneisses) affected by rockfall processes. In most parts of the catchment the stream actively cuts into the bedrock. During heavy cloudbursts, active landslide masses from the south slope may clog the river flow, where the channel bed is at its narrowest, hence blocking the stream waters, until a sudden LOF occurs, as in 1974. Downstream, these LOFs processes are causing bank erosion and riverbed widening along the Ghatte khola fan, and near the confluence with the KG, each newly built debris fan may encroach over the KG river bed with varying magnitude.

The series of photos taken during the last decade provide good evidence of the very dynamic functioning of this watershed. In April 2010 (Fig. 8A), like in in April 2014 (Fig. 8B), a relatively common situation can be observed at the outlet of this torrential river which, each summer, is depositing abundant sediments composed of fine and coarse elements, transported for the most part from the upstream part of the watershed, with additional boulders (gneisses) that have been dislodged by the torrent from the downstream banks of the fan (KG alluvium, overtopped by Ghatte khola debris). Nevertheless, this sediments heterogeneity bears evidence of the power of the flows reinforced by an increase in their density due to the presence of fines (schistose elements). These hyper-concentrated flows are triggered by irregular stormy episodes occurring upstream of the catchment area at the beginning (Fig. 8C), or at the end of spring, as in 1974. In autumn, a few weeks after the end of the monsoon, it is very often observed that most of the debris fan's inflow has been cleaned off by the abundant but regular monsoon rains as well as by the high waters of the KG (Fig. 8D).

Nevertheless, during some specific episodes of intense rainfall during the monsoon, the aggradation can be exceptionally voluminous (5,000 m^3 ±1,000), as was the case in August 2017 (Fig. 8E) according to the inhabitants we interviewed. But the most unprecedented situation was observed in autumn 2018, after a monsoon that was marked by a few episodes of exceptional rainfall that caused a wave of erosion along the KG valley that propagated from the south of Mustang to Dana, as shown in Fig. 8F. The previously deposited fan was completely stripped off, and the edge of the upper cone was also eroded, the whole representing a volume of 8,500 m^3 ± 1,000 (Bell et al. 2021).

To sum up, many events of the same nature yet of varying magnitude occurred in this Ghatte catchment during the last forty years (about one every two years, according to local people). The development of debris/hyper-concentrated flows is favored by a rapid process-response system to the LOF processes, due to the small size, compactness and asymmetry of the catchment, and to a very short response time to peak discharge, hence controlling the short-term alternation of aggradation and incision stages at the confluence. Such "landslide catchment" poses serious threat to the future Ghatte khola road bridge and to nearby infrastructure and settlements (Gurung et al. 2020).

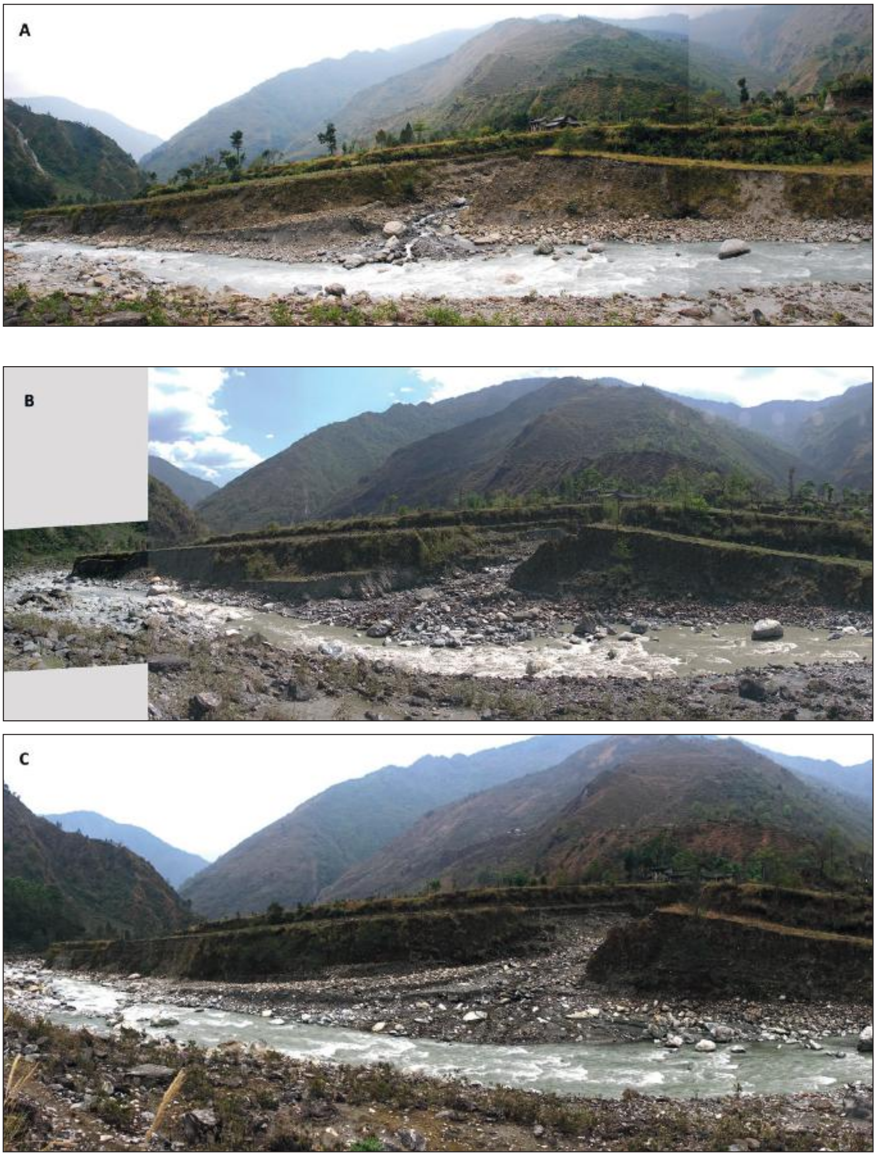

Fig. 8. 2010–2018 sequence of photos showing the rapid changes at the junction (1,412 m a.s.l.) between the KG river (foreground) and the GK. The repeated photos have been taken from the opposite bank, at the playing ground of the school of Garpar (1,420 m a.s.l.), (photo M. Fort). A: April 2010. The GK fan displays a rather complex morphology, with several small cut-and-filled fans into the main, higher fan, upon which the houses (police station) are built; B: April 2014. Note that if there is some refreshment of the lower fan scarp, the larger boulders observed along the GK channel close to the KG river bed have not been removed; C: April 2016. The GK activity has been significant: a large amount of debris has built the present active fan, whereas the lower Ghatte fan (left) is nearly totally eroded; D: November 2016. A few months later, after the rainy monsoon season, most of the fine sediments were washed away. A few large boulders remain on the surface; the white one, a few meters from the confluence, was

buried in April 2016, whereas it was already in place in 2010 (A) and 2014 (B); E: In November 2017, a vast debris fan more than one meter thick was built by the massive inflow from the GK, impeding the flow of the KG, as suggested by the relatively calm waters of the river upstream. The downstream extension of the fan is attributable to the powerful current of the KG river that redistributed the coarser debris; F: In late October 2018, the situation is completely different. The confluence has become “ordinary”, with a small torrential river joining a major axis, the KG, which caused much destruction during the previous monsoon. The fan visible in 2017 has completely disappeared as well as part of the perched fan that towered it, whose banks have also been eroded. Note the new electricity pylon and the top backfilling of the original cone, in conjunction with the construction of a transformer field (in the background), and the diversion of the canalized waters formerly used to irrigate the fields on the main upper cone, before the transformers

THAPLYANG

Thaplyang is our northernmost site along the KG river. Located south of Ghasa, this W–E oriented catchment (3.6 km^2) is a very steep, right bank tributary developed at the contact between a north dipping, gneissic hillslope (NNE 50°–60°) and a large prehistoric (yet undated) rockslide outcropping along the northern hillslope (Fig. 9). Until recently, there was no mention of this particular site, but during the monsoon 2014, a large collapse affected the rockslide material in the lower catchment and blocked the road (1,915 m a.s.l.). Debris were transported downstream to the KG bed (1,865 m a.s.l.) and deposited as a large fan, that nearly dammed the valley.

The physiognomy of the KG valley has been completely modified (Fig. 10). Upstream of the cone from the Thaplyang valley, the KG River flow was

Fig. 9. Geomorphological context of the Thaplyang catchment (lower section), seen from the left bank of the KG (December 2019). The right bank of the ravine (left) is made up of gneiss from the Higher Himalayas (NNE 50–60° dip). The left bank, strongly eroded, consists of landslide material (age unknown). Under the road ("Kali Gandaki Corridor"), perched some 40 meters above the river bed, one can identify the remains of the ancient debris cone that formed in 2014 (see Fig. 11A). Not initially planned, the construction of a passageway to safely cross the ravine became necessary. But the chosen solution – a bridge – poses technical problems because the anchoring of the piers to the north, where the landslide material outcrops, is far from being solved. (photo M. Fort)

Fig. 10. KG Valley, downstream view from the road (November 2016). On the left (upstream), the river is subdivided into several channels, which have invaded the ripisylve, as evidenced by the dead trees and pebble accumulations that lie across it. This evolution is linked to the partial dam formed by the debris cone originating from the Thaplyang ravine (not visible, right, see the white arrow), which caused the water to rise and slow down upstream. Downstream of this area, debris inflow from the Thaplyang khola obstructed the former channel of the KG (right bank, rocky hillslope), whose waters were diverted to the left bank. (photo M. Fort)

blocked for a few hours, a period of time sufficient to submerge the forest of the valley bottom and favor the deposition of finer sediments transported in suspension. On the other hand, at the cone section and downstream, it is the abundance of boulders that predominates in the riverbed. Similarly, the active channel of the KG has been abandoned as the river was diverted on its left bank by the Thaplyang debris (Figs 10, 11A, 12A). But in 2018, the river returned to its former channel, following heavy monsoon flows that allowed it to carry away most of the materials stored within the cone of the Thaplyang khola (Figs 11B, 12B).

Since the first event in 2014, the Thaplyang site has become a real concern for traffic. The recurrence of erosion during each monsoon is blocking occasionally the road, sometimes for several days. The decision to build a bridge was late, after 2014 and, in view of the work in progress, including abutments that were not anchored in stable ground (is there any stable ground around?), it was questionable whether there was not a better and cheaper solution, for example that of building a concrete ford that could be easily scraped off in the event of the road being plugged by debris. In fact, during the monsoon of 2020, the new bridge was swept away by a new wave of erosion and the road became impassable (N. Gurung, pers. com.).

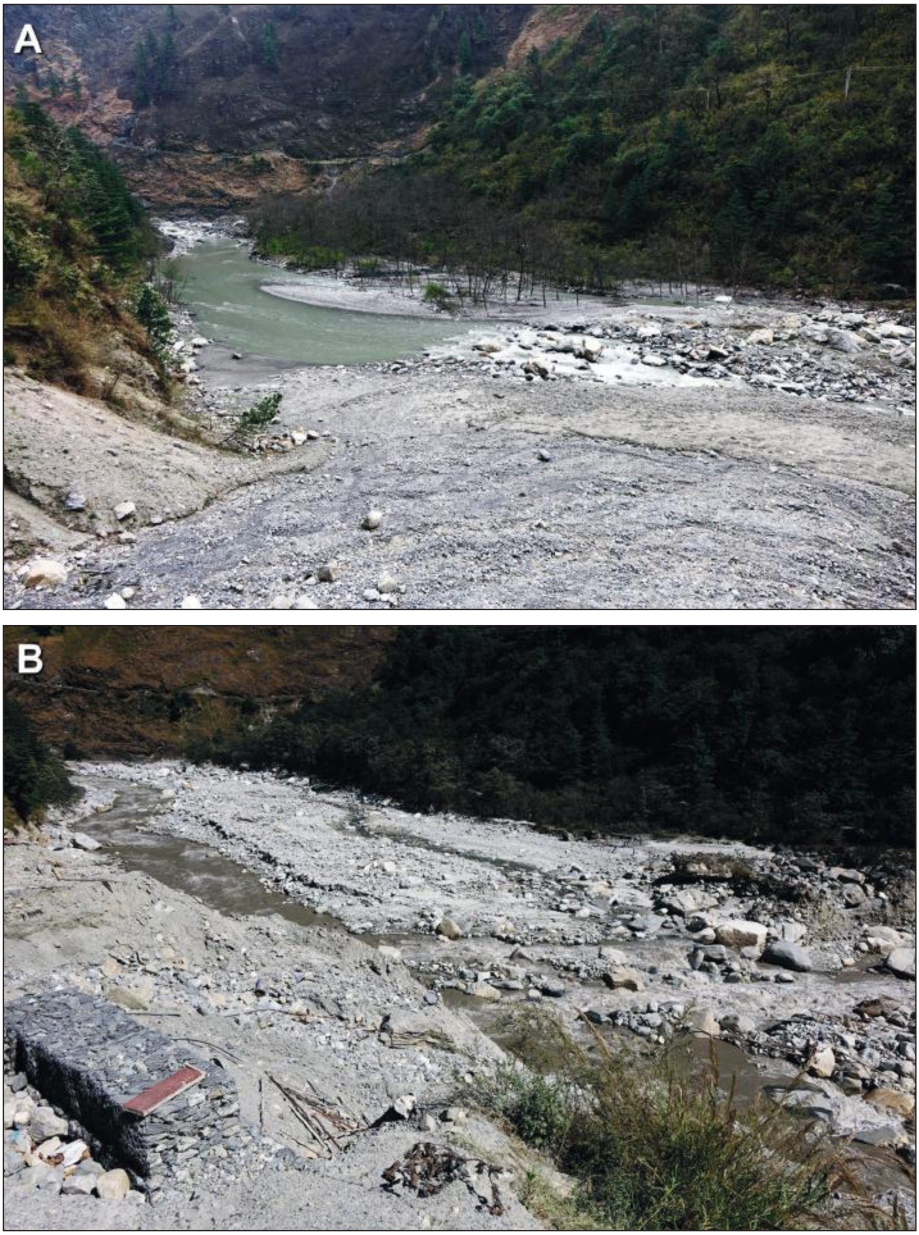

Fig. 11. The junction of Thaplyang catchment with the KG river bed (photo M. Fort). A: November 2016: The debris fan from the Thaplyang khola, seen from south to north, opposite to the previous photo (Fig. 10). The initial blockage (in 2014) of the KG is still visible, with a contrast between the calm waters upstream and the resumption of the torrential flow downstream, in a bed cluttered with large blocks; B: November 2018. In the foreground, road protection element and start of the construction of the bridge. In the background, the KG has restored the continuity of its flow, following the big flood of summer 2018. The remains of the old flooded forest (Fig. 10) have disappeared

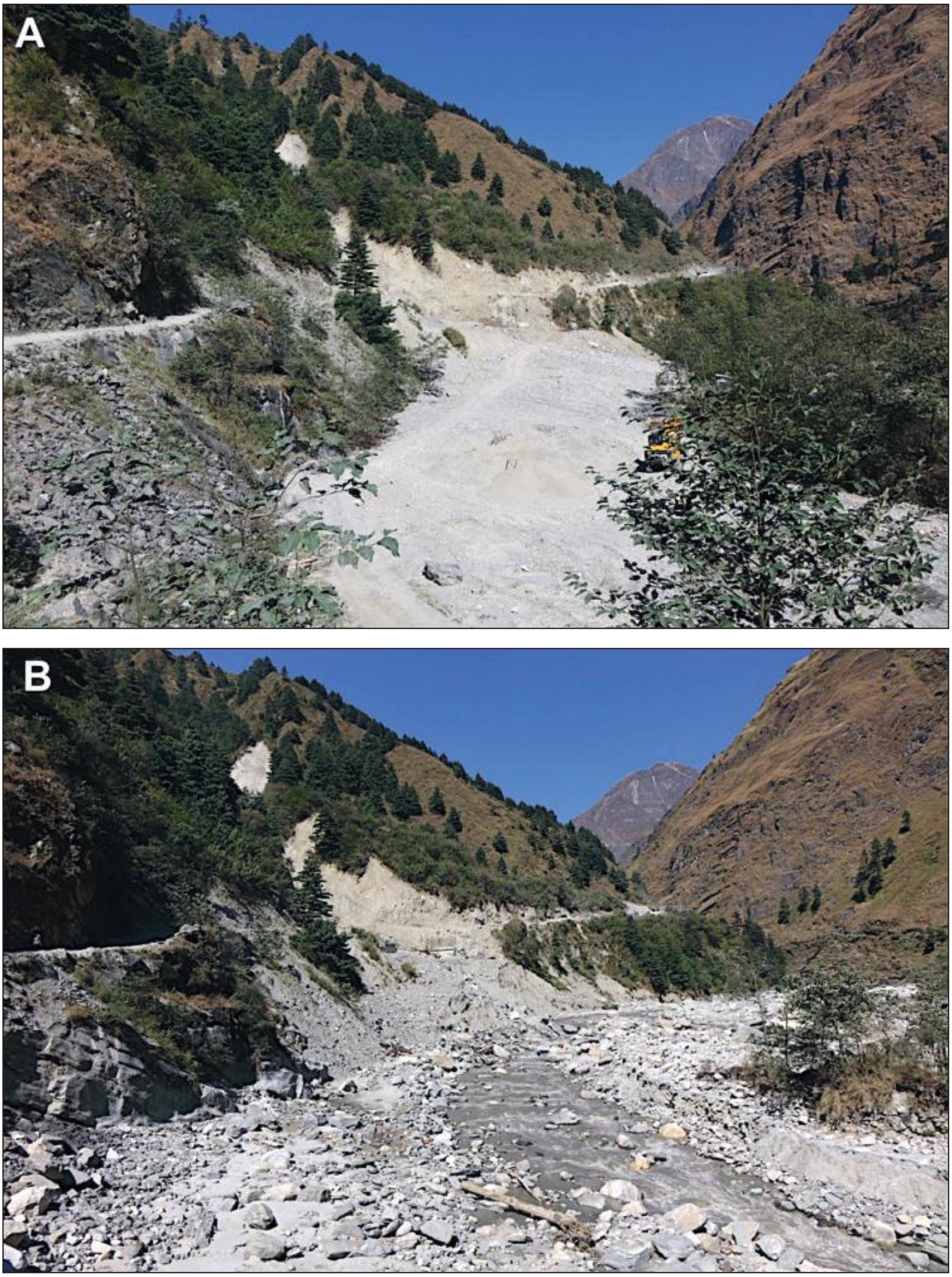

Fig. 12. Lower Thaplyang khola catchment, view northwards from the road (photo M. Fort). A: November 2017. In the background, active landslides of the Thaplyang gorge. In the foreground, the former channel of the KG buried by the cone of debris from the Thaplyang khola. The wheel tracks are those of the engines used to construct the Thaplyang bridge; B: November 2018. Taplyang landslides were reactivated during the 2018 monsoon (road closure for several days). In the foreground, the KG has moved back to its former channel

Central Nepal was affected in April–May 2015 by the Gorkha earthquake sequence, which caused thousands of fatalities, damaged and destroyed entire villages, and triggered thousands of landslides (Collins, Jibson 2015; Kargel et al. 2015; Bollinger et al. 2016; Roback et al. 2018). We present here two examples from the Solukhumbu, an area rather marginal compared to the core areas, but which was also impacted by shallow, very superficial landslides, and more specifically along the Dudh Koshi (DK) river sides.

The Nakchung village (2,225 m a.s.l., site 5) is settled on a right bank terrace of the DK river, opposite to the Lukla airport. This cultivated terrace (+ 60–65 m) is bounded by sharp, vegetated banks and displays irregular contours (Fig. 13A). During the earthquake sequence, the Nakchung site was affected by two types of landslides: rockfalls and debris slides (Fig. 13B). According to the villagers, the slopes were first destabilized during the April 25 earthquake, but the major collapses occurred after the May 12, main aftershock (Fort et al. 2019). North of the village, two rockfalls developed along the 50° steep slope overlooking the DK: the rockfall tracks (350 m long for the northernmost one) suggest that most of the blocks run across the slope down to the river. In addition, several debris slides affected the edges of Nakchung terrace, hence revealed a loose, alluvial material superposed on old rockslide deposits probably part of the Lukla rockslide (Goetz et al. 2015). Interestingly, these new debris slides collapsed mostly at the same sites as those previously affected by bank erosion generated by the 1985 DigTsho Glacial Lake Outburst Flood event, which took place more than 30 km upstream (Vuichard, Zimmermann 1987).

The last site (site 6), more than 10 km further to the north (Fig. 2), is located south of the Menjo village (2800 m) settled on the left bank terrace (+30 m) of the DK river. This section is another good example of the impacts of the 2015 Gorkha earthquake. The comparison of both photos (Fig. 14) shows how the terrace cliff was « cleaned off » by the quake, to the detriment of coarse torrential, mud-supported alluvial deposits from the Menjo tributary, and to the grove of pine trees. However, the collapse represents less than one meter in thickness, as shown by the large blocks outcropping before and after May 12, 2015. Yet, on the top of Menjo terrace, cracks opening (<2 m from the vertical section) had favored further collapses during the following 2016 monsoon, as reported by a villager.

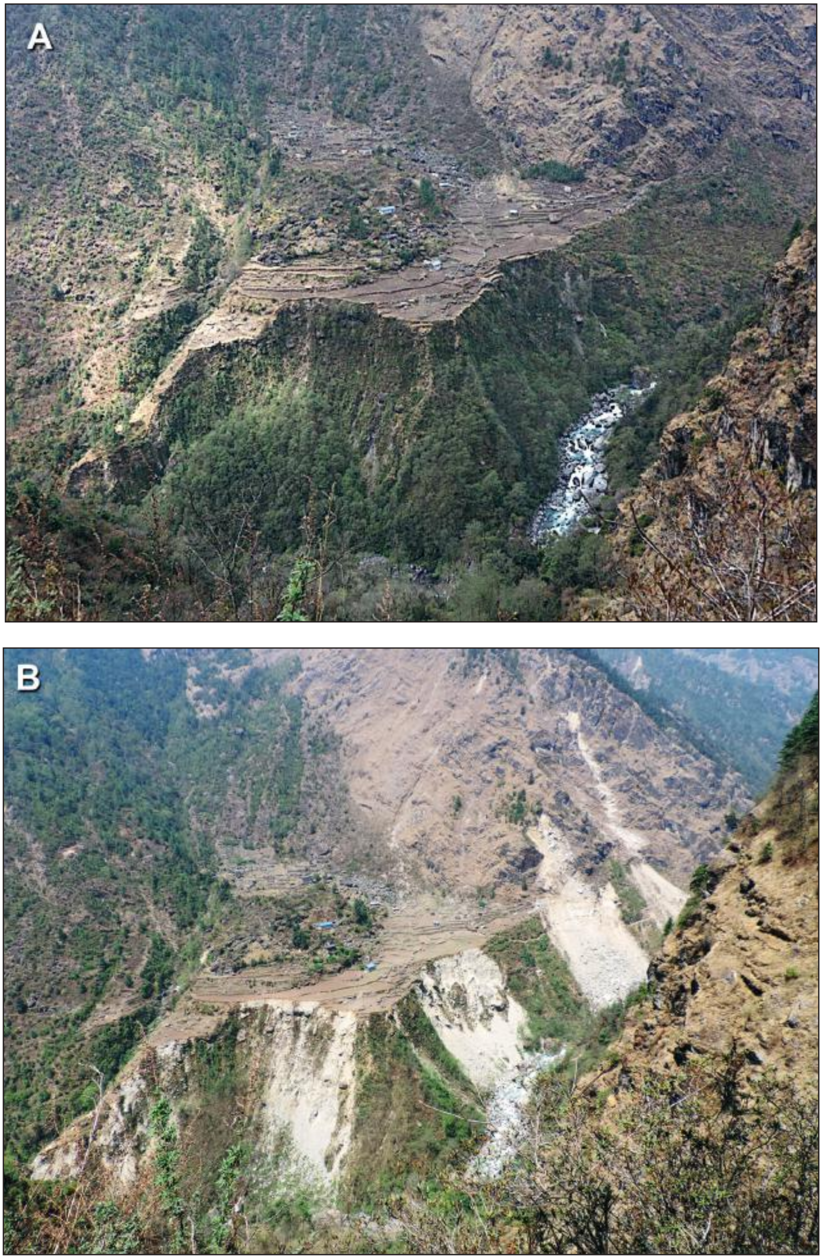

Fig. 13. The site of Nakchung, as observed south of Lukla, from the trail to Surkhe (photo M. Fort). A: March 2015, before the Gorkha earthquake. The village is settled on a terrace of the Dudh Koshi, partly covered by a massive rockfall cone. The edges of the terrace are vegetated and rather sharp; B: October 2015, after the Gorkha earthquake. The terrace edges were affected by thin collapses, revealing a rockslide material overtopped by the Dudh Koshi river gravels. Upstream from the village, rockfalls developed from a paragneissic ridge (35–40°N dip), along the 50° steep slope above the Dudh Koshi

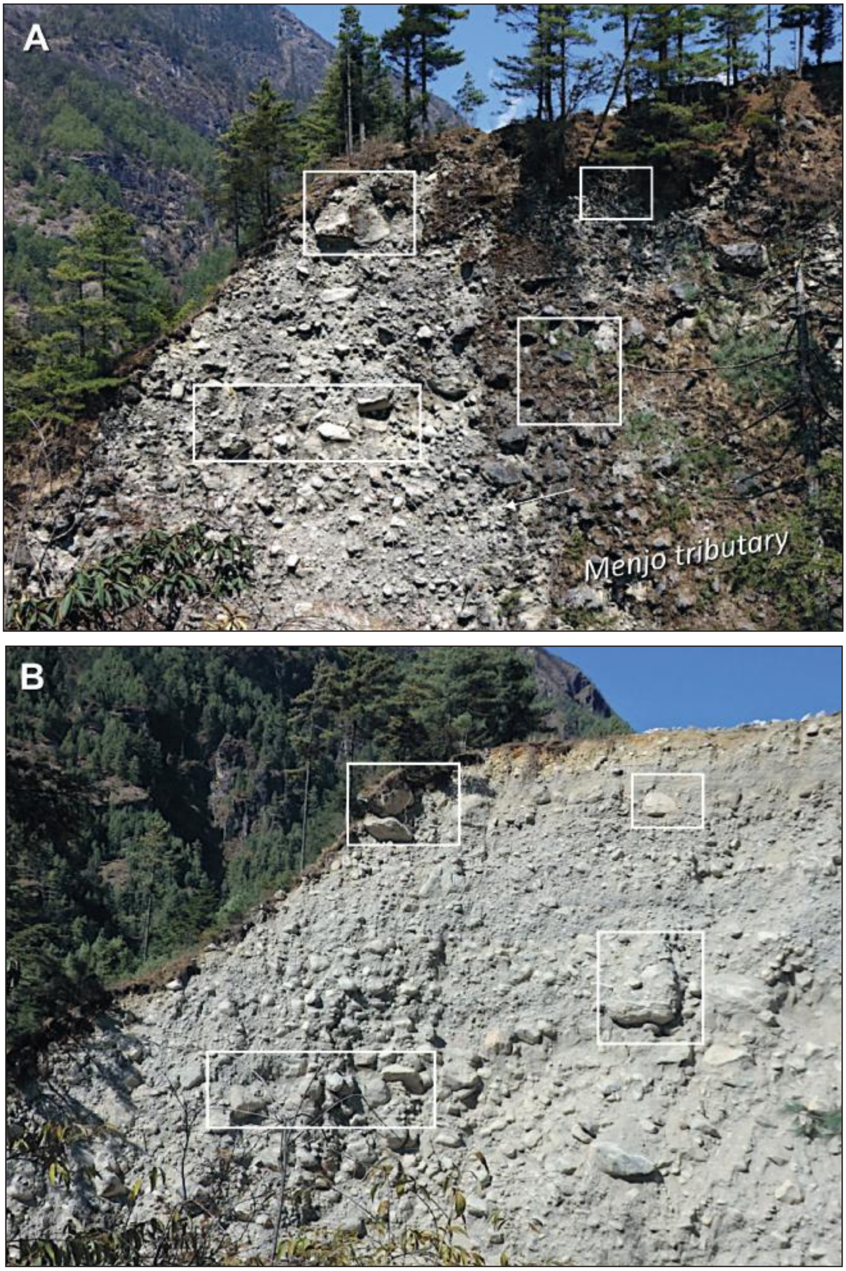

Fig. 14. The site of Menjo, located close to the confluence of the Menjo khola and the Dudh Koshi (left). A: March 2015. This outcrop along the right bank of the Menjo tributary displays torrential, coarse, mud-supported alluvial deposits. (photo M. Fort); B: April 2016, after the Gorkha earthquake. The section has been cleaned off, and the pine trees have toppled over into the riverbed. However, we can still spot the large blocks (i.e. framed) already present on the previous picture, which suggests a limited thickness (<1 m) of the collapsed part (photo J. Smadja)

CONCLUSION

With hindsight, and as we have just tried to demonstrate, the use of repeated photography has proved to be a very interesting method for a geomorphic approach in a region such as the Nepalese Himalayas. Indeed, it is a quick way to identify a recent natural disaster, to record changing dynamics in previously visited areas, and to compare these recent photos with older photos that may have been taken by other researchers or visitors (Byers 2017), although in the present case the photos presented are all but one mine. For several decades, my field missions were all on foot, along more or less steep trails. The conditions were not yet in place to set up field laboratories, as we are now beginning to see (Andermann et al. 2012; Regmi 2017; Watson et al. 2017), to name but a few examples.

If this approach – comparing old photographs with the current situation – were systematically used as a prerequisite for the design and implementation of infrastructures such as roads and bridges (McAdoo et al. 2018; Sudmeier-Rieux et al. 2019), it is likely that the design engineers of the selected alignments would not make the same mistakes as now, which are very costly both in terms of infrastructure construction and maintenance. As we have seen from the above examples, understanding the natural dynamics of mountain slopes and rivers triggered either by rainfall or rarer events such as earthquakes, as well as their induced impacts from upstream to downstream, both at the level of tributaries and main rivers, is also crucial in order to avoid potential risks to the inhabitants and travelers in these regions.

If old photos can arouse a certain nostalgia, they also show how much real-time observations, in the field, in interaction with the people living there, can be very enriching. This approach should not be totally abandoned even if the new techniques, which are very performing in terms of quantifying the magnitude, frequency and rates of geomorphic processes, have now become unavoidable in any current research work.

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Monique Fort
University of Paris
Geography Department and UMR 8586 Prodig (CNRS)
Bâtiment Olympe de Gouges
8 Place Paul Ricoeur
75205 PARIS CEDEX 13, France
e-mail : fort.monique@gmail.com