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Hillslope-channel coupling in the Nepal Himalayas and threat to man-made structures: The middle Kali Gandaki valley

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ABSTRACT

In mountain areas, the confinement of valleys favours landslide interaction with rivers, causing channel changes or short-lived dams and lakes that may threaten trails, roads and human settlements. Their impacts may occur successively in space and time, and they affect randomly the functioning of the sediment fluxes. The present study focuses on the interaction patterns between unstable mountain slopes and the Kali Gandaki River, in the Nepal Himalayas. In this valley, the deepest on earth, a road linking the Myagdi and Mustang districts has been under construction for the past 5 years, either cutting into the bedrock or crossing areas affected episodically by debris slides, earth flows, debris flows and rock slides. On the basis of the geomorphic evolution observed over the last three decades, we assess the potential threats that now arise following completion of the road. We mapped three areas of recurrent mass wasting features characteristic of the most frequent situations encountered in this valley. We analyzed the combination of the hydro-geomorphic processes involved. With the use of a DEM, we assessed the volume and spatial impact of temporary river dams on infrastructure located along the valley floor. We estimated hydraulic parameters to document the geomorphic efficiency of river flooding after dam breaching. We reconstructed the spatial extent of (1) areas threatened by backwater flooding upstream of the dams and (2) areas threatened by the collapse of the dams. We describe the current geomorphic and sedimentary adjustments still at work along the valley sides. Our findings confirm that in the High Himalaya, medium scale landslides (10^{5-6} m^3) play a major role in the overall process of denudation and sediment transfer. They highly influence the transient nature of bedload transport in the channel. In reducing the residence time of sediments in temporary, spatially limited traps of the valley bottom, they enhance the vulnerability of land and people attracted by a roadside location.

1. Introduction

Landslides are a major hazard in mountainous regions throughout the world. In the Himalayas, tectonically active mountains characterized by rapid uplift and river incision rate, mass wasting features are common features, triggered either by heavy rain or/and by earthquakes, and favoured by steep terrain and locally by weak bedrock. Each year during the summer monsoon, landslides and debris flows cause high levels of economic losses and fatalities, a figure that increases with demographic growth and development of infrastructures (Froehlich and Starkel, 1987; Gerrard, 1994; Sah and Mazari, 1998; Starkel and Basu, 2000). According to Upreti et al. (2008), 35% of the global death due to landslides occurs in the Himalayas, and this represents about 30% of the world's total landslide-related damage value. Nepal Himalaya is particularly affected because of the current process of development as occurring through urbanization and construction of roads across a country that is still rural and remote for most of its part (Petley et al., 2007).

Landslide hazard is particularly acute across the Greater Himalaya, where the confinement of valleys favours landslide interaction with rivers. Landslide impacts may occur successively in time, depending on their magnitude and their capacity to act or not as a barrier; they are often responsible for off-site hazards such as channel diversions, short-lived dams and impounded lakes, hence outburst floods, all processes that threaten trails, roads and human settlements, as reported in many Himalayan valleys (Brunsden et al., 1981; Yagi et al., 1990; Marston et al., 1998; Higaki et al., 2000; Weidinger and Ibetsberger, 2000; Naithani, 2001; Paul et al., 2000; Bhattarai et al., 2005; Gupta and Sah, 2008).

The context of our study is the road linking the Myagdi and Mustang districts (and indirectly connecting China to India) that has been under construction for the past 5 years. The road follows the same design as the old salt-trade-route. Its construction has not proceeded without difficulty. It has been necessary either to cut into the bedrock or to cross areas affected episodically by natural debris

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slides, earth flows, debris flows and rock slides, the runout of which may potentially dam the valley. This contribution aims at illustrating interaction patterns between unstable mountain slopes and Kali Gandaki river (Nepal Himalayas), at short (10^2 years) to very short (10^{-2} years) time scale, in a context of road development. We selected three sites where blockages of different types and duration have occurred. First, we mapped the areas of recurrent mass wasting features and analyzed the combination of the hydro-geomorphic processes involved. Second, with the use of a DEM, we calculated the volume of sediment dams and deduced the spatial extent of (1) areas threatened by backwater flooding upstream of the dams and (2) areas threatened by the collapse of the dams. Third, on the basis of a multi-temporal approach, we try to assess the potential threats that now arise following the completion of the road.

2. Geomorphic setting

2.1. Regional context

The Kali Gandaki river originates from the southern edge of the Tibetan Plateau, and cuts across the >8000 m high peaks of Dhaulagiri and Annapurna Himal, forming the deepest gorges (>6000 m) in the world (Fig. 1). It drains all the different Himalayan lithotectonic units before joining the Ganges alluvial plain: the Tethyan sedimentary series and Mustang–Thakkhola graben (Fort et al., 1982; Colchen et al., 1986), then the High Himalayan Crystalline Series (mostly gneisses) and the Lesser Himalayan Series (mostly quartzites, limestones and schists) (Colchen et al., 1986), then the Siwalik molasses (Delcaillau, 1986). These structural units correspond to a series of

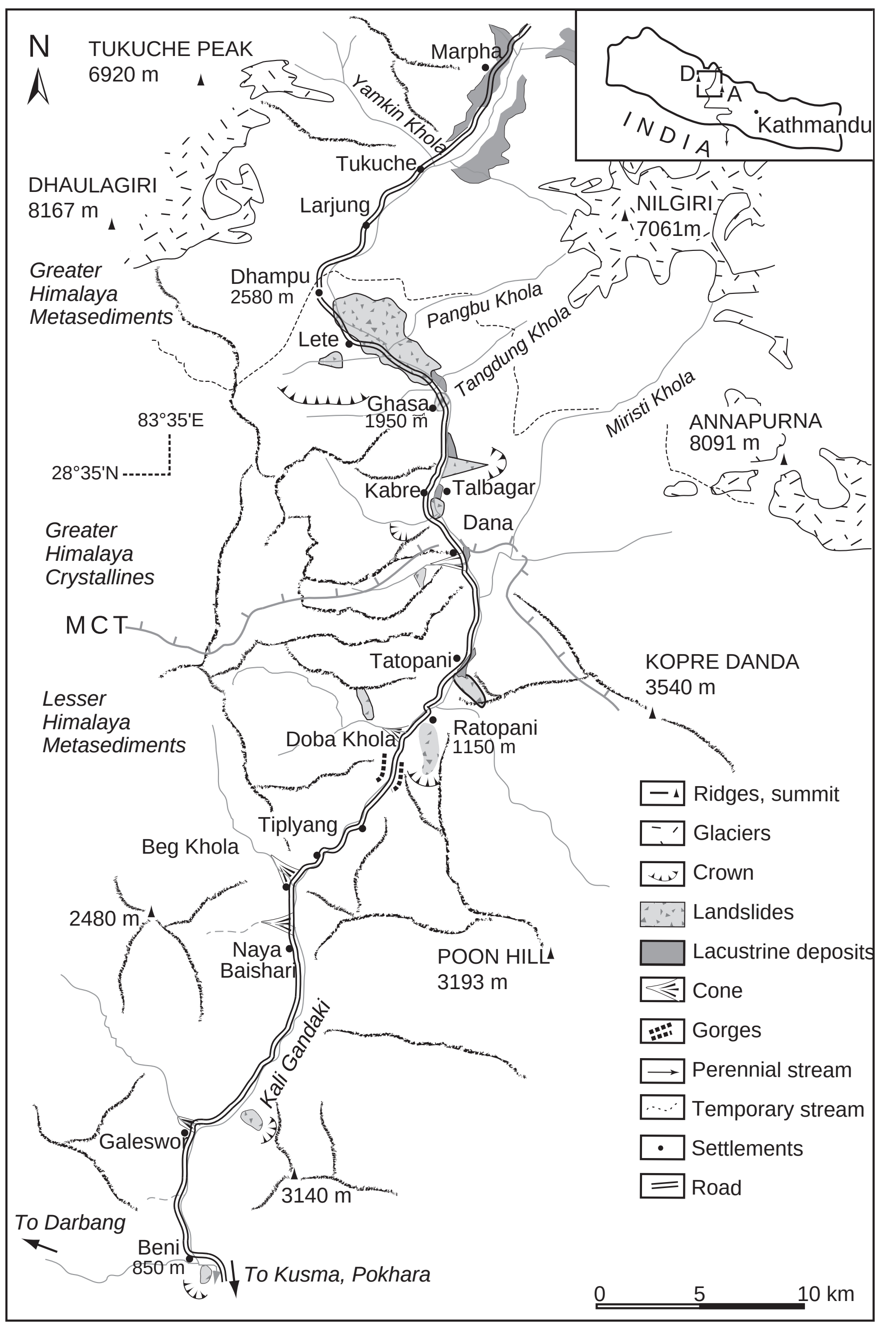

Fig. 1. Location map of the middle Kali Gandaki valley. The river cuts across three main Himalayan structural units (the Tethyan sedimentary series, the Higher Himalayan Crystalline and the Lesser Himalayan units) in a deep and narrow gorge. The valley is locally obstructed by mass wasting features of different ages, the material of which is a permanent threat to the new road (opened in 2008).

thrust sheets (North Himalayan Fault, Main Central Thrust, Main Boundary Thrust, and Main Frontal Thrust), connected in depth to the Main Himalayan Thrust Fault (Avouac et al., 2001). The presence of a north-dipping crustal ramp at about the limit between the Lesser and the Greater Himalayas correlates well with a zone of active uplift (2–5 mm/a) matched by river incision rates (Seeber and Gornitz, 1975; Wilett et al., 2001; Avouac et al., 2001; Burbank et al., 2003; Hodges et al., 2004).

Our study area is located in the south of the Annapurna Range; it spans the lower part of the Greater Himalaya, the hanging wall of the Main Central Thrust (MCT) zone. This is a zone particularly prone to geomorphic instability because of the combination of very steep slopes, lithologic units of varying resistance, and highest amount of rainfall of the Nepal Himalaya. The relief (s.s.) along the valley slopes varies between 1000 m (Benighat) and 6000 m (Lete) (Fig. 1). The Kali Gandaki valley is mainly V-shaped, with very narrow gorge segments controlled by N10° oriented dip slopes (dip gradient varying between 30° to nearly 90°). Slope angle is close to or even greater than the critical angle for landsliding (>30°). Evidence of former glacial history is scarce and debated, except from Ghasa village upstream, where morainic and fluvio-glacial deposits are locally present (Fort, 1985, 2000). The valley bottom displays a narrow floor with discontinuous patches of aggradational terraces of late Pleistocene and Holocene age (Yamanaka, 1982; Fort, 1993, 2000; Monecke et al., 2001; Zech et al., 2009), similarly as those reported in the adjacent valleys of the Greater Himalaya (Higaki et al., 2000; Pratt-Sitaula et al., 2004). The mountain slopes are either made of rocky spurs with segments exceeding 70° in slope angle, or unstable, debris-covered slopes (slope gradient <30°) corresponding to older landslide material most prone to be re-mobilized (Fort, 1987a; Fort et al., 1987; White et al., 1987). The nature of mountain slope material directly influences the current slope processes (rock-fall, landslide, debris flow, and debris avalanche) acting along the Kali Gandaki.

The highly seasonal southwest monsoon brings abundant precipitation during summer exceeding 5 m/a, preceded in spring by convective cloudburst rains. These climate conditions favour soil saturation and high pore pressure in densely shattered rock material, all the more efficient along the steep flanks of the river valley where tension cracks are quite frequent. In such a context, vegetation cover, whatever its nature, plays a minor role in slope stability control. Although it can be effective in reducing surface soil erosion, it has little effect to prevent landslide developed either in soils (colluvium and loose material derived from former landslides) or bedrock. In fact, most of the slope failures observed develop with depth exceeding 10 m, well below the tree root level.

The present Kali Gandaki valley appears as a fragmented river system (*sensu* Hewitt, 2002, 2006) interrupted by a series of landslides and/or large debris flow fans that temporary blocked water and sediment transfer to downstream reaches (Fig. 1). From north to south, several landslide barriers were recognized (Fort et al., 2009). 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, 1993, 2000). Further downstream, the valley was again blocked by the undated Talbagar and Kopchepani landslide dams, that forced the Kali Gandaki river to incise two epigenetic gorges. Other modern features are intermittently impounding the valley: the Tatopani landslide, and the two debris cones of the Ghatte and Dhoba kholas (khola = river, Nep.), both supplied by right bank tributaries of the Kali Gandaki.

2.2. Study cases

Among these unstable situations, we selected three sites along the middle Kali Gandaki valley, i.e. the Tatopani, Dana and Talbagar sites. In both Tatopani and Talbagar sites, landslides dammed the Kali valley and caused upstream water and sediment ponding, whereas at Dana, the Ghatte khola tributary is sporadically behaving as a debris flow, hence disturbing the continuous flow of the Kali River.

The Tatopani (= hot waters, Nep.) landslide site is located southeast of the Tatopani village (Myagdi District), on the left bank of the Kali Gandaki river (Lat. 28°29′19″N and Long. 83°38′57″ E). The gorges, cut across >2000 m long hillslopes, are bound by adjacent, 550 m high, steep (70°) rocky slopes (quartzites and schists), overlooking three aggradational fluvial terraces, respectively +40 m, +25 m and +15 m above the river level. The failure of this mountain slope took place in several events, in 1988, 1989, and 1998 respectively, the last one in the form of a wedge rock-fall, which evolved into a rock avalanche, that caused the damming of the Kali Gandaki river and the flooding of the lower Tatopani village.

The Talbagar (= the boulders near the lake, Nep.) debris slide, also referred to as Pairothapla (= the flat area of the landslide, Nep.), developed on the left bank of the valley (Lat. 28°34′14″ N and Long. 83°38′25″ E, southernmost Mustang District) along a 2000 m high mountainslope, cut into the Greater Himalayan crystallines (Colchen et al., 1986), where weaker biotite and hornblende rich bands alternate with steeper calcareous gneiss (Upreti and Yoshida, 2005). The landslide runout buried the gorges of the Kali Gandaki and forced the sedimentation upstream (mostly lacustrine, alluvial and slope sediment) (Fort, 2000).

The Ghatte Khola (= the river of the mills and/or = the river affected by water gusts, Nep.) is an intermittent, right bank tributary of the Kali Gandaki, which behaves occasionally as a debris flow, in relation with slope instabilities that affect its upstream catchment. The debris flows are usually triggered during heavy cloudbursts, and can cause damages and losses downstream, along the wide alluvial fan built at the tributary junction and upon which Dana village (Myagdi District) is settled. Inhabitants are aware of this ephemeral, yet threatening behaviour of the stream that may also affect the Kali Gandaki valley upstream from the confluence (Lat. 28°32′22″ N and Long. 83°39′03″ E).

These three examples typify the interactions between the mountain slopes and flood plain in a Himalayan valley where there is hardly a space left for settlements. This confinement explains why the design of the old salt-trade route connecting India to Tibet (von Fürer-Haimendorf, 1975) along the Kali Gandaki gorges was many times adjusted with regard to natural hazards occurrences (rock wall collapse, landslides, torrent gullies, swollen rivers, and sodden paths). The recent construction of the road (open to traffic in 2008) that mostly follows the valley bottom is now an additional threat to travellers and settlements (Fig. 2). The maintenance of this road, meant to link China to Nepal, is a real challenge that requires the full recognition and understanding of potentially damaging hydro-geomorphic processes that may create persistent physical traffic blockages by water and/or rubble during the sensitive period lasting nearly 6 months per year (from May to October).

3. Methods

On the basis of diachronic (1974–2000–2007–2008–2009) geomorphic surveys and mapping, and with the help of digital elevation model (DEM) facilities, we reconstructed the extent of the landslide deposits, the volume of the resulting lakes and/or sedimentary traps, and the evolution of landslide masses (Fig. 3).

3.1. Fieldwork

Our approach firstly relies on extensive field investigations and geomorphic mapping, and on repeated observations (for one of us) at the same sites during the last three decades (Fort, 1974). The geomorphic context, together with the landslide outline, shape and material (size and sorting) were characterized. In addition, interviews with local people helped in assessing the frequency of some described

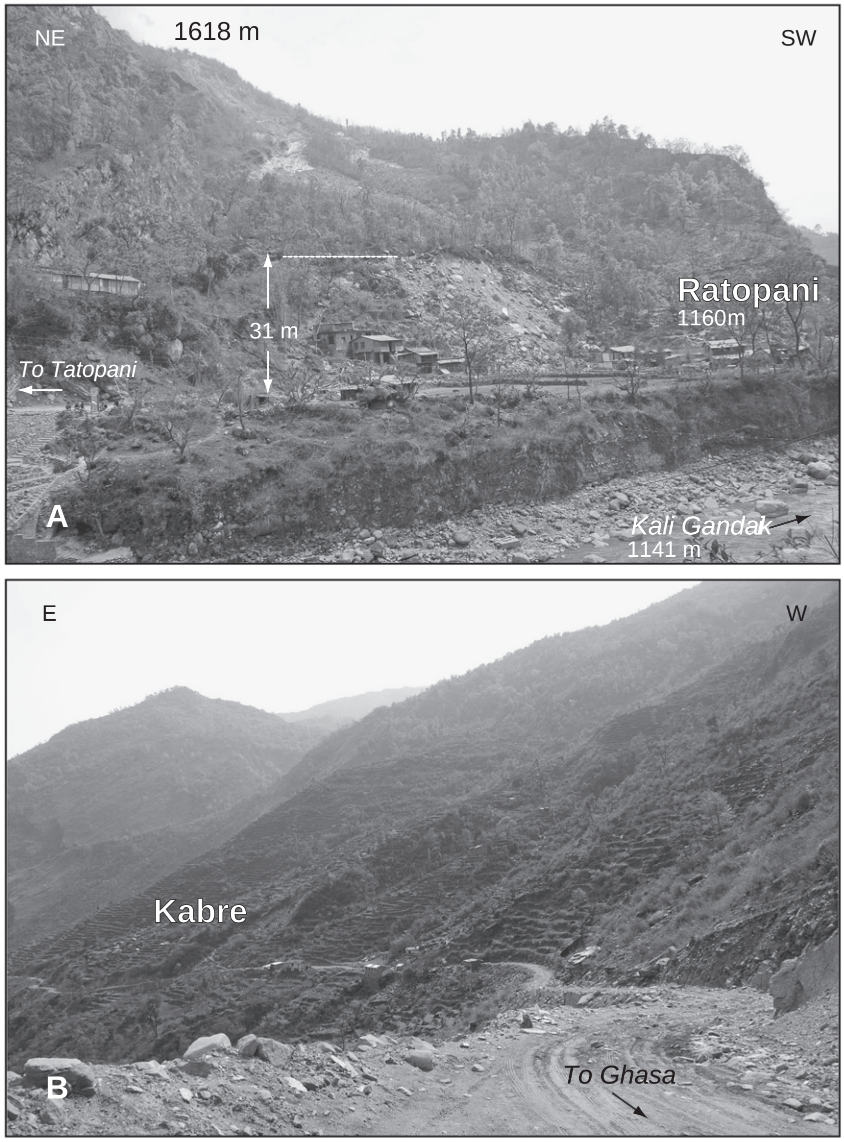

Fig. 2. Two examples of geomorphic hazards threatening the newly built road of the Myagdi–Mustang districts. A: Ratopani landslide is a wedge rock-fall/debris slide, quite comparable in its development to Tatopani landslide; B: Kabre mountain slope: the road is terraced across a creeping landslide colluvium that covers the entire Kabre slope. This road section was blocked for 10 days during September 2009.

features (e.g. Ghatte Khola and Tatopani) 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. Yet, three human casualties were reported in one studied case (Ghatte Khola).

3.2. Reconstitution of the landslide mass volume

In order to reconstruct the volume of the landslide masses, we carried out a topographic survey and established the cross-section of each landslide/earthflow mass. Basic measurements (height, width, etc.) were acquired with a laser telemeter (accuracy ranging from 0.1 m to 0.5 m), well adapted to this kind of remote area. The geometry of the landslide mass/bedrock contact was also reconstructed, based on previous observations made prior to the occurrence of the landslides and/or their later reworking (Fort, 1974). Whenever such observations were not available (older and undated events), the geometry of the bedrock below the landslide mass was estimated according to the geological structure and to a morphometric analysis. More specifically, the combination of dip slopes and vertical joints and/or faults favours wedge failures whose geometry can be modelled (Fig. 3). Whenever Quaternary deposits were present in the form of alluvial terraces, we removed their volume from the model, whereas we added to the model the volume of debris eroded since the landslide occurrence in order to reconstruct the original landslide shape. Eventually, the combination of both bedrock modelled surfaces and landslide mass areas within a raster GIS allowed us to assess the runout thickness and the volume of debris involved.

3.3. Reconstitution of impounded lakes

The assessment of the extent of former lakes, impounded upstream of the landslide or debris dams, needs both (1) a topographic survey of the valley in which the lakes took place and (2) an estimation of the level reached by the lake (Fig. 4).

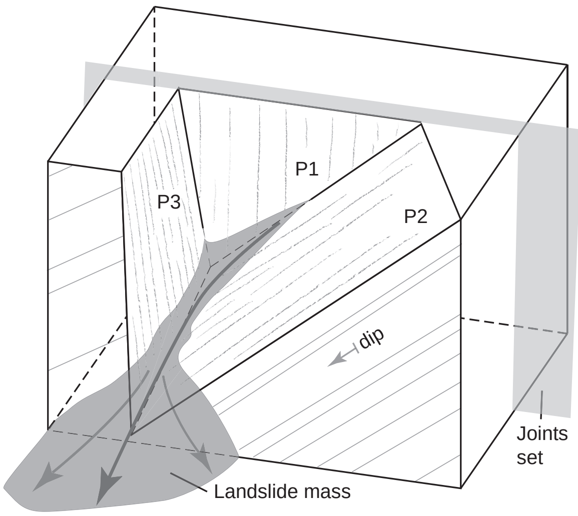

Fig. 3. Wedge geometry modelling. The mountain slopes constituting the wedge were assumed to be straight planes, characterized by a uniform slope value.

The valley bottom was carefully investigated and mapped in order to provide geometric data to a DEM. Absolute geometric coordinates (in UTM WGS 1984) were acquired by a GPS on some overlooking observation points, from which relative geometric data were obtained by a laser telemeter (accuracy ranging from 0.1 m to 0.5 m), with a special attention to the topographic edges (changes of inclinations such as terrace scarps). Distance, difference in elevation and azimuth were measured on 150 to 200 points from the observations points. Such altimetric data were then integrated in a DEM (through ArcGIS) to provide a three dimensional reconstruction of the valley floor. Interpolation of altitudes between altimetric points was realized by a TIN interpolation (Delaunay criterion), particularly well suited for irregular topography characterized by abrupt changes, such as in the case of fluvial terraces (Bonin and Rousseaux, 2005).

The level reached by the former lakes was estimated on the basis of three main criteria: (1) observations reported by the local population and/or (2) marks left on buildings, electric poles or trees (recent events), (3) identification of lacustrine and/or any backwater deposits (older events). In each study area, the level of the lake was computed at various cross-sections, to verify whether the data are consistent or not. We then computed in a DEM a plane modelling the level of the lake. Finally, with the use of the cut-and-fill tool in ArcGIS software, we subtracted the level of the lake from the topography of the valley floor in order to quantify the area, the volume and the depth (maximal and average) of the lake.

3.4. Hydraulic parameters

When chronological constraints of the event are accurate (e.g. Tatopani event), the volume of impounded lake can provide some estimates of hydraulic parameters where no data were hitherto reported. We quantified: (i) the water discharge upstream of the dam, (ii) the time necessary for the landslide–dam lake formation (once the lake volume was reconstructed; see above), (iii) the duration and the volume of the water release through of the dam, together with the discharge downstream of the lake once the landslide dam was breached.

To estimate the discharge upstream of the Tatopani lake (corresponding to the Kali Gandaki inflow to the lake), we relied upon the information given by the villagers (answers to our questions were several times cross-checked) to know how long time (T, in h) was necessary to fill in the lake. From the volume of the lake (V_L in m^3) and T we could deduce the discharge Q_u (in m^3/s) that contributed to the filling of the lake:

$$Q_u = (V_L / T) \qquad (1)$$

To validate both the discharge and the rapidity of filling of the lake, we also reconstructed the hydraulic geometry of the river upstream of the lake in order to estimate its discharge at the time of the landslide failure and valley bottom obstruction. Our field data and information collected from the inhabitants were convergent, and have shown that the discharge was quite similar to the regular low flow discharge.

To document the geomorphic efficiency of river flooding after the breaching of the landslide dam, we ought to estimate hydraulic parameters. From the reconstructed water level we calculated the

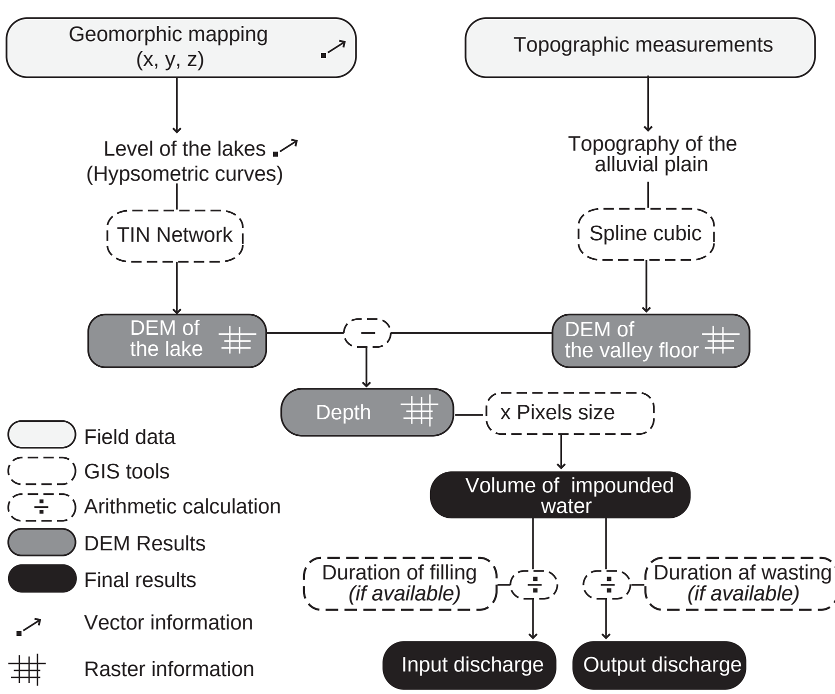

Fig. 4. Data processing to reconstruct lake volume, water inflow and release.

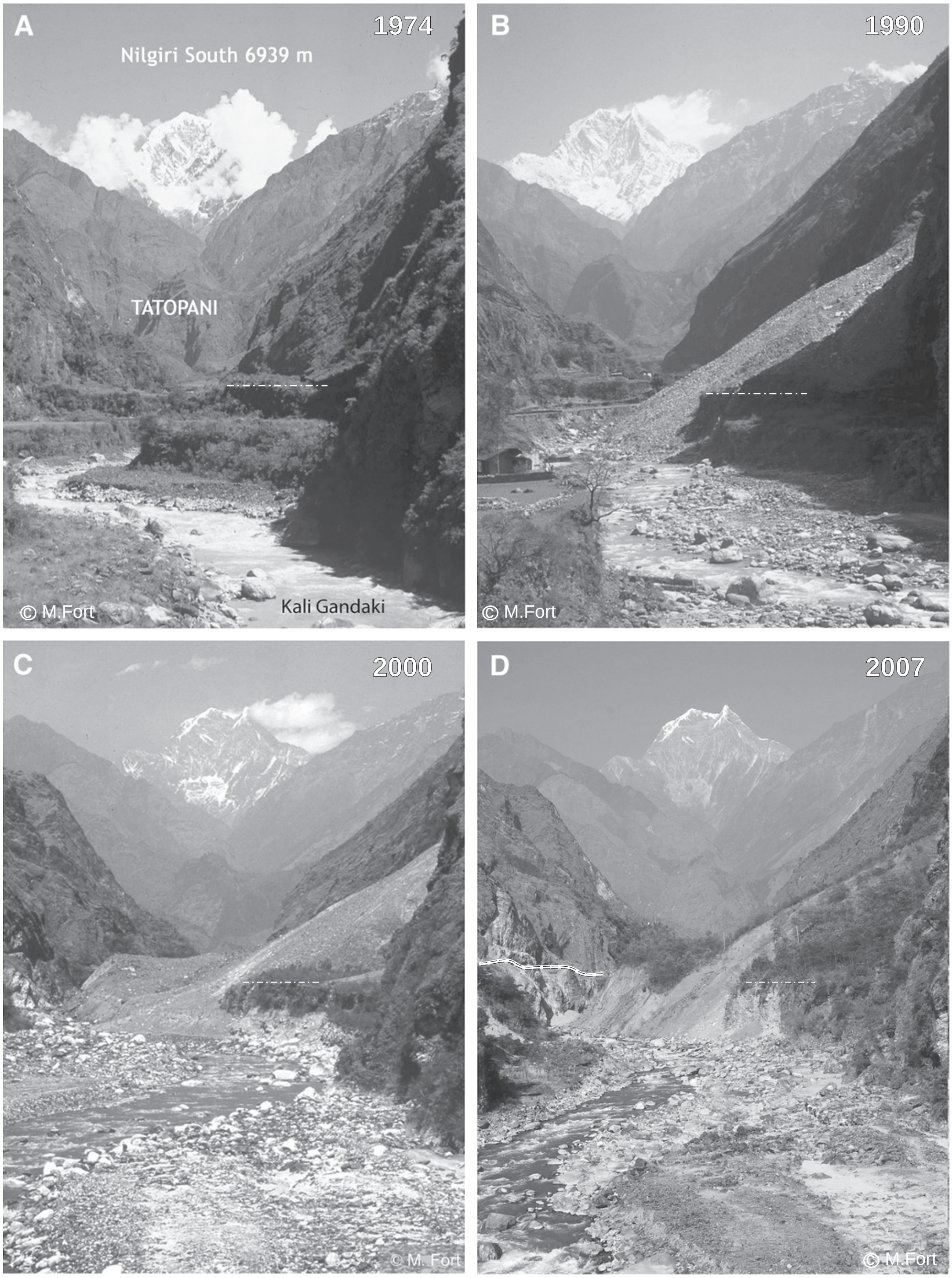

Fig. 5. 35 years of morphological change of the Kali Gandaki valley downstream of Tatopani village. Note the strong hillslope-channel coupling and its impact on valley bottom morphology. A: The valley as it was in 1974, with the terraces well visible on both sides of the river; B: in 1988, a first collapse partly buried the left bank terraces; the shifting of the river triggered incipient erosion of the lower terrace along the right bank; C: during the summer monsoon 1998, the landslide mass caused the damming then, after breaching, the diversion of the Kali Gandaki river, that was followed by a complete erosion of the right bank alluvial terraces; the river is eroding the quartzitic bedrock (photo in spring 2000); D: 9 years later, the landslide mass is covered by trees whereas the construction of the road is under progress; the road, completed in Spring 2008, is threatened by undermining by the Kali Gandaki (all photographs acquired by M. Fort from the suspended bridge, upstream view).

river width (W), the wet area (A), the wet perimeter (P) and the hydraulic radius (R) corresponding to the A/P ratio. Channel slope (S) was measured with a laser telemeter approximately 100 m upstream and downstream of each cross-section. The resistance coefficient (n) was estimated with the Jarrett equation (1985). This equation is the most appropriate to estimate roughness in high energy torrential rivers that are characterized by a slope greater than or equal to 0.002 m/m (Jarrett, 1984; Wohl, 2000). In addition, these basic hydraulic parameters coupled with grain/particle-size measurements of the bedload (D_{50}; D_{90}) allowed us to estimate the flow velocity (U; Manning–Strickler), the critical shear velocity (U_{cr}; Costa, 1983), the discharge (Q; Manning, 1891; Rotnicki, 1991), the stream power (Ω) and specific stream power (ω; Bagnold, 1966) and the shear stress (τ_o).

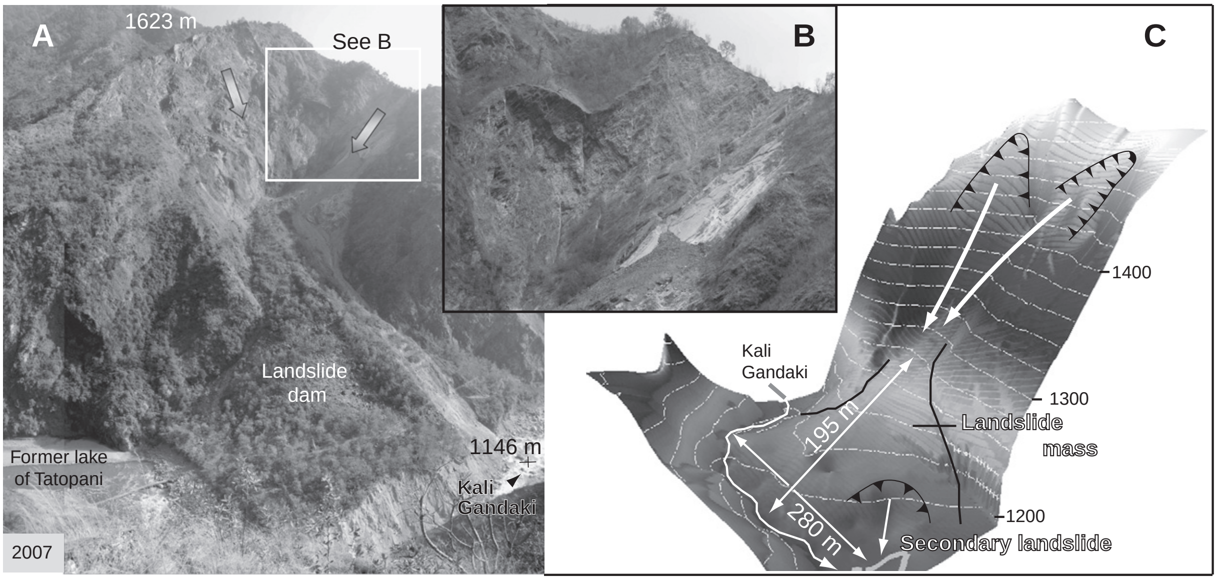

Fig. 6. The Tatopani landslide. A: The landslide corresponds to a wedge failure, controlled by the north dip of white quartzites of the Lesser Himalaya formations and by nearly vertical and listric fault planes (view from the right bank of the Kali Gandaki). Note on the left the emplacement of the lake that built up in response to the Kali Gandaki valley damming; B: detailed view of the crown area, with quartzitic bedding planes overlain by chloritic phyllites crossed cut by vertical joints; and C: DEM of the Tatopani landslide mass as reconstructed from field surveys.

To estimate the duration of the lake water release, we combined eyewitness information with our field data. These latter are based on the reconstitution of the discharge downstream of the landslide dam that was required to empty the lake. But it was also necessary to consider the Kali Gandaki inflow upstream of the lake, which was still supplying the lake even though this latter was progressively emptied downstream. To estimate the downstream discharge (Q_d) after the dam failure, we integrated the time (T) necessary to empty the volume of the lake (V_L) as reported by the inhabitants together with the river discharge upstream of the lake (Q_u) such as in the equation

$$Q_d = (V_L / T) + Q_u \quad (2)$$

Collectively such data can document the magnitude of “ordinary” basic geomorphic events that can threaten infrastructures and settlements sited at the foot of mountain slopes and all along the valley floor of Himalayan valleys.

4. Results

4.1. Tatopani landslide

The Tatopani landslide that dammed in 1998 the Kali Gandaki valley occurred in a context of general, permanent instability of the mountain slope, as suggested by rockfalls continuously supplying the foot of the slope, hence reducing the cohesion and buttress effects of the rock mass. This slope has experienced a series of retrogressive, large scale, failures during recent decades (Fig. 5) that affected the quartzites and phyllites (mostly green chloritoschists) of the upper part of the Lesser Himalaya formations. In the mean time, rock-falls continuously supplied the foot of the slope, hence reducing the cohesion and buttress effects of the rock mass, and maintained the slope in an unstable state. In fact, this slope is affected in depth by slow rock creep (Voelk, 2000), as expressed by almost vertical shear planes that bend into a listric shape in the lower part of the slope (Fig. 6B). In addition, in the upper part, the phyllite beds are highly weathered, hence forming, when saturated, a thick overburden of clayed materials at the surface of the mountain slope close to the landslide crown (Sikrikar and Piya, 1998).

The large destabilization of the mountain slope took place in several events. The first large failure occurred on August 22 1988, triggered by the Udayapur earthquake (magnitude 6.4) that was strongly felt in this area and the failure was reactivated by heavy rainfall 1 year later, in August 1989 (Sikrikar and Piya, 1998). The collapsed debris accumulated in the form of a large cone of rubble that buried most of the remnants of Holocene terraces underneath and caused the Kali Gandaki river diversion on its opposite, right bank (Fig. 5B).

A new, larger event occurred 10 years later that developed in two episodes. Firstly the slope started failing on September 10, 1998, as a translational slide along the 40° north-dipping foliation planes at the contact between quartzites and talcosic–phyllitic beds, forming about a 50–60 m wide zone of displaced surface (Sikrikar and Piya, 1998), with debris accumulated at the foot of the mountain slope. A few weeks later, on Sept. 28, 1998, a new, larger wedge rock-fall took place in the upstream part of the slope (Figs. 5C, 6). The event was quite dramatic and evolved into a rock avalanche. 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 in the valley bottom the debris piled up and impounded the river flow. The failure lasted several hours. The level of the Kali Gandaki started rising, causing backwater flooding that eventually inundated the Tatopani village settled upon the middle gravel terrace (+23 m above the Kali Gandaki flood plain); the water level reached the second floor of the Tatopani school and reached the old bazaar (Fig. 7A sites 1 and 2). 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 enlarged the dam breach and re-established the full conveyance of water and debris along the Kali Gandaki channel.

We tried to reconstruct the geomorphic impacts of the 1998 landslide dam and its failing. We first assessed the volume of the landslide (1.1×10^6 m^3), landslide dam (0.7×10^6 m^3) and lake (1.5×10^6 m^3) respectively (Figs. 7, 8) relying upon surveyed cross-sections. Traces of the highest level reached by the lake water gave a minimum height (+23 m) of the landslide dam (Fig. 7B, C). We also estimated the inflow discharge, responsible for the lake filling that lasted 8 h: we obtained a value of 54 m^3/s (Table 1), comparable to

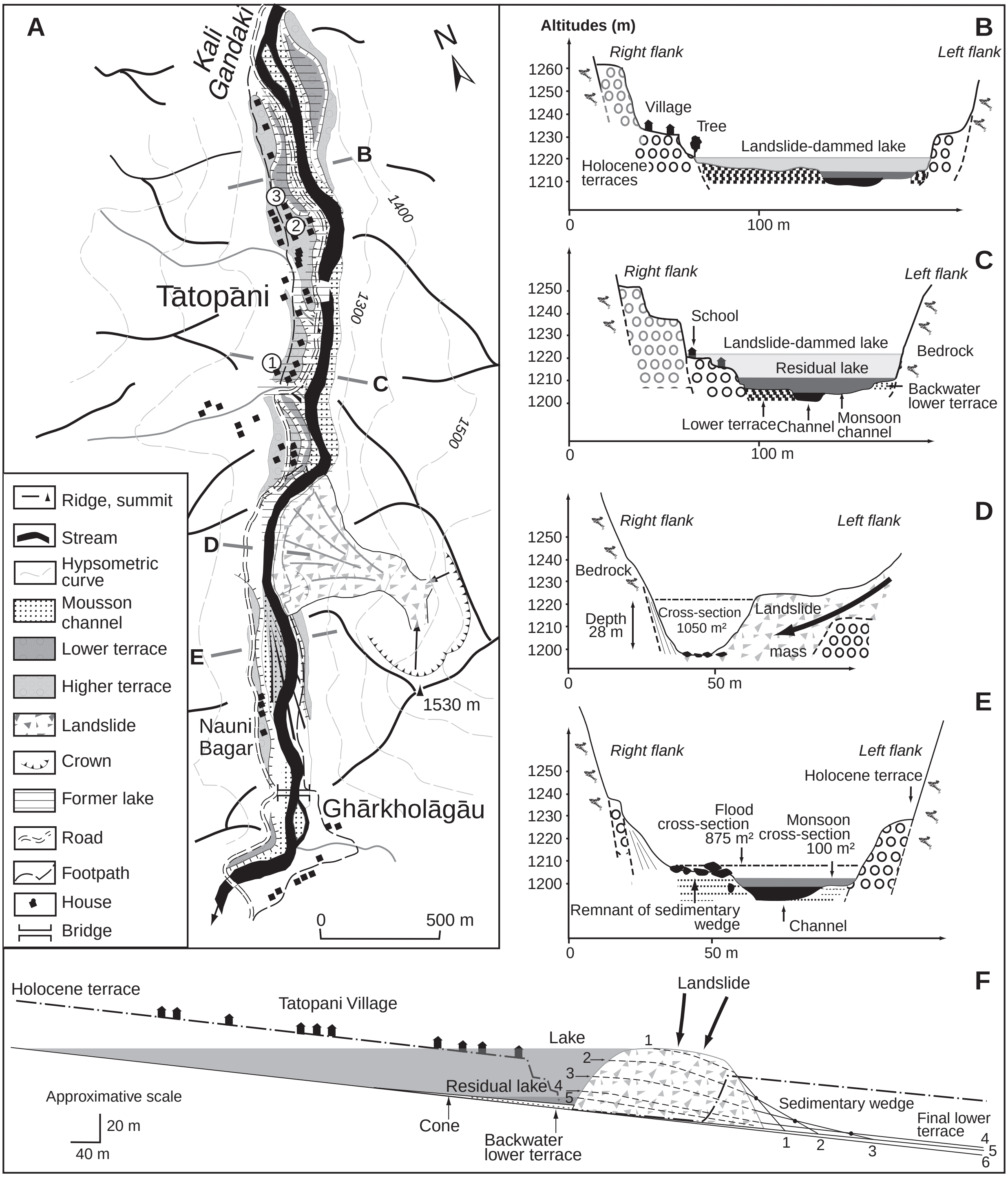

Fig. 7. Hydro-morphologic impacts of the Tatopani landslide along the Kali Gandaki valley. A: Map of the affected area. Note that the downstream part of the Tatopani village was inundated by the landslide dammed lake, 1: school, 2: Dhaulagiri lodge, 3: Old Kamala lodge; B, C, D, E: surveyed cross-sections, with reconstructed lake levels, breach across the landslide dam, and sedimentary wedge downstream; F: reconstruction of the progressive breaching of the landslide dam (duration 2-to-3 h) and aggradation of the sedimentary wedge. Note the existence of a residual lake that persisted 9 months after the landslide and the draining of the "large" lake.

data collected in Nepal valleys of similar importance and climatic context (Cenderelli and Wohl, 2003; Pratt-Sitaula et al., 2007). In contrast, the discharge reconstructed downstream of the dam amounts to an average of 389 m^3/s (min. 289 m^3/s; max. 528 m^3/s), a value that would theoretically indicate a little less than one hour for the complete draining of the lake (Table 1). However, crosschecking of interviews with the local populations indicates the draining of the lake lasted between 2 and 3 h, hence suggesting an average discharge much lower during most of the draining stage. The discharge was calculated as follows

$$Q(\text{average}) = \left[138{-}207\ \ m^3/s/2\,h\right] + 54\ \ m^3/s = 192{-}261\ \ m^3/s \tag{2}$$

This implies that the breaching of the landslide dam was not instantaneous but progressive. In fact, when the lake level reached the

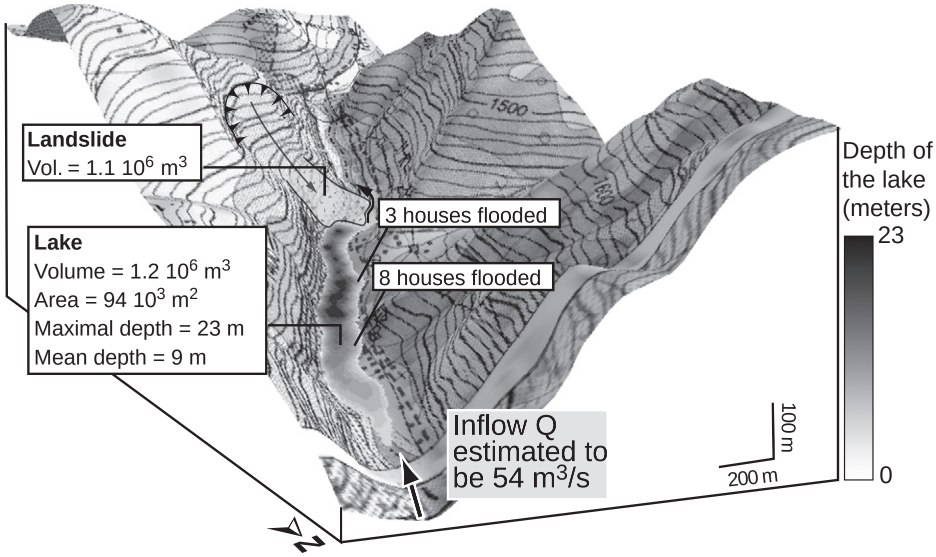

Fig. 8. Estimation of the main geometric and hydraulic parameters derived from field surveys and DEM (wrapping of the 1:50,000 Nepal toposheet).

Table 1
Summaries of variables by hydrological regime.

CS	No.	W (m)	S (m/m)	A (m^2)	P (m)	R (m)	n	K	U (m/s)	$U_{cr}^{(a)}$ (m/s)	$U_{cr}^{(b)}$ (m/s)	$U_{cr}^{(c)}$ (m/s)	$Q^{(a)}$ (m^3/s)	$Q^{(b)}$ (m^3/s)	$Q^{(c)}$	$\Omega^{(a)}$ (W/m)	ω (W/m^2)	$\tau_o^{(a)}$ (N/m^2)	D_{50} (mm)	D_{90} (mm)
Low water level (2007–12)																				
Lake	14	26.7	0.050	25.1	27.1	0.9	0.104	10	2.1	2.7	3.0	2.8	51	50	51	24,826	931	455	250	4000
Lake	13	85.0	0.040	44.8	85.0	0.5	0.104	13	1.6	2.7	3.0	2.8	56	54	55	21,580	254	207	250	1000
Lake	1	19.9	0.040	24.7	21.4	1.2	0.092	13	2.7	2.7	3.0	2.8	59	57	58	22,629	1137	452	250	1000
Lake	27	33.0	0.045	27.2	34.0	0.8	0.102	12	2.1	3.1	3.5	3.3	49	47	48	21,178	642	353	350	1500
Lake	26	25.0	0.040	30.4	26.0	1.2	0.092	13	2.8	2.7	3.0	2.8	73	70	72	28,154	1126	459	250	1000
Lake	25	27.3	0.040	29.9	28.1	1.1	0.093	13	2.6	2.7	3.0	2.8	67	64	66	25,718	941	418	250	1000
Gorge	6	14.5	0.090	16.5	15.6	1.1	0.127	12	3.6	2.1	2.3	2.2	40	40	40	35,262	2434	931	150	1500
Downstream	4	23.6	0.070	28.3	24.6	1.1	0.113	13	3.6	2.7	3.0	2.8	72	69	70	48,391	2051	789	250	1000
Downstream	5	13.0	0.060	17.8	15.2	1.2	0.107	13	3.4	3.1	3.5	3.3	45	44	44	26,179	2011	687	350	1000
Downstream	3	26.9	0.050	27.9	27.9	1.0	0.103	13	2.8	3.1	3.5	3.3	61	58	59	29,184	1083	490	350	1000
Downstream	9	34.1	0.040	29.4	34.5	0.9	0.097	18	3.3	0.6	0.6	0.6	55	53	54	21,059	618	334	10	100
Downstream	7	37.2	0.020	33.2	38.9	0.9	0.074	16	2.0	1.2	1.3	1.3	57	55	56	10,954	295	167	50	250
	Max.	85.0	0.090	44.8	85.0	1.2	0.127	18	3.6	3.1	3.5	3.3	73	70	72	48,391	2434	931		
	Mean	30.5	0.049	27.9	31.5	1.0	0.100	13	2.7	2.4	2.7	2.6	57	55	56	26,260	1127	479		
	Min.	13.0	0.020	16.5	15.2	0.5	0.074	10	1.6	0.6	0.6	0.6	40	40	40	10,954	254	167		
Monsoonal regime																				
Lake	14	46.7	0.050	121.6	49.4	2.5	0.089	10	4.1	2.7	3.0	2.8	559	517	538	396,025	8477	1813	250	4000
Lake	13	88.0	0.040	167.0	89.0	1.9	0.085	13	3.8	2.7	3.0	2.8	597	552	574	338,079	3842	1104	250	1000
Lake	1	49.9	0.040	135.1	54.5	2.5	0.082	13	4.6	2.7	3.0	2.8	607	562	585	344,101	6893	1459	250	1000
Lake	27	52.0	0.045	143.0	55.0	2.6	0.085	12	4.7	3.1	3.5	3.3	679	628	653	432,453	8316	1722	350	1500
Lake	26	97.0	0.040	180.0	101.0	1.8	0.086	13	3.7	2.7	3.0	2.8	616	570	593	349177	3600	1049	250	1000
Lake	25	57.0	0.035	153.0	60.0	2.6	0.077	13	4.4	2.7	3.0	2.8	693	641	667	343,608	6028	1313	250	1000
Gorge	6	22.0	0.090	85.0	27.0	3.2	0.107	12	7.5	2.1	2.3	2.2	513	475	494	654,820	29765	4169	150	1500
Downstream	4	46.6	0.070	112.2	50.0	2.3	0.102	13	5.7	2.7	3.0	2.8	497	460	479	493,201	10,591	2313	250	1000
Downstream	5	68.0	0.060	125.0	70.0	1.8	0.100	13	4.5	3.1	3.5	3.3	450	417	434	382,769	5629	1577	350	1000
Downstream	3	92.6	0.050	202.4	95.1	2.1	0.091	13	4.6	3.1	3.5	3.3	824	762	793	583,302	6298	1566	350	1000
Downstream	9	70.6	0.040	174.2	75.2	2.3	0.082	18	6.4	0.6	0.6	0.6	741	685	713	419,447	5941	1363	10	100
Downstream	7	90.1	0.020	162.8	94.0	1.7	0.066	16	3.2	1.2	1.3	1.3	501	464	483	142,034	1577	510	50	250
	Max.	97.0	0.090	202.4	101.0	3.2	0.110	18	7.5	3.1	3.5	3.3	824	762	793	654,820	29,765	4169		
	Moy.	65.0	0.048	146.8	68.3	2.3	0.090	13	4.8	2.4	2.7	2.6	606	561	584	406,585	8080	1663		
	Min.	22.0	0.020	85.0	27.0	1.7	0.070	10	3.2	0.6	0.6	0.6	450	417	434	142,034	1577	510		
Exceptional discharge (dam breach)																				
Downstream	5	108.6	0.060	875.8	121.0	7.2	0.080	10	9.0	3.7	4.2	3.9	10035	9250	9643	851,3430	78,385	6395	500	4300
Downstream	3	138.6	0.050	481.5	142.6	3.4	0.084	10	4.9	3.7	4.2	3.9	2872	2648	2760	2,030,698	14,649	2484	500	4300
Downstream	9	103.4	0.040	452.8	113.6	4.0	0.076	11	5.3	3.7	4.2	3.9	3016	2781	2899	1706128	16498	2346	500	2700
Downstream	7	90.1	0.020	162.8	94.0	1.7	0.066	10	2.1	3.7	4.2	3.9	501	464	483	142,034	1577	510	500	3400
	Max.	138.6	0.060	875.8	142.6	7.2	0.080	11	9.0	3.7	4.2	3.9	10035	9250	9643	8,513,430	78,385	6395		
	Moy.	110.2	0.043	493.2	117.8	4.1	0.080	10	5.3	3.7	4.2	3.9	4106	3786	3946	3,098,073	27,777	2934		
	Min.	90.1	0.020	162.8	94.0	1.7	0.070	10	2.1	3.7	4.2	3.9	501	464	483	142,034	1577	510		

CS[a] is cross section; No. is cross-section number; W is channel width; S is channel slope; A is cross-sectional area; P is wetted perimeter; R is hydraulic radius; n is Manning's n (Jarrett, 1985); K is Strickler's coefficient; U is mean velocity (Manning–Strickler); $U_{cr}^{(a)}$ is critical velocity (Costa, 1983, eq. X); $U_{cr}^{(b)}$ is critical velocity (Costa, 1983, eq. Y); $U_{cr}^{(c)}$ is critical velocity (mean a, b); $Q^{(a)}$ is discharge (Manning, 1891); $Q^{(b)}$ is discharge (Rotnicki, 1991); $Q^{(c)}$ is discharge (mean a, b); $\Omega^{(a)}$ is stream power (Bagnold, 1966; water density = 1); $\Omega^{(b)}$ is stream power (Bagnold, 1966; water density = 1.5); ω is specific stream power (Bagnold, 1966); $\tau_o^{(a)}$ is bed shear stress (Du Boys, 1879; water density = 1); $\tau_o^{(b)}$ is bed shear stress (Du Boys, 1879; water density = 1.5); D_{50} is median bed material grain size; and D_{90} is particle diameter for which 90% are finer.

landslide crest the water spilled over, and the breach progressively developed (Fig. 7D). This led to an eroded entrenchment volume estimated to be 0.2×10^6 m^3, causing an increasing injection of both coarse and fine solid discharges, that partly aggraded downstream in the form of a sedimentary wedge or prism (Fig. 7F). As the breach enlarged the further the aggradation encroached downstream on the alluvial plain. This accumulation, less than 1 km long, represents however no more than 10% of the debris removed from the breach. The remaining, finer particles were flushed away by the Kali Gandaki river.

The Tatopani landslide diverted the Kali Gandaki on its right bank, caused the undercutting of the Holocene terrace deposits and the partial removal of colluvium, which the new road is now cut into. In the valley bottom, the largest blocks (>4 m^3) remnants of the sedimentary wedge (Fig. 7F) are clustered near the landslide dam and eroded banks, attesting their transport occurred on short distances only; they are now armouring the river channel of the Kali Gandaki.

Yet, more than 10 years after the 1998 landslide occurrence, the morphology of the Kali Gandaki flood plain is still changing (Fig. 5). During each monsoonal high flow, the landslide dam is subject to superficial landsliding triggered by bank erosion and high pore pressure, whereas across from and downstream of the dam sediments are still removed from both sides of the valley, threatening settlements, cultivated lands and infrastructures. South of Tatopani village, on the right bank opposite to the landslide dam, the new road that cuts into alluvial and colluvial soils is already threatened on both sides by rock-falls and small debris slides (upslope), and by shallow landslides triggered by river undermining (downslope); in September 2009, the road along this section was blocked during several days by a rock-debris slide. Further to the south at Nauni Bagar, the erosion of the right bank of the Kali Gandaki caused the abandonment of houses in this site at risk, very close to the terrace scarp and to the river bed.

4.2. Talbagar debris avalanche cone

The Talbagar landslide developed along a section where the Kali Gandaki valley is at its narrowest (Fig. 1), and the longitudinal slope gradient of the river characterized by a distinctive knick point (gradient passing from less than 3% upstream to >22% downstream of the landslide). This landslide corresponds to a debris avalanche cone (Fig. 9A) that flattens away (40° to 5° slope) and buried the initial gorges of the Kali Gandaki (Fig. 9C). Not dated so far, it is in fact a quite complex feature that, similarly to the Tatopani landslide,

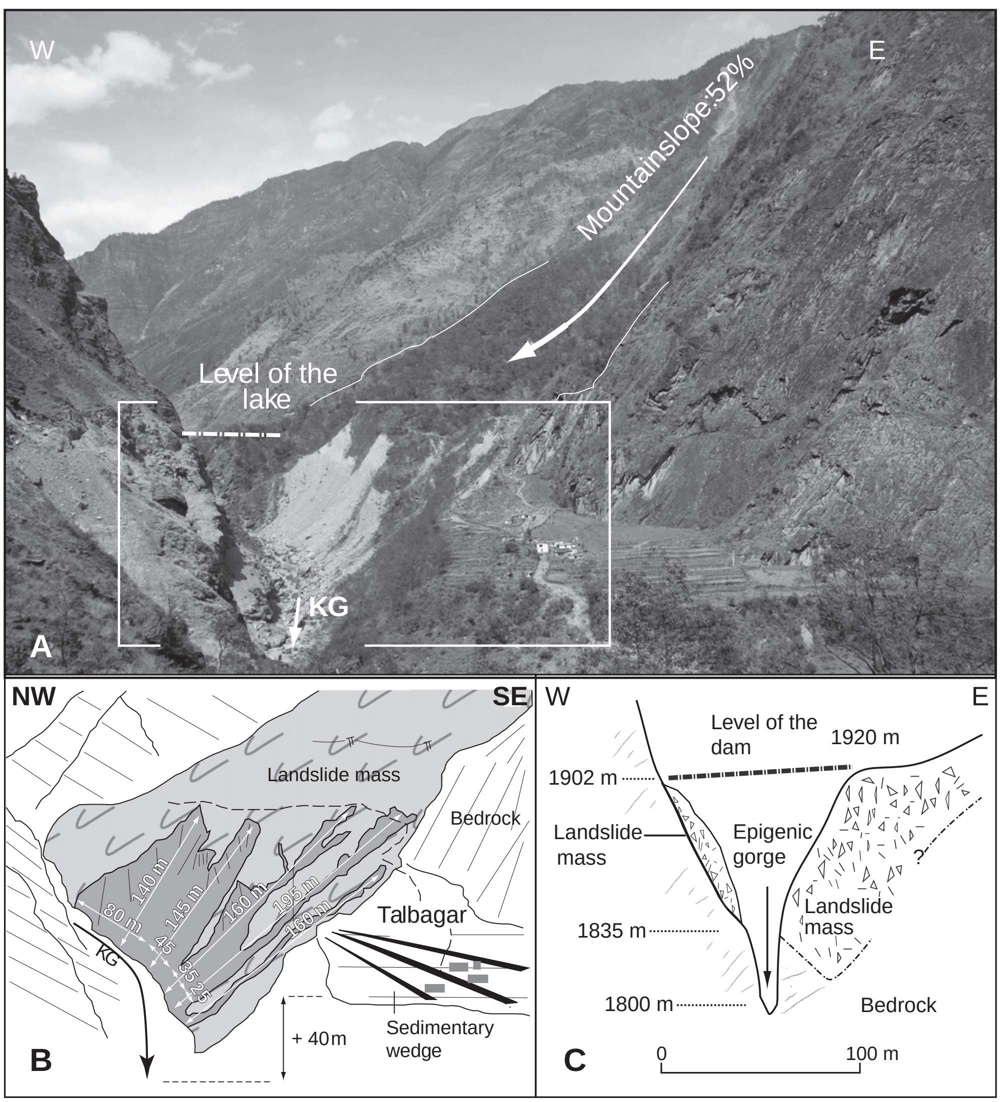

Fig. 9. The Talbagar landslide. A: General view from downstream: the crest elevation is close to 4000 m, and the Kali Gandaki river bed at 1700 m; B: sedimentary wedge built up after the breach of the landslide dam (foreground), and active gullies affecting the landslide mass (middle ground); and C: detail of the epigenetic gorge, cut into the gneissic bedrock after the superimposition of the Kali Gandaki river upon the landslide mass.

reflects a continuous instability of mountain slopes on both sides of the valley.

The Talbagar landslide occurred along a steep mountain slope (3890–1800 m), with a slope gradient exceeding 52° in the crown area, close to the crest ridge. The failure initially derived from a wedge failure, controlled by both dip slope and subvertical, N10° oriented fault planes, cutting across the crystallines of the Greater Himalayan unit, close to the contact of quartz-rich and carbonaceous gneissic formations (Upreti and Yoshida, 2005). The landslide material observed along the eroded scars and gullies of the left bank of the Kali Gandaki appears as predominantly composed of fine (sandy) particles, including very large blocks (i.e. 350 m^3, or 1000 t) embedded randomly into the landslide mass. In fact, the present Talbagar debris avalanche cone, totalling a volume of about 10×10^6 m^3 (Fig. 10), likely results from the superposition of successive failure events. However the largest (and most probably the earliest) of them buried the former Kali Gandaki valley, dammed efficiently the river (landslide dam volume of 2.7×10^6 m^3), and created a lake upstream that persisted long enough to be entirely filled in (Fort, 2000) (Figs. 10 and 11A). Yet it has been shown that sedimentation in such a context may be very rapid (Pratt-Sitaula et al., 2004).

The section observed along the left bank of the Kali Gandaki exhibits 18 m thick, well bedded, sandy lacustrine layers, with ripple marks reflecting a shallow water body (Fig. 12). However, the lower limit of the lacustrine deposits could not be specifically defined in the field because of the presence of thick talus debris (+6 m) down to the bedrock river channel. Accordingly, the lake depth may have ranged from 18 m (minimum) to 23 m (maximum, down to the bedrock). Depending on the depth value considered, the reconstructed volume of the lake impounded by the Talbagar landslide ranges from 8.9×10^6 m^3 to 13.9×10^6 m^3 (Fig. 10).

Above the lake filling, the presence of 15-to-20 m thick diamictic material indicates that slope instability persisted after the valley damming and continued to supply more debris to the cone, particularly on its northern and southern edges. This had the double effect of pushing the Kali Gandaki against the opposite bedrock valley wall and of preventing the river from cutting through the landslide dam, thus resulting in a progressive rise of its channel bed behind the increasingly higher and more stable landslide (Fig. 11B). This is well expressed by the valley longitudinal profile (Fig. 11C), where the section across the Talbagar debris cone exhibits a marked asymmetry, with a nearly flat (<2°) slope gradient to the north on the upstream side of the cone (Pairothapla), contrasting with a much steeper slope to the south on the downstream side (40%). This pattern indirectly suggests that the Kali Gandaki re-established the continuity of its flow by progressive entrenchment across the landslide dam down to a certain depth, where the river became superimposed on the gneissic bedrock and developed a dramatic, very narrow (2-to-4 m wide) epigenetic gorge, along which a series of waterfalls accommodate a total of 35-to-40-meter drop of the long profile.

The landslide dam breach and subsequent reworking of landslide material favoured the downstream aggradation of a 4×10^6 m^3 sedimentary wedge, that now forms a large alluvial terrace perched 40 m above the present river bed (Fig. 11C); it is composed of a coarse material, with a few very large boulders (>10 m^3) still observable on the top edge near the terrace scarp, hence suggesting a dense, very competent flow. The thickness of this aggradation was probably partly forced downstream by the narrowness of the Kopchepani–Rupshe epigenetic gorge, cut into the gneissic bedrock in response to another, older landslide dam that buried the Kali Gandaki palaeovalley in its eastern side (Fig. 11C).

Retrogressive erosion from the Kopchepani gorge caused the incision of the Kali Gandaki river across the sedimentary wedge, and the active reworking and gullying of the Talbagar debris avalanche cone mostly in its downstream side. This erosion together with modern debris-flow pulses continuously supplied from the mountain slope to the Talbagar cone, still forces the diversion of the Kali Gandaki river on its right bank (gneisses). The resulting steepening of this valley wall and the induced pressure release act as triggers for recurrent rock-falls, that have in

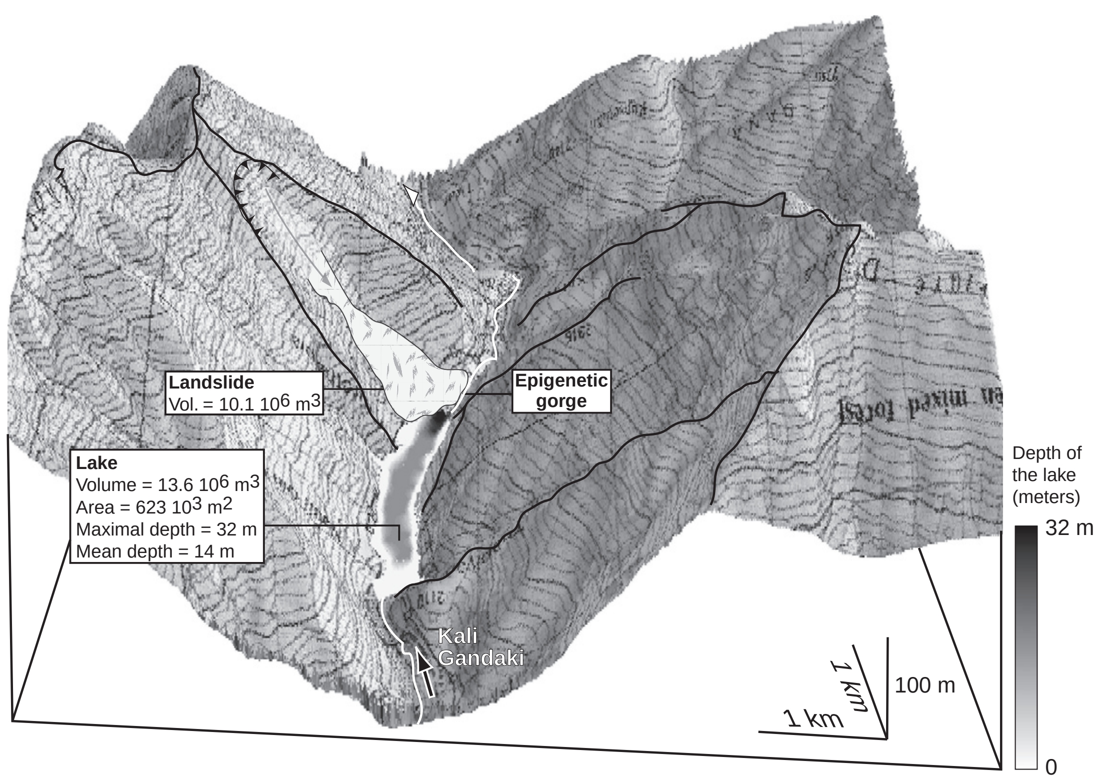

Fig. 10. Estimation of the main geometric and lacustrine parameters related to the Talbagar landslide, derived from field surveys and DEM (wrapping of the 1:50,000 Nepal toposheet).

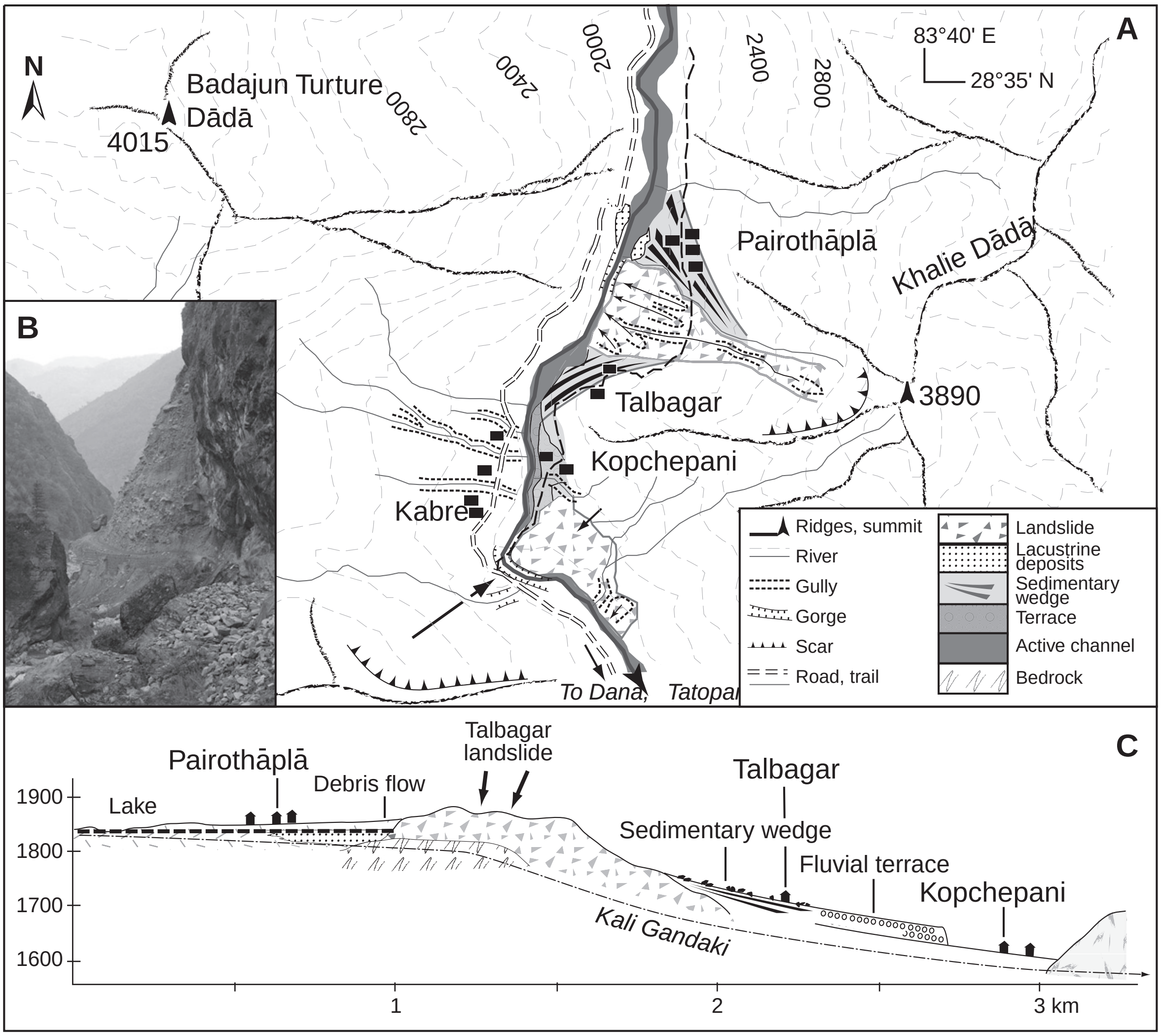

Fig. 11. The Talbagar–Pairothapla landslide and its geomorphic context. A: Map of the affected area. Note that south of Kopchepani, other rock failures blocked the Kali Gandaki valley and favoured the upstream aggradation of debris reworked from the Talbagar landslide; B: the Kali Gandaki gorge at its narrowest (downstream view): on the left foreground, the Kali Gandaki river starts its epigenetic entrenchment across the gneissic bedrock, whereas remnants of landslide debris are still plastered against the rock wall (middle ground), directly threatening the new road that cut across them; and C: longitudinal profile, showing off-sites impacts upstream (lacustrine deposits) and downstream (aggradation wedge) of the landslide dam.

recent decades necessitated the many realignments or abandonments of the old salt-route tracks directly cut into the bedrock (Fig. 12C). The rock-fall rubble in turn forces the Kali river on to its opposite, left bank, hence accelerating the erosion of the Talbagar landslide mass in a positive feedback. As a result, the channel of the Kali Gandaki is clogged by very large boulders, armouring the river bed and slowing down bedrock incision. However, this armouring effect does not totally prevent ongoing slope instabilities on both sides of the valley. Some of these instabilities, such as rainfall-triggered shallow landslides, may be large enough to supply debris to the river and increase the density hence the transport capacity of the flow downstream so that armouring boulders can be set into motion again.

Eventually, the new motor road cut into the gneissic bedrock, which approximately follows the design of the old salt-route, would probably and similarly be endangered by the pressure release of the mountain wall and resulting rock-falls, and/or by undermining caused by rapid landslide material reworking and their impacts on the opposite bank.

4.3. Ghatte Khola fan

The new road also has to cross tributary streams that may cause problems for the traffic. The Ghatte Khola stream, a right bank tributary of the Kali Gandaki, is a good example of such a case. It drains a small (7.8 km^2), yet steep (37%), east–west elongated catchment, striking perpendicular to the northward general dip of the Himalayan structures that is responsible for a pronounced asymmetry between the 40° steep dip slopes (right bank) and the >70° scarp slopes (left bank) (Figs. 13A, 14A). The Ghatte Khola built up a large, distally confined debris fan (~1.5 km wide and ~2 km long), encroaching more than 350 m over the 135 m wide Kali Gandaki flood plain.

Whereas most of the year the channel bottom of the Ghatte Khola is completely dry in its fan (a situation aggravated by the upstream water intake to mills), sporadic debris-flow events may occur abruptly in response to heavy cloudbursts distinctive of the pre-monsoon season. Such an event developed in less than half an hour in early May 1974 (Fort, 1974). Within 15 min, the stream flow became very muddy (hyper-concentrated flow) and occupied the entire active channel, with occasional pulses of muddy waves transporting "floating" boulders characteristic of a debris flow. Fifteen minutes later, a debris fan (mud, gravels and boulders) built up rapidly at the confluence with the Kali Gandaki; the volume of the fan was large enough to efficiently slow down the Kali Gandaki, which actually was nearly dammed (lake with outlet) (Fig. 14A).

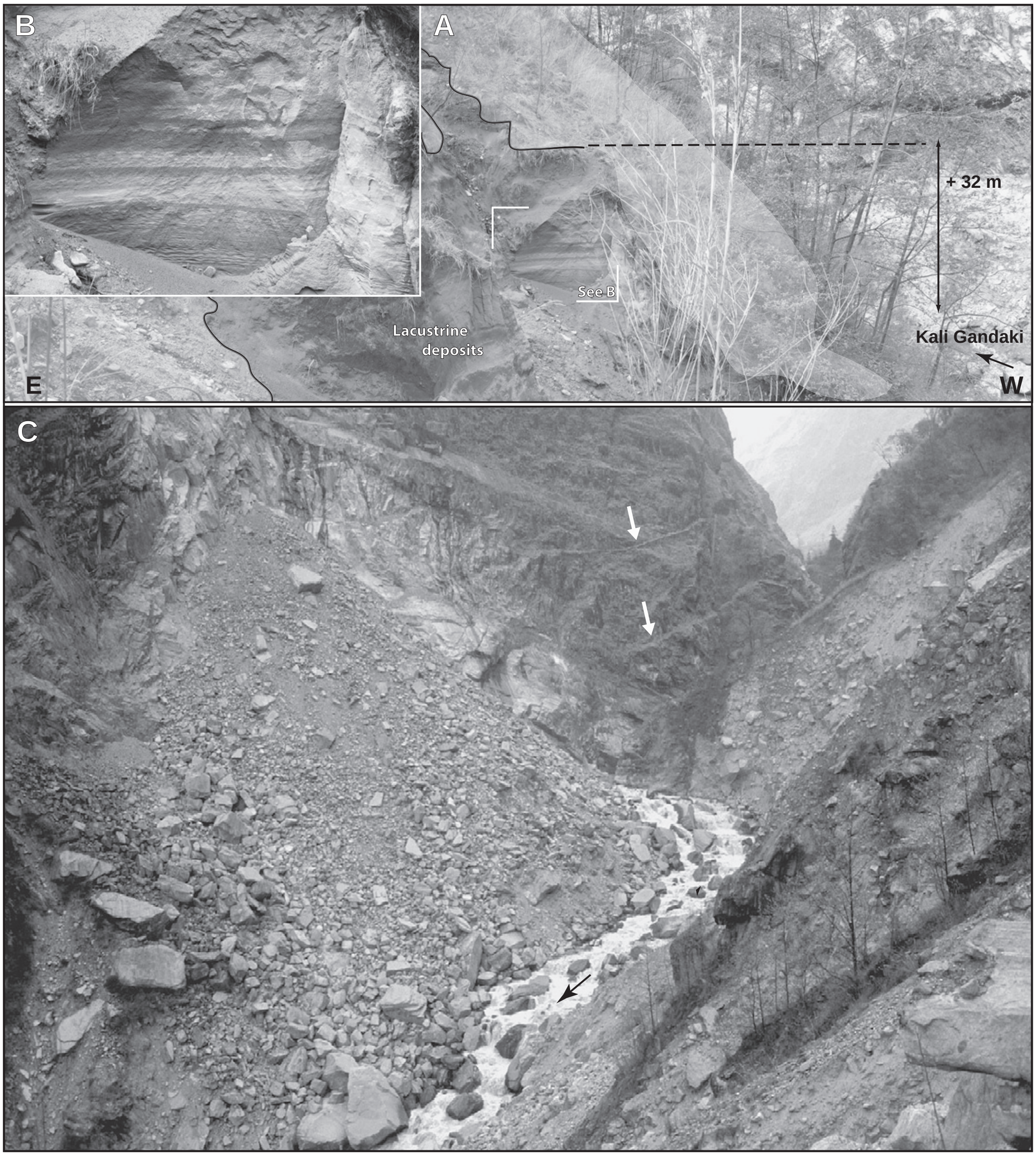

Fig. 12. Lake caused by the Talbagar landslide dam; A: Major section of lacustrine deposits (left bank of the Kali Gandaki); B: detailed section (height 2 m), showing the superposition of horizontal sandy beds (cm-to-dm thick) with ripple marks figures, likely suggesting a rapidly filled shallow lake; and C: the Talbagar debris avalanche cone (right) facing a rock-fall cone on the opposite right bank of the Kali Gandaki that started failing in the late seventies. The river channel is clogged with very large boulders that slow down the incision of the bedrock. Note the successive positions (arrows) of the old trade route cut into the gneissic bedrock (Photo taken in 2000).

The cause of the debris flows is a series of persistent planar slides (Fig. 13C, D) that develop along the north-facing dip slopes of the watershed underlain by aluminous schists of the upper Lesser Himalaya Formation (Colchen et al., 1986; Upreti and Yoshida, 2005). These slides, that were first triggered about 40–50 years ago, are occasionally reactivated during heavy rains falling on the upper, forested watershed. Over a few hours or days the slide masses may clog the very narrow valley bottom of the Ghatte stream upstream of the fan apex (Fig. 13D). Usually, the water slowly percolates throughout the landslide dam(s). However, when the slide masses are larger the dams resist longer, the water accumulates upstream until a sudden, landslide lake outburst flood occurs.

The resulting debris flows may be very destructive in three different ways. Firstly, they can cause bank erosion, riverbed widening and occasional crops and cattle losses downstream, to the detriment of the alluvial fan occupied by settlements and fields. Inhabitants are concerned with this sporadic, damaging behaviour of the stream, occurring once or twice a year in association with heavy, localized rainfalls (thunderstorms), in a context of abundant antecedent precipitation conditions. In the late 1980s, one of these events caused three human fatalities. Secondly, the debris cone built by the Ghatte Khola at the Kali Gandaki junction may cause the damming of the Kali Gandaki for a few hours (Fort, 1974). Villagers reported that during the largest damming episodes, the Kali Gandaki level may exceptionally rise more than 10 m in height and reach the elevation of the “lower terrace”, visible on the right of Fig. 14B, hence resulting in the inundation of adjacent sports ground and cultivated land of Garpar village. Thirdly, the confluence zone appears as an area of very short-term storage of sediments, and its morphology is constantly changing. In fact, the Ghatte Khola channel is perched a few meters above the Kali Gandaki channel, and every fan occasionally built at the junction by a debris flow event is generally remodelled and/or its debris

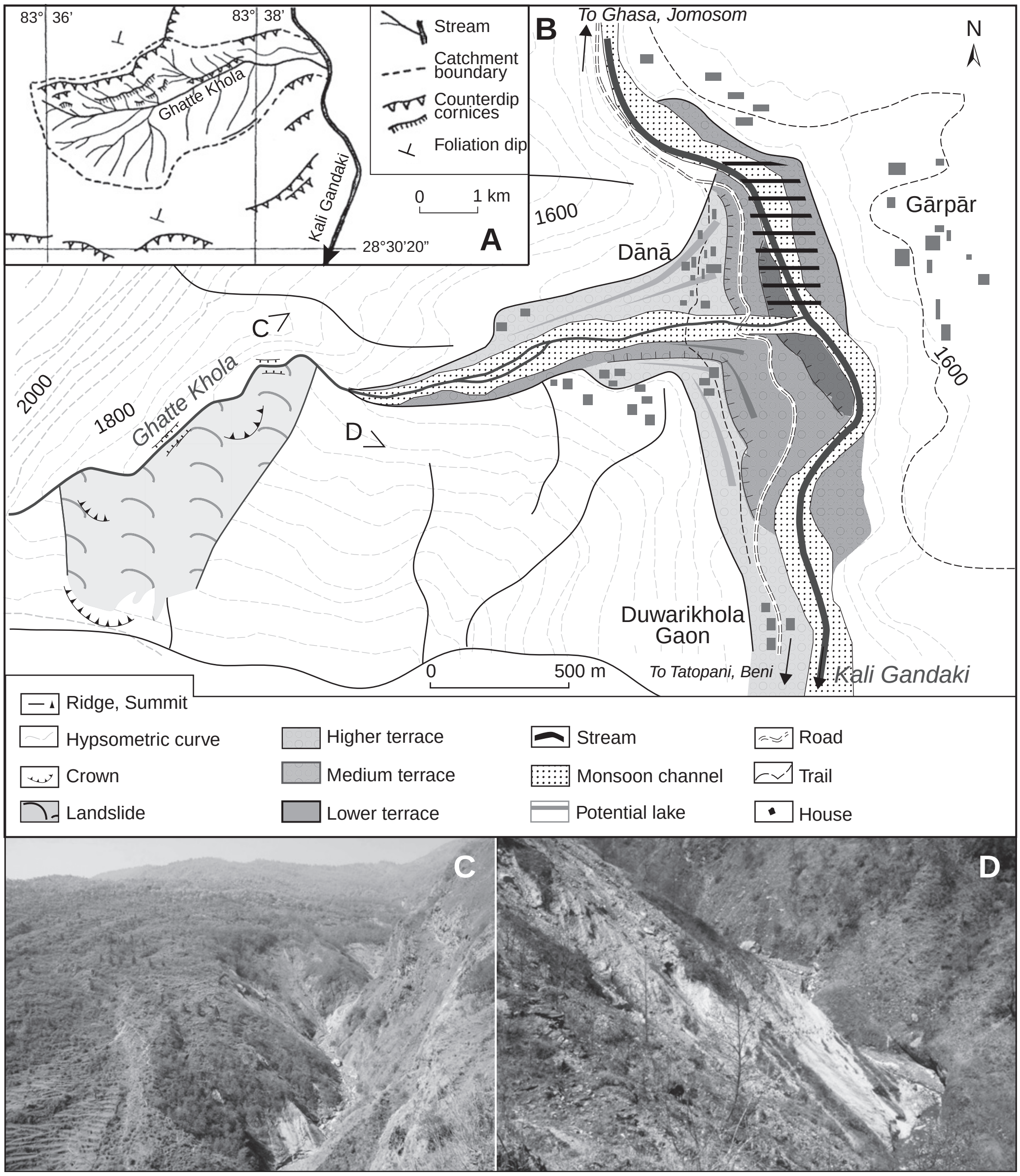

Fig. 13. The Ghatte Khola and its functioning. A: The Ghatte Khola watershed, a right bank tributary of the Kali Gandaki river. B: map of the lower part of the Ghatte Khola catchment, with the alluvial debris fan and potential damming of the Kali Gandaki river and resulting lake; the monsoon channel has significantly widened during the last 35 years; C: view upstream of the Ghatte Khola catchment, from the left bank above the apex of the debris-alluvial fan. Note the distinctive asymmetry of the valley, its vegetal cover, and the many translational landslides along the dip slope of the dark, aluminous schists of the upper formation of the Lesser Himalaya unit; D: hillslope-channel coupling along the Ghatte Khola (view from the right bank of the watershed); the landslide mass (foreground) blocks temporarily the Ghatte Khola channel, before the landslide outburst and the resulting debris flow.

removed during the next monsoon high flows by the Kali Gandaki river (Fig. 14B), a fact that may endanger any permanent structure across the Ghatte Khola channel. As a consequence, the design of the new road across the apparently “safe”, large, flat Ghatte Khola alluvial fan may turn out to be a more dangerous place than initially thought.

5. Discussion

Events described here are very recent and their associated landforms have constantly evolved during the last three decades, together with the course and morphology of the Kali Gandaki riverbed. Some issues are still a matter of discussion, such as the dating of Talbagar event, the causes of landslide triggering and development, the specific interactions between steep mountain slopes and riverbed, the exact role of roads construction and the potential threat to them in a general context of landscape disequilibrium and economic development.

5.1. Age of Talbagar rock avalanche

Whereas the incipient stages of Tatopani and Ghatte Khola slope instabilities are precisely dated, there is still poor chronological control for the Talbagar landslide. No datable material has been found in the lacustrine deposits to date, yet some arguments might be used to constrain the age of this landslide. Firstly, the absence of deep organic soil development either on the surface or buried in the landslide mass suggests both a recent age and a rapid succession in the sequence of the events that built up the debris cone. This hypothesis is reinforced by the significance of Talbagar's name “the boulders near the lake”, which suggests some memory of the event by the population. Secondly, the maximum size of the largest trees that densely cover the slopes (mostly *Alnus nepalensis* in the lower part, and *Acer* and Pine trees in the higher part) suggests their age of being about sixty-to-hundred years old. In fact, this assumed age postdates

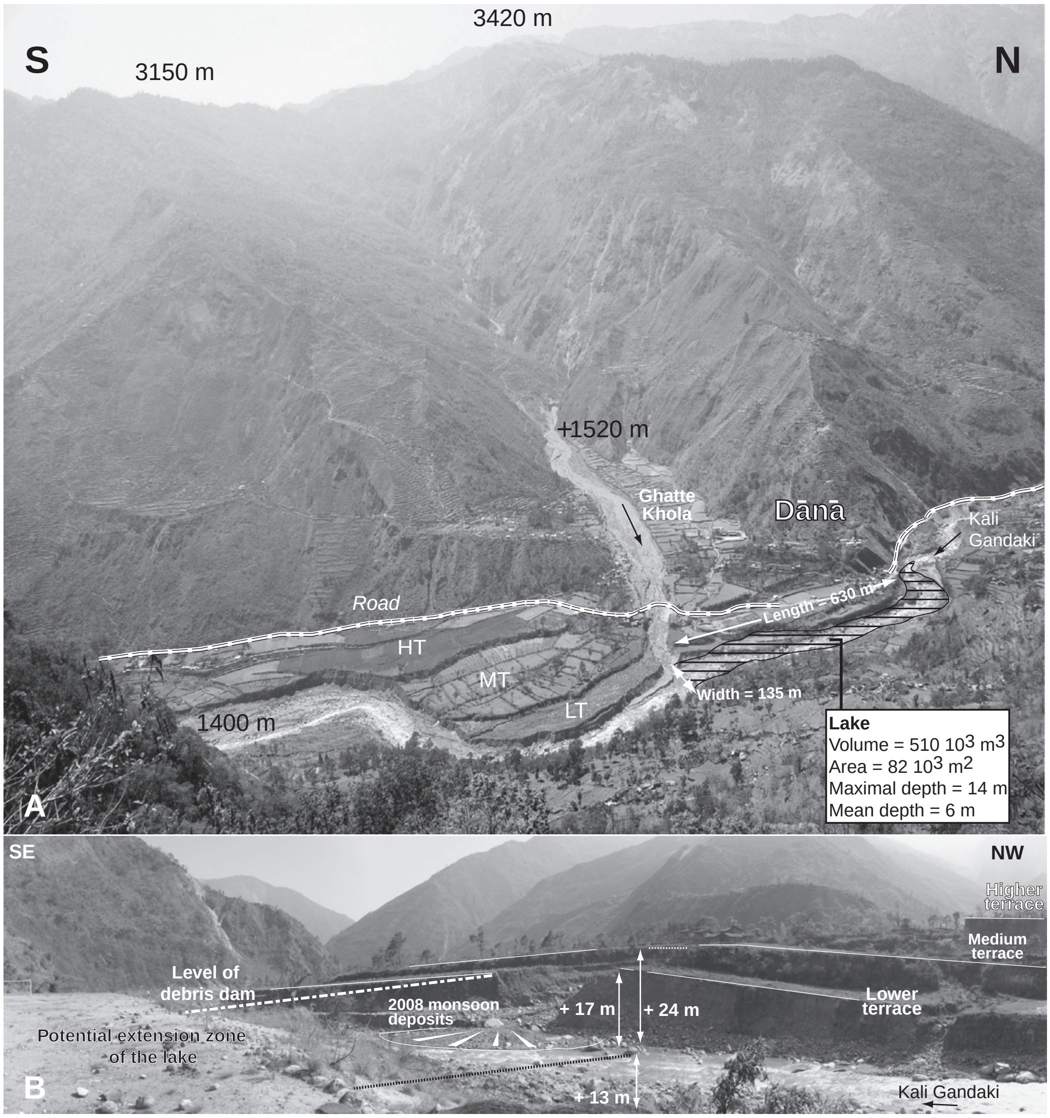

Fig. 14. The confluence of the Ghatte Khola with the Kali Gandaki river. A: The alluvial fan of the Ghatte Khola progrades across the Kali Gandaki river flood plain. The Ghatte Khola channel is sporadically affected by debris-flow events that are now threatening the newly built road. Note the sensible location of Dana settlements, on sites sheltered from the debris-flow hazards; B: confluence site (as observed in April 2009): the Ghatte Khola is entrenched into three main terrace levels; the lower level corresponds to a volume of aggradation susceptible to dam the Kali Gandaki up to the soccer ground of Garpar village (on the left). Note the small confluence fan built in 2008 by the Ghatte Khola at the junction with the Kali Gandaki river.

the massive debris supply that caused the damming of the valley, and does not account for the debris flows that are still active and are responsible for the formation of longitudinal gullies that convey debris down to the Kali Gandaki thalweg. Both soils and vegetation arguments suggest that the Talbagar debris avalanche is probably not much older than 100 years.

Another argument could be provided by the rate of incision of the epigenetic gorges. In the absence of strath terraces along the Talbagar section of the Kali Gandaki valley, we assume a continuous entrenchment of the Kali Gandaki in this ramp zone where rock uplift (2–5 mm/a) is at its maximum (perched potholes are found all along the rock walls of the gorge section). In addition, landslide debris is a much more erodible matter compared to bedrock, even though the large boulders contained in it may temporarily reduce river incision. After the valley damming by the landslide, retrogressive downcutting by the Kali Gandaki River progressed upstream from Kopchepani to the Talbagar gorge, together with lateral erosion of the landslide deposits. The rate at which the Kali Gandaki has cut its epigenetic gorge could not be precisely assessed to date, yet some assumptions can be made. Ouimet et al. (2008) have shown that incision of local epigenetic gorges associated with recent landslide dams and with short-lived, very steep knickpoints usually greatly exceeds any plausible long-term and regional bedrock incision rate. Fastest incision rates in bedrock typically range from <1 mm/a to >10 mm/a (Alaska, Whipple et al., 2000); in the tectonically active mountain belts of Taiwan, Schaller et al. (2005) reported average incision rate of 26 ± 3 mm/a. Conversely in the adjacent Pokhara valley south of the Annapurna Range, Fort (1987b) calculated a modern incision rate as high as 10–20 cm/a through the 100-to-60 m thick loose Pokhara gravels and underlying consolidated Gachok conglomerates cut into epigenetic gorges (<500 years). Similarly, Pratt-Sitaula et al. (2007) did not dismiss a rate as high as 10 cm/a following Holocene river incision across the Lamtarang landslide and associated epigenetic gorge (NE of the Annapurna–Lamjung Range). Therefore if we assume a “reasonable” incision rate of the order of 10 cm/a, it would give an age of about 350–400 years for the Talbagar epigenetic gorge. A slower incision rate would give an older age accordingly, yet this is at odds with the lack of organic soil development. Our assumption does not contradict the chronological range provided by vegetation development, since we have shown that subsequent, more recent debris-flow episodes occurred after the damming episode. If our chronological hypothesis (400 years) is correct, it means that later superficial reworking represents, in terms of sedimentary budgets, only a small portion of the landslide mass (Fort et al., 2009), and consequently represents an unlimited source of debris on a very short-term timescale.

5.2. Causes of the landslides

Monsoon climate, seismic activity, excess internal stress, together with stream undercutting of slopes, are the main natural triggers for landsliding in Himalayan mountains, to which human activity may add its effect (see below). These factors however are not always easy to separate and more than one of them may play a role in a single event.

Seasonal monsoon rains are an efficient and repeated trigger and are the cause of most landslides observed in Nepal Himalaya (Thouret, 1983; Petley et al., 2005; Dahal et al., 2006). Most rainfall-triggered landslides are generally small and shallow (<2.5 m thick) and affect mostly surface soil and regolith (Caine and Mool, 1982; Gerrard and Gardner, 2000). Rainfalls can also trigger larger, deep-seated landslides, affecting either bedrock or ancient debris slide material (Brunsden et al., 1981). The representative rainfall thresholds to trigger landslides have been a matter of debate. Several daily rainfall values have been proposed in the Nepal Himalaya, ranging from 100 mm (Caine and Mool, 1982) to 230 mm (Khanal and Watanabe, 2005) and 260 mm (Dahal et al., 2006). In the Darjeeling Himalaya, Starkel (1972, 1976) and Froehlich et al. (1990) proposed a threshold of 250 mm/24 h or three-day rainfall of >350 mm to trigger landslides. More recently, Gabet et al. (2004) suggested that antecedent rainfall of 528 mm must accumulate before landslides develop. From an inventory of 677 landslides, Dahal and Hasegawa (2008) concluded that landslides might be initiated when the daily precipitation exceeds 144 mm; they also pointed the critical role of antecedent rainfall of 3 days to as much as 4 months, in saturating soils and influencing ground water level. This confirms Carson's statement (1985) based on a large inventory across Nepal that landslide occurrence reaches a peak in September, when the pore pressure is at its maximum. This holds true for the 1989 and 1998 landslides of Tatopani: both occurred following heavy rainfall, even if the collapse itself did not develop during a very rainy day. Rainfall data (reported in Sikrikar and Piya, 1998) indicate a cumulative rainfall of 1172.5 mm during the 3 months that preceded the 26 September 1998 event. Similarly, the 5×10^6 m^3 landslide that occurred in 1988 in Darbang (Myagdi District, only 30 km distant from Tatopani) is attributed to meteorological anomalies (Ibetsberger and Weidinger, 2000), with an extreme dry period preceding the onset of the monsoon: deep cracks developed in the dried out soils and favoured the penetration of the water along fractures and joints. Rainfall in August 1988 was in excess of 17% above the decade-average, and the peak of precipitation in early September led eventually to the collapse of the mountain flank, which claimed 109 lives (Yagi et al., 1990; Ibetsberger and Weidinger, 2000).

However, it is worth noticing that in both Tatopani and Darbang failures, seismic shaking by the 1988 Udayapur event also contributed to slope instability (Fig. 6B). Earthquake and associated ground crack opening is indeed a very efficient trigger of slope collapse, as exemplified by recent, catastrophic events in Kashmir Himalaya (Dunning et al., 2007; Sato et al., 2007; Kamp et al., 2008; Owen et al., 2008) and in Sichuan (Cui et al., 2009; Huang and Li, 2009; Sato and Harp, 2009; Wang et al., 2009; Xu et al., 2009; Yin et al., 2009). Authors insist upon the fact that seismic shaking is amplified by mountainous topography, both increasing the vertical component, hence the rapid motion of the landslides and their geomorphic consequences (river dams and continuous rock-falls) and induced heavy human and economic losses. Once a series of earthquake-triggered landslides develop, then their evolution will depend strongly on the rainfall pattern of the following years. Yet the landslide evolution was rather small following the October 8, 2005, Kashmir Himalaya earthquake despite the heaviest monsoon season that followed (Khattak et al., 2010). However Tang et al. (2009), on the basis of the many debris flows triggered by the heavy monsoon rainfall following the M7.9 Wenchuan earthquake, consider that the ground shaking likely reduced both the critical amount of accumulated precipitation and the hourly rainfall intensity necessary to initiate those debris flows, now making these areas more sensitive to this geo-hazard.

Even though the magnitude of the Tatopani slope failure cannot be compared to the Hattian Bala rock avalanche in Pakistan (Dunning et al., 2007) or to the Tangjiashan landslide in Sichuan (Xu et al., 2009), its evolution during the last 30 years illustrates well the rainfall-earthquake interplay in landslide triggering and further re-activation. Clearly, the 1988 Udayapur earthquake (magnitude 6.4) weakened both the Darbang (Yagi et al., 1990) and the Tatopani slopes (Sikrikar and Piya, 1998), developed in the same predisposing lithostructural context of alternating bands of black to green slates (chlorite–sericite schist facies) with fractured quartzites distinctive of the upper Lesser Himalaya formations (Colchen et al., 1986; Upreti and Yoshida, 2005). In the Tatopani site, once the slope was destabilized by the shake, the monsoon rains decreased the shear resistance of the weathered bedrock, increased the pore water pressure and soil weight that eventually led to a sudden collapse of the mountain slope along the predefined set of joints and foliation dip. The August 1989 rainfall-triggered collapse occurred just 1 year following the Udayapur earthquake. This earthquake has modified the mountain rockslope cohesion; therefore we also presume that the two mountain slope failures that occurred in September 1998 indirectly resulted from the disequilibrium created by this former earthquake-induced ground cracking. The presence of water seepages still coming out of the Tatopani landslide face more than 10 years after the event (observation December 2009, in the dry season) is a good evidence of the connection between surface cracks opening, building up of pore water pressure and final slope failure. This also clearly indicates that the mountain slope is not in an equilibrium state. We can refer to the 1988 Darbang landslide that dammed the Myagdi river for 6 h, and occurred exactly at the same place as the 1926 landslide which killed more than 500 people, a disaster which forced the bazaar to move across the river to its present location (Yagi et al., 1990). This last example evidences the fact that once the mountain slope starts failing, it does persist a great potential for future failures. This may be a major threat for the adjacent Tatopani village and the new Kali Gandaki road, respectively located upstream and downstream from this landslide.

From the above discussion, it appears difficult to discriminate between tectonic and climate triggers as the dominant mechanism controlling Himalayan slope evolution at a short time scale. Densmore and Hovius (2000) proposed a probabilistic measure of hillslope morphology to distinguish between these two triggers. From their study they concluded that areas dominated by storm triggered landslides have steep topographic slopes concentrated in the lowermost part of the mountain slopes, whereas earthquake-triggered landslides led to more uniform, planar mountain slopes. This would suggest the Talbagar debris avalanche, the scar of which developed near the ridge crest, might have been earthquake triggered which would explain the subsequent efficient blockage of the valley. Yet, along the studied Kali Gandaki section, we did not find such a clear morphological correlation, probably because both triggers may act concurrently if not simultaneously. At a larger spatial scale, our observations 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), such as in Tatopani (Voelk, 2000), is certainly more generalized than is usually described, and is a direct response to the rate of river downcutting, as illustrated by other examples in the Himalayan Range (Paul et al., 2000).

5.3. Dynamic coupling between river channel and hillslope processes: complexity of the processes involved

Fluvial incision is indeed another efficient trigger that control erosion rates of tectonically active mountain slopes. Whereas over 10^5–10^6 year timescales, hillslope evolution (landsliding or colluvial debris accumulation) adjusts to bedrock incision rate by rivers (Whipple, 2004), and may depend on a critical threshold slope angle independent of tectonic and climate triggers (Burbank et al., 1996), on shorter timescales, there is a complex yet efficient hillslope-channel coupling (*sensu* Harvey, 2002) that controls the morphology of, and the sediment fluxes in, both the mountain slopes and the valley bottoms. Gabet et al. (2004) observed that rivers traversing the High Himalaya present evidence of supply-limited channels that are very dependent on inputs of sediment from the hillslopes.

Our diachronic observations have shown that at short (10^1–10^2 years) to very short (10^{-1}–10^{-2} years) timescales the evolution of the Kali Gandaki valley is in fact characterized by a great unsteadiness, and by a rapid alternation in both time and space of debris aggradation and erosion (Fort et al., 2010). In this context, there is a strong dynamic coupling between hillslopes and riverbed, with distinctive impacts depending on the valley width and of slope components (either bedrock or colluvium).

Where the valley is wide enough such as at the Ghatte Khola/Kali Gandaki junction, the successive inputs of debris flows cause both erosion (stream banks) and pulsed aggradations at the confluence that may transfer the erosion point to the opposite (left bank) side of the Kali Gandaki river and cause backwater inundation upstream. This process resulted in the diversion of the Kali Gandaki course more than 50 m eastward in the last 40 years. Sediment storages are of very short duration (10^{-2} to 10^{-1} years), except for the largest boulders inherited from perched, catastrophic (Holocene), fluvial discharges (Fort, 1993; Monecke et al., 2001) and/or from possibly earthquake origin, as also observed downstream of the Miristi Khola–Kali Gandaki junction.

Where the valley is narrower (such as in the Tatopani site), blockages of moderate magnitude (10^4 to 10^6 m^3) are common features in the Himalayas (Marston et al., 1998; Paul et al., 2000; Weidinger and Ibetsberger, 2000; Dunning et al., 2006). Most of them are temporary dams that are partly reworked and exported by the rivers during the monsoon high flows. About one fifth of the Tatopani landslide–dam volume was readily eroded when the dam was breached, hence releasing debris and activating the sediment cascade efficiently. Over the last 10 years the landslide mass has been affected by shallow translational slides during each rainy season, supplying a continuous flux of debris (mostly pulverized slates) to the Kali Gandaki river. However, the "regular" monsoon high flows are insufficient to remove the larger boulder lags that are now armouring 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; these debris pulses in turn increase the density and the transport capacity (*sensu* Lisle and Smith, 2003) of the flow downstream.

Such events are the main cause of recent (last two decades) undercutting of alluvium fills, as observed along the right bank of the Kali Gandaki north of Talbagar, south of Dana (Duwarikholagaon), north of Tatopani (bus station) and south of Tatopani (Nauni Bagar).

The site north of Talbagar is particularly interesting in that respect, illustrating the hillslope-channel coupling at a short timescale (Fig. 15). During the 1978 monsoon high flows, a large part of alluvium of the lower terrace (right bank) of the Kali Gandaki was cleaned off, and the old winter foot trail had to be abandoned and replaced on the left bank by a new trail traced over the Talbagar debris avalanche cone. In 1982, a "small" rock-fall cone (2×10^2 m^3) developed at the foot of the right bank cliff, as if the removal of the former alluvium had a debuttressing effect (Fig. 15A). In 2000, the same site was affected by a new rock-fall failure of similar volume, whilst the former one had already been cleaned off by another high density flood of the Kali Gandaki (Fig. 15B).

When the valley is very narrow (such as across the Talbagar rocky gorges), landslide dams may persist longer in time. Yet, the river capability (discharge, regime and stream power) to incise its bed, controlled by channel long profile and by headwater erosion into the landslide runout, leads to partial clearing out that eventually permits incision into the bedrock and hillslope processes (rock-falls) to develop along the adjacent rock walls (Fig. 12C). However, the shape of the runout (constrained by the topography), the percentage of fine material (dependent on bedrock lithology, i.e. gneisses vs schists/flyschs), and the potential undermining and dam material removal counteracted by bed armouring by the largest boulders remain control factors of the persistence of landslide dams, as reported elsewhere (Costa and Schuster, 1988; Korup, 2002, 2005).

As a result, complex assemblages of sediment are preserved in temporary stores that reflect the varying modes of erosion/reworking/deposition of landslide material (Fig. 16). These processes are very unsteady both in space and time (Pratt-Sitaula et al., 2007; Fort et al., 2009), independently of any mid- or long-term climate change. Our observations of efficient (i.e. fast) sediment trapping upstream of temporary dams are also good evidence for large mechanical erosion rates related to steep topography, suggesting that uplift/downcutting forcing is probably as efficient as climate forcing (Fort et al., 2009).

5.4. The role of, and the threat to, new infrastructures

Landslide triggering by road construction has often been underlined, particularly in the geologically unstable slopes of the Lesser Himalaya (Kuncha schists) across which most of the trunk roads connecting recently grown urban centers in Nepal are located (Brunsden et al., 1975; Deoja, 1994; Bhandary et al., 2008; Petley et al., 2007). Despite the fact there might be a bias in landslide database compilation leading to an underestimate of slope failures occurring in undisturbed forested mountain slopes (Marston et al., 1998), the construction in recent years of access roads in mountain rural areas of Nepal has undoubtedly triggered a large number of small landslides as a result of slope undercutting and surcharges by the disposal of spoil (Deoja, 1994; Petley et al., 2007). Across the Higher Himalaya, the Arniko Highway connecting Kathmandu to Lhasa is regularly cut north of Bharabise by very large landslides, and the same holds true for the Trisuli road (around Ramche; Burtin et al., 2009). We presume that the new Kali Gandaki road would similarly be affected; in fact, after only two monsoon rainy seasons, this road has been blocked at sections highly susceptible to landsliding. All these major roads are cut either into bedrock or old landslide material that can reach several tens of meters thick (Fig. 2B). The main reason governing road designs is indeed the location of the villages, settled upon loose debris (i.e. landslide colluvium) rather than upon sound bedrock so that terracing and agricultural activities are facilitated. Therefore, more than a triggering agent of slope destabilization, road construction rather appears as an aggravating factor for both vulnerability of land and people to natural hazards (rock-falls, landslides, and debris flows), as synthesised on Fig. 16. The morphology of the valley, its width and its slope material, in particular the loose debris (alluvial fills and ancient landslide material) inherited from earlier events (ranging from 10^{-2} to 10^4 years time span), collectively create the conditions for blockages of varying causes, intensity and duration (Fig. 7B, C, D, E). Therefore, the coupling with an actively eroding river

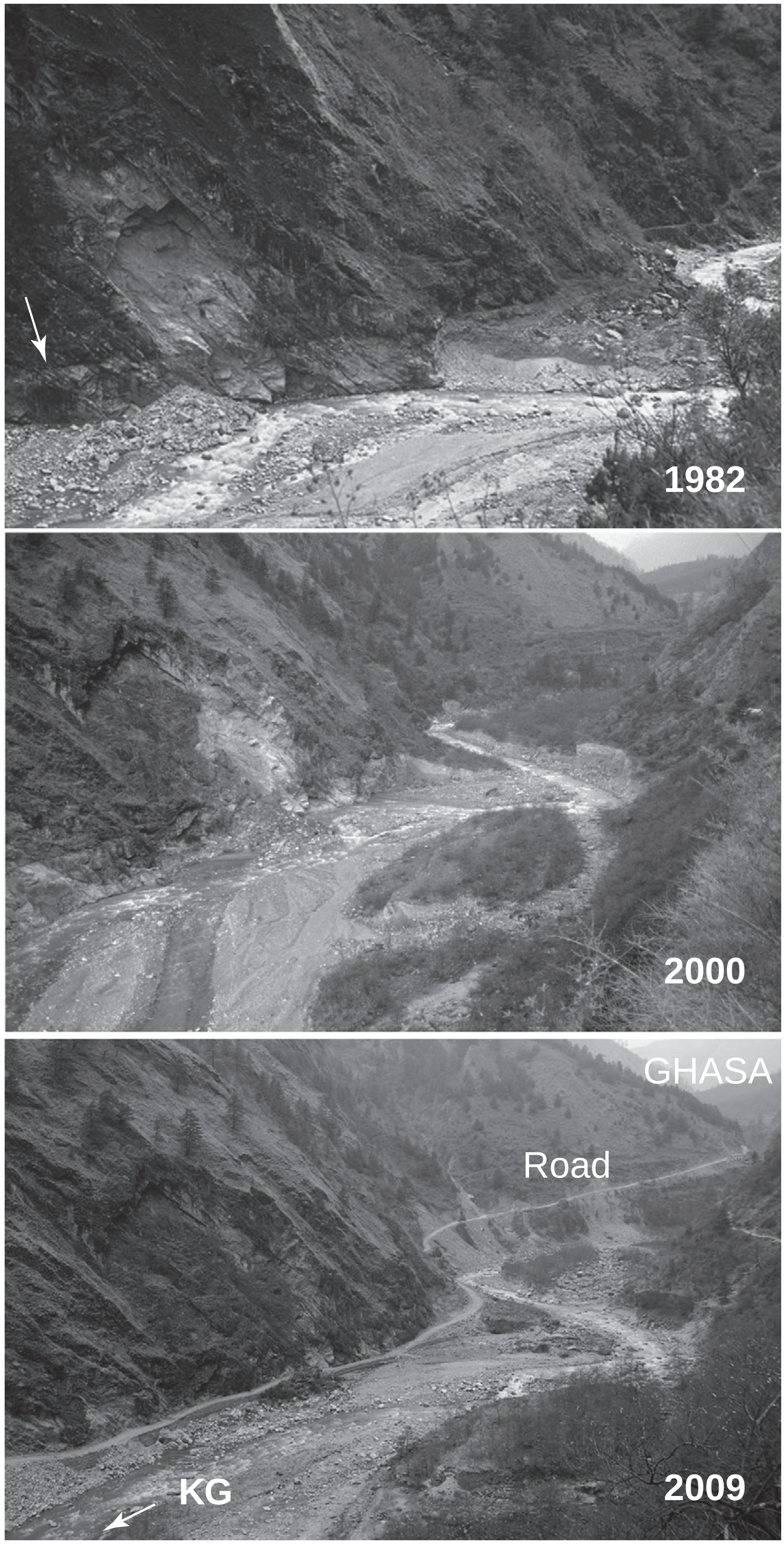

Fig. 15. Right bank of the Kali Gandaki, upstream of the Talbagar site. A: In 1978, a flood removed the alluvial fill, as underlined by the absence of lichens on the bedrock (former upper limit of alluvium below arrow); note a "small" rock-fall cone at the foot of the cliff that developed in 1982; B: the same site in 2000, where another, new "small" rock-fall failure occurred, whilst the 1982 one had been cleaned off by the Kali Gandaki; and C: in 2009, the newly built road of the Kali Gandaki follows the old trade route, and passes along the rocky cliff, ignoring both rock-fall threat and potential flood hazards.

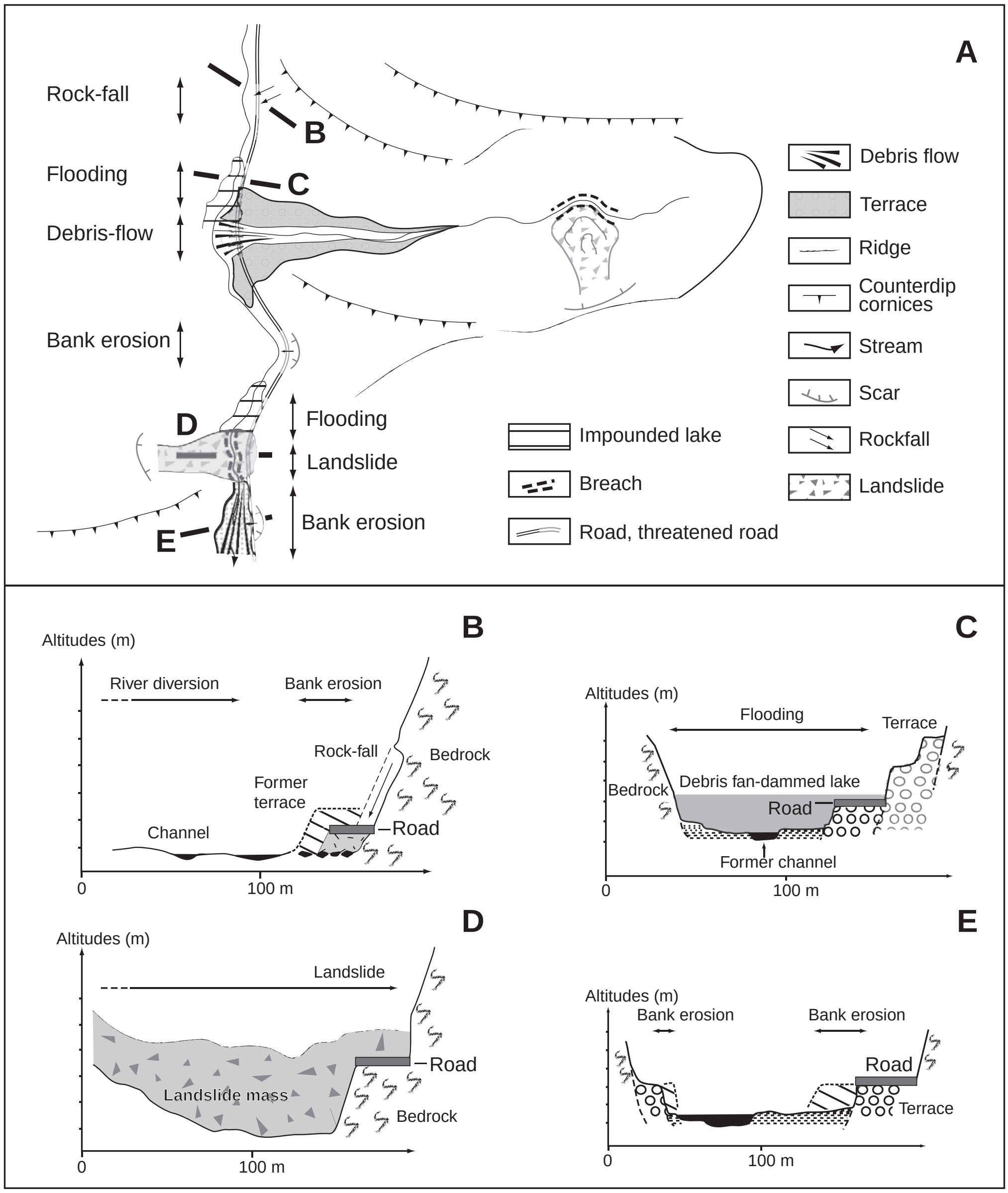

Fig. 16. Synthesis of natural hazards that may potentially threaten a Himalayan road such as the Kali Gandaki road, following a confined valley. A: Types of hydro-geomorphic hazards (rock-fall, landslide, and debris flow) and their impacts (damming, flooding, and bank erosion) along the valley bottom; B: road excavated in bedrock, with road bed located close to the river (possibility of road bed undermining); C: road on a lower terrace, with potential inundation by a landslide dam lake; D: road buried under a landslide runout; and E: road threatened by bank erosion (alluvial material) possibly triggered by river diversion.

may result in complete road destruction and heavy human and economic losses in this less developed country.

In addition, the construction of new roads in remote places attracts population who find new facilities and opportunities in a roadside location, which in turn might expose them to hazards. This is the case at Dana, where the design of the road built on the middle terrace led to the construction of an undersized bridge. During the first monsoon season following road completion, the bridge was destroyed by a debris flow of moderate magnitude. It can be considered as fortunate that the destruction occurred early enough after the road opening, when Dana settlements have not yet much expanded. If not, this could have given rise to a disaster like in Larcha, when on July 22, 1996 a debris flow developed along the Arniko Highway and the Bhote Kosi river: there, because of the size of the settlement, the toll was very high, with 56 people killed, 16 houses, one temple and five mills destroyed, and 2 houses damaged (Adhikary and Koshimizu, 2005). In fact, most of the time the development of road projects in rural Nepal has led households to occupy hazard prone areas through lack of choice because their everyday concerns (food, reliable income, children's education, and access to medicine) are perceived as more immediate threats than their exposure to unfamiliar, infrequent hazards (Oven et al., 2008). Conversely, the construction of roads along the valley bottom favours outmigration from mountain areas affected by landslides which in turn may lead to reactivation of landslides due to the lack of stabilization control by terracing efforts by village communities (Khanal and Watanabe, 2004).

In the case of the Kali Gandaki road, built rapidly without proper concern for geotechnical constraints, the forthcoming occurrence of landslides and debris-floods can easily be foreseen. At many places, indiscriminate blasting or excessive back cutting into the rock have been carried with no regard for natural hazards; the fractured bedrock is not consolidated, retaining walls are lacking or have already been destroyed only 18 months after completion. North of Talbagar, the road passes along the rocky cliff, ignoring both rock-fall threat and potential flood hazards (Fig. 15 C). The traffic along this road is not yet very high, but the comparison with existing national roads (e.g. Kathmandu–Pokhara–

Narayanghat, Bhandary et al., 2008; Kathmandu–Kodari–Chinese border, Deoja, 1994) suggests that unavoidable day-to-week-long closures may cause heavy economic loss and a growing number of people affected. During the summer 2008 (a few months after the road opened to traffic), the Kali Gandaki road was closed several days across the Talbagar gorges (Fig. 11B) and at Ratopani (Figs. 1, 2), where the landslide activity also destroyed several houses, now resulting in a progressive abandonment of the village. Obviously, this road would require a massive maintenance budget to repair or rebuild the damaged road sections (i.e. sections north of Kabre or south of Tatopani), as elsewhere in the Himalayas (Haigh, 1984; Derbyshire et al., 2001), a budget that Nepal probably cannot afford.

6. Conclusion

The three examples studied are quite characteristic of the most frequent situations encountered across the Higher Himalayan valleys, that are generally confined and where the structures and litho-units control both morphology and debris supply from slope. Mountain walls made of steep, weathering-limited, bedrock outcrops contrast with gentler slopes following the foliation grain and supplying the lower slopes by pulses of passing debris that may directly reach the river bed. Comparison with other features observed along the middle Kali Gandaki and adjacent valleys confirms that in the High Himalaya, medium scale landsliding plays a major role in the overall process of denudation and sediment transfer. Despite the fact that hillslope debris inputs are very unsteady in time (they occur mostly during the monsoon season), when coupled with high fluvial activity, they highly influence the transient nature of bedload transport in the channel, hence favouring sediment fluxes and their conveyance outward from the mountain zone. Indirectly, by causing river diversion and subsequent bank erosion, they reduce the residence time of sediments in the temporary, spatially limited traps of the valley bottom, hence threatening human settlements and new road structures.

This work also shows that repeated observations of the same sites (now geometrically constrained and included in a DEM) may provide a better understanding of the functioning of the landform system itself at a very short timescale. This, together with continuous updating of detailed geomorphic maps, would be a most readily useful tool to avoid an increase of damage and fatalities as observed in Nepal over the last 20 years following rural road-building projects in relation to demographic growth and subsequent development of urban centers.

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