revue en ligne : https://journals.openedition.org/geomorphologie/

Géomorphologie : Relief, Processus, Environnement

vol. 31, n°4 (2025), p. 303-325
Mise en ligne le 12 novembre 2025 sur journals.openedition.org
http://journals.openedition.org/geomorphologie/20556
https://doi.org/10.4000/154up



https://gfg.cnrs.fr/

# The Kagbeni flood event (August 13, 2023), Mustang District (Nepal): Triggers, sediment cascades, aggravating infrastructures and disaster risk management

## *La crue de Kagbeni (13 août 2023), district de Mustang (Népal) : déclencheurs, cascades sédimentaires, infrastructures aggravantes et gestion des risques de catastrophe*

Monique Fort [a*], Narayan Gurung [b], Perrine Yvrard [a], Rainer Bell [c], Katy Burrows [d], Bhagawat Rimal [e], Gilles Arnaud-Fassetta [a]

[a] Université Paris Cité, UMR 8586 PRODIG, 75205 Paris Cedex 13, France.
[b] Kadoorie Agricultural Aid Association, Pokhara, Nepal.
[c] Department of Geography, University of Bonn, Germany.
[d] University of Milano-Bicocca, Italy.
[e] College of Applied Sciences-Nepal (CAS), Tribhuvan University, Kathmandu, Nepal.

## ABSTRACT

Located in the northern, rain-shadow zone (< 300 mm/yr) of the Nepal Himalaya, Kagbeni village (2810 m, 420 inhabitants, at the junction between Jhong Khola and Kali Gandaki) was affected by a disastrous, unusual hyper-concentrated flood on August 13, 2023. It caused significant damage to property and infrastructure (cost estimated at USD 7.4 millions), fortunately without fatalities.

For several years, increased rainfall has been recorded at Jomsom station (2720 m), a trend confirmed by residents. However, no single extreme rainfall event that could have triggered the flood was recorded at Jomsom station or in CHIRPS rainfall data for the Jhong Khola valley. Considering the geomorphological context, we hypothesized that the flood event was most likely triggered by a landslide-lake outburst. The landslide existence and source area (upstream from Chhiongur gorges) were confirmed by analysis of Sentinel-1 InSAR coherence time series. Downstream, the flood spread over the entire valley floor, as evidenced by new deposits, bank cuttings and reactivation of landslides providing additional debris and making downstream flooding even more destructive (bridges, buildings, livestock, orchards...). The volume of debris transported was estimated at 647,000 m$^3$, followed by rapid post-flood re-incision (215,000 m$^3$).

The inhabitants of Kagbeni also contributed to disasters by settling on very low terraces and encroaching on the Jhong Khola riverbed. Upstream of the village, the Upper Mustang Road bridge also amplified the damage through a bottleneck effect: its concrete deck collapsed, and its transport was very destructive downstream.

Given the general trend towards climate change, the probability of future, similar flash floods remains high in Kagbeni, yet some residents have rebuilt their homes and continue to live on hazardous floodplains. We suggest some measures for preventing future risks, such as (*i*) applying the Freedom Space for Rivers concept to avoid encroachment of floodplains by anthropogenic activities, and (*ii*) managing a concrete ford-type structure instead of poorly calibrated bridge deck along the Upper Mustang Road. More generally, a nationwide natural risk-reduction policy should be implemented.

**Keywords:** flash flood, data acquisition, sediment cascade, natural risk management, dry Nepal Himalaya, climate change.

## *RÉSUMÉ*

*Situé dans l'Himalaya continental et sec, le village de Kagbeni (2810 m) a été affecté par une crue hyper-concentrée dévastatrice et inhabituelle le 13 août 2023, heureusement sans perte humaine. Aucune pluie exceptionnelle n'a été enregistrée en 2023 par la station de Jomsom, ou par les données pluviométriques CHIRPS (Jhong Khola). Vu le contexte géomorphologique, nous avons considéré que cette inondation fut déclenchée par la rupture d'un lac de barrage formé par un glissement, dont l'existence et le site furent confirmés en amont par l'analyse des séries temporelles de cohérence d'images satellitaires Sentinel-1 InSAR. En aval, la propagation du flot a entraîné dépôts, érosions de berge et réactivation de glissements de terrain, rendant l'inondation encore plus destructrice. Le volume de débris transportés a été estimé à 647 000 m$^3$, suivi d'une ré-incision rapide après l'inondation (215 000 m$^3$). Deux facteurs aggravants ont contribué à cette catastrophe : habitations empiétant sur la plaine d'inondation et pont routier mal calibré. La probabilité que de telles crues se reproduisent reste non négligeable (cf. réchauffement climatique). Nous suggérons donc* (i) *l'application du concept d'espace de liberté et* (ii) *la mise en place d'un gué en béton, plus éco-responsable qu'un pont.* (iii) *Une réglementation sur la prévention des risques naturels devrait aussi être développée à l'échelle du Népal.*

***Mots-clés :*** *crue éclair, acquisition de données, cascade sédimentaire, gestion des risques naturels, Himalaya népalais sec, changement climatique.*

**ARTICLE INFORMATION**
Received May 16, 2025.
Accepted October 24, 2025.

*Corresponding author. ORCID 0000-0002-1866-1152
E-mail adresses:
fort.monique@gmail.com
jyonus@hotmail.com
perrine.yvrard@gmail.com
rbell@uni-bonn.de
k.a.burrows987@gmail.com
bhagawatrimal@gmail.com
gilles.arnaud-fassetta@u-paris.fr

## 1. Introduction

The Himalayas, together with the Tibetan Plateau and its margins, belong to what is known as the "Water Tower of Asia", which contributes crucially to the water supply of > 1.5 billion of people during the dry season (after and before the monsoon), feeding seven of Asia's major rivers (Immerzeel et al., 2010). In the Himalayas, water is derived from glaciers, snow melt and from rainfall, the proportion of which depends on annual and seasonal temperatures, and on topography and geographic position in the range (Lutz et al., 2014). In central Nepal, glacial and snowmelt waters contribute less than 30 % to the total flow, whereas monsoon rains represent 70 % of that total flow (Lutz et al., 2014). However, climate and water flow vary according to position in relation to the Higher Himalayan range: while the southern side is affected by a warm and humid climate largely influenced by summer monsoon rains, the northern, rain-shadow side is much dryer with contrasted (continental-influenced) temperatures (Dobremez, 1976; Böhner et al., 2015), and with water mostly provided by snow and glaciers melting during spring and summer.

The evolution of mean annual and seasonal temperatures during the last decades, and projections until 2100 show a general trend towards higher temperatures in the Himalaya-Karakoram mountains, more than the global average (Krishnan et al., 2019; Sharma et al., 2019). This makes extreme weather events and subsequent natural hazards more frequent, with significant change in precipitation, that may affect river flow (both in volume and timing), hence threatening both livelihoods and infrastructure in countries where vulnerable, exposed and ill-prepared communities still predominate. This is the case in India, as demonstrated by the 2013 flood of Kedarnath (Allen et al., 2016; Tamta and Joshi, 2019), the 2021 mass flow in Chamoli (Shugar et al., 2021), and the 2023 Sikkim Glacial Lake Outburst Flood (Sattar et al., 2025).

Recent trends of global warming are expressed in the southern part of Himalayan Range by more frequent disastrous floods (variable death tolls), that may be triggered by at least three recurrent factors, as the following examples in Nepal illustrate (fig. 1). (*i*) GLOFs (Glacial Lake Outburst Floods; Bajracharya et al., 2020) caused by the sudden rupture of a proglacial lake, as recent events in Bhotekoshi (2016, Cook et al., 2018), in Barun (2017, Byers et al., 2018), or in Khumbu Thyanbo-Thame (2024, ICIMOD 2024; Cook et al., 2025; Hille et al., 2025; Maharjan et al., 2025) have demonstrated. (*ii*) Rock and ice collapse from high mountain walls, caused by the combination of permafrost degradation and ice falls: *e.g.*, the Seti Khola (May 5, 2012 flood in Nepal; Gurung et al., 2021; Fischer et al., 2022). In this specific case, rock and ice collapsed from the West face of Annapurna IV (7525 m), inducing a rock-avalanche mixed with ice and fresh snow, followed by the disintegration of

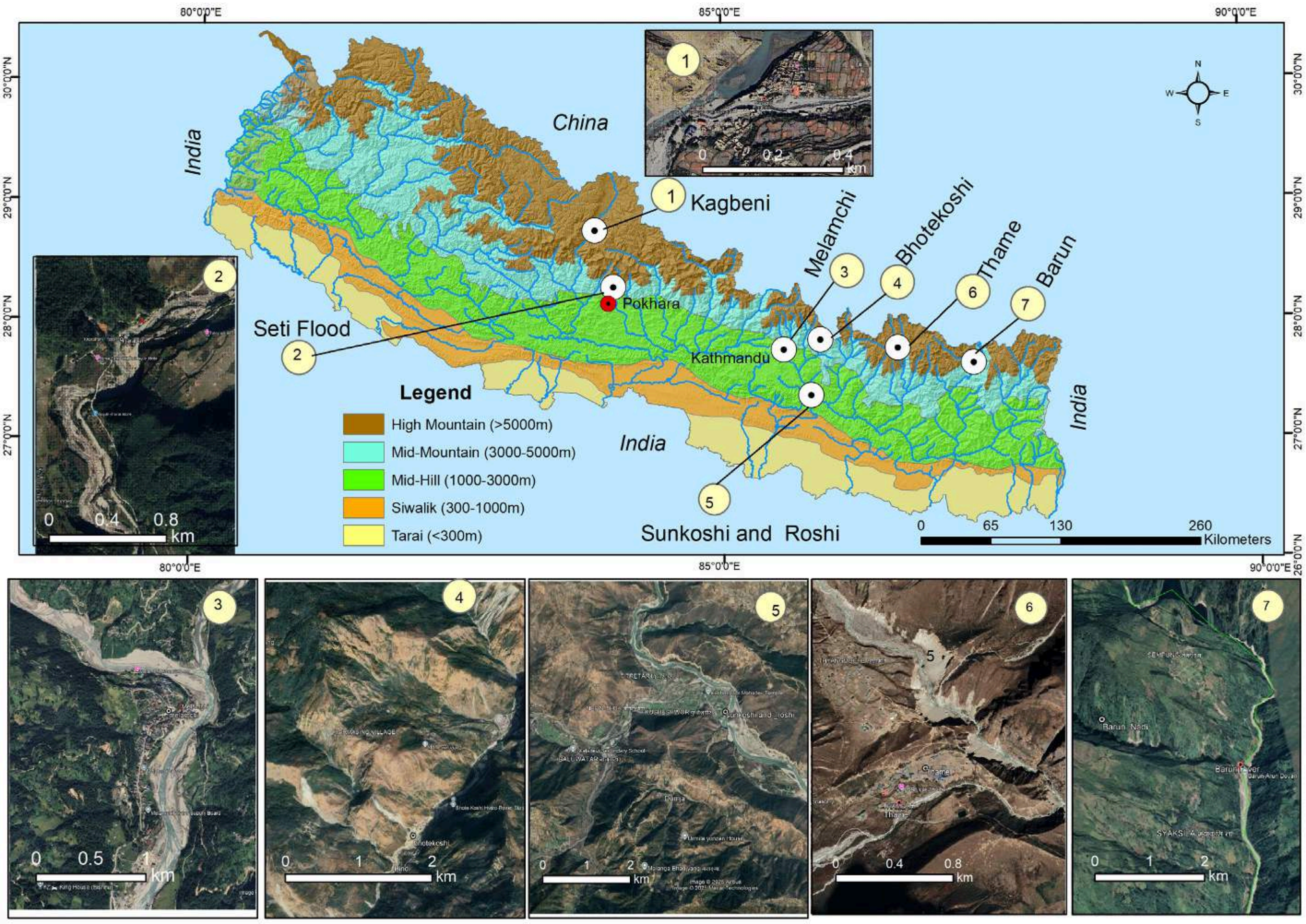



**Fig. 1 – Topography of Nepal and location of recent, extreme flood events.**

***Fig. 1 – Topographie du Népal et sites d'inondations exceptionnelles récentes.***

the rocks and incorporation of meltwater, progressively initiating the debris flow  that, after a constrained flow across the Seti Khola gorges, turned into a hyper-concentrated flood before reaching (35 km downstream) the north of Pokhara (900 m), the second largest city in Nepal located in an intra-mountainous basin (Fort, 1987a; Fort et al., 2018). (*iii*) Other recent flood events are related to abundant rainfall and landslide collapse like the June 16, 2021, Melamchi flood (Maharjan et al., 2021; Adhikari et al., 2023; Chen et al., 2024; Duwadi et al., 2024) or the recent disastrous floods of September 2024 (Petley, 2024; NDRRMA, 2024; Lamichhane et al., 2025) which have affected the Kathmandu valley and the adjacent Roshi River (Kavrepalanchowk district), a right tributary of the Koshi River, in the central-eastern Nepal (Bagmati Province). In all the cited examples, the flood waters were very rich in debris (hyper-concentrated flows), making them very destructive.

In the northern, drier part of the High Himalayan mountains, floods have always been exceptional events, with sporadic humid air masses crossing the orographic barrier. But they seem to be becoming more frequent with intense moisture transport during the monsoon season, mainly along major valleys crossing the Higher Himalaya (Bookhagen et al., 2005; Bell et al., 2021). In fact, in these continental environments, climate change impacts appear in different ways: increased gullying and slope instabilities (in substrates like Quaternary terraces and/or shales/marls), occurrence of flash floods, permafrost degradation and induced ice- and rock-falls/slides both generating potential debris floods (Fort, 2015).

Here, we report on an exceptional, extreme flood that occurred in the lee-side part of the Annapurna-Nilgiris Himalayas (Mustang District), an area usually unaffected by monsoon rains (fig. 2). A severe and complex, polygenetic flood event occurred in the Muktinath area of Mustang, on the evening of August 13, 2023, causing significant damage to property and infrastructure worth approximately of USD 7.4 millions at Kagbeni Village, which is nestled along both riverbanks of the Jhong Khola (sometimes called KagKhola), a major left-bank tributary of the Kali Gandaki River. About 29 buildings, 1 motorable bridge, 1 steel truss bridge, and 6 smaller bridges were destroyed, while more than 25 cows and other livestock were killed (Gurung et al., 2024). Fortunately, human lives were spared because the community was warned to move to safety before the mud and sludge hit the village.

Our study intends to illustrate this unusual hyper-concentrated flash flood, to decipher what were the triggering and aggravating factors, to understand the effects of the sediment cascade in the catchment, and to suggest some potential adaptations to both ordinary river activity and to climate change for the local communities.

## 2. Study area

The village of Kagbeni (2810 m, 420 inhabitants, Rural Municipality of Varagaon, Mustang District) lies in the northern Himalayan, rain-shadow area (north of the Annapurnas and Nilgiris ranges) (fig. 3). While early studies mentioned rather low (< 300 mm/yr) precipitation (Dobremez, 1976; Dobremez and Jest, 1976), recent trends show a progressive increase in annual precipitation (Böhner et al., 2015; Bell et al., 2021; Environment statistics of Nepal, 2024), well expressed by the data recorded by the Jomsom station (operating for the last 40 years) and in the Jhong khola catchment (fig. 4), as better described in section 3.1.

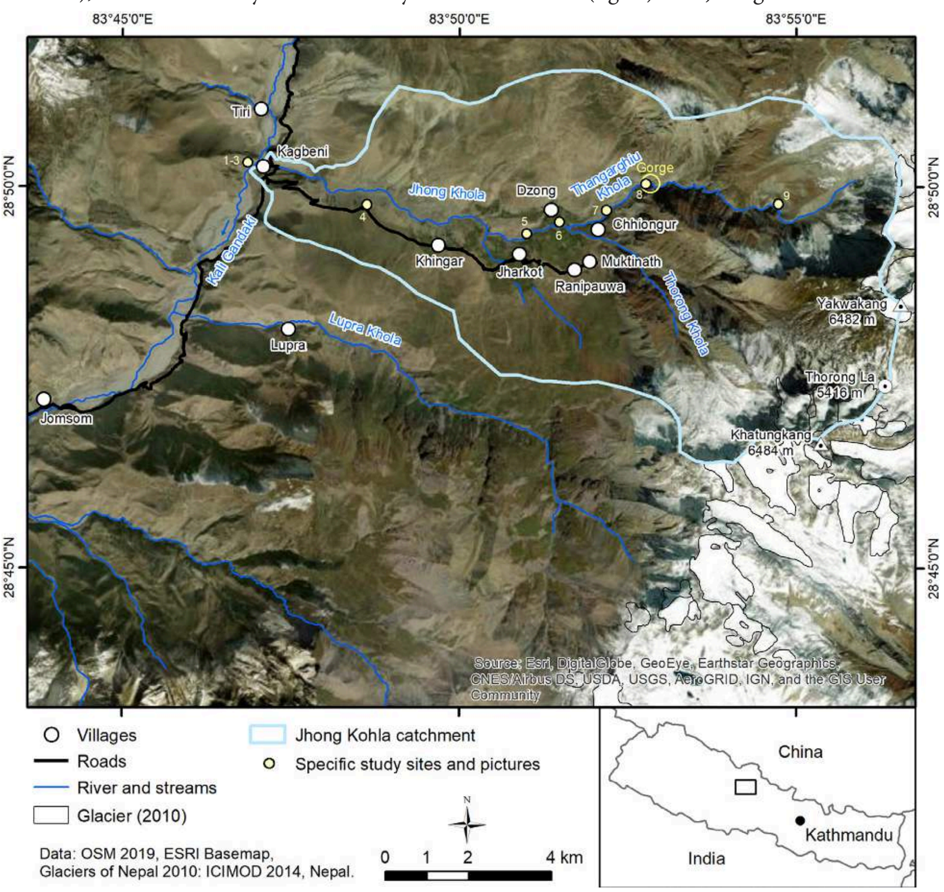



**Fig. 2 – Jhong Khola catchment. The Kali Gandaki flows southwards.**

The small circles and numbers refer to study sites and photos mentioned in the other figures. (1-3): fig. 3, 13B, 13C, 14-18; (4): fig. 9; (5): fig. 11; (6): fig. 12; (7): fig. 10; (8): fig. 7; (9): location of landslide sites, fig. 6

***Fig. 2 – Bassin versant de la Jhong Khola. La Kali Gandaki s'écoule vers le sud.***

*Les petits cercles et les chiffres renvoient aux sites étudiés et aux photos mentionnées dans les autres figures. (1-3) : fig. 3, 13B, 13C, 14-18 ; (4) : fig. 9 ; (5) : fig. 11 ; (6) : fig. 12 ; (7) : fig. 10 ; (8) : fig. 7 ; (9) : localisation des sites de glissement de terrain, fig. 6.*


**Fig. 3 – Kagbeni and the Jhong Khola catchment viewed from the opposite, right bank of the Kali Gandaki seven months after the flood.**

The old Kagbeni village (center left of the picture) is perched on the right bank, with the Bhuddist monastery (tallest buildings) close to the junction. Downstream from the Mustang Road and along the village, the natural width of the Jhong Khola riverbed has been reduced by artificial channelization. The August 13, 2023, hyper-concentrated flood event has widely affected both riverbanks of the Jhong Khola, and more specifically the left bank (on the right). A large part of the fan built by the flood debris is still present, controlling the flow of the Kali Gandaki. In the back and bounded by two peaks (elevation close to 6500 m), the Thorung Pass (5416 m) gives access to the adjacent Manang/Marsyangdi valley to the East, whereas on the south (right), the Nilgiris range (> 7000 m) is hiding the Annapurna Range (> 8000 m) located to the South (photo: M. Fort, March 12, 2024).

***Fig. 3 – Kagbeni et le bassin versant de la Jhong Khola vus d'en face, depuis la rive droite de la Kali Gandaki, sept mois après l'inondation.***

*Le vieux village de Kagbeni (au centre gauche de l'image) est perché sur la rive droite, avec le monastère bouddhiste (bâtiments les plus élevés) proches de la confluence. En aval de la route du Mustang et le long du village, la largeur du lit naturel de la Jhong Khola a été réduite par une chenalisation artificielle. La crue hyper-concentrée du 13 août 2023 a largement affecté les deux rives de la Jhong Khola, et plus particulièrement la rive gauche (à droite). Une grande partie du cône construit par les apports détritiques de la crue est encore présente, contrôlant le cours de la Kali Gandaki. En arrière-plan et entourés par deux sommets (altitude proche de 6500 m), le Thorung Pass (5416 m) donne accès à la vallée adjacente de Manang/Marsyangdi située plus à l'Est, tandis qu'au sud (à droite), la chaîne des Nilgiris (> 7000 m) masque la chaîne des Annapurna (> 8000 m) située au Sud (photo : M. Fort, 12 mars 2024).*

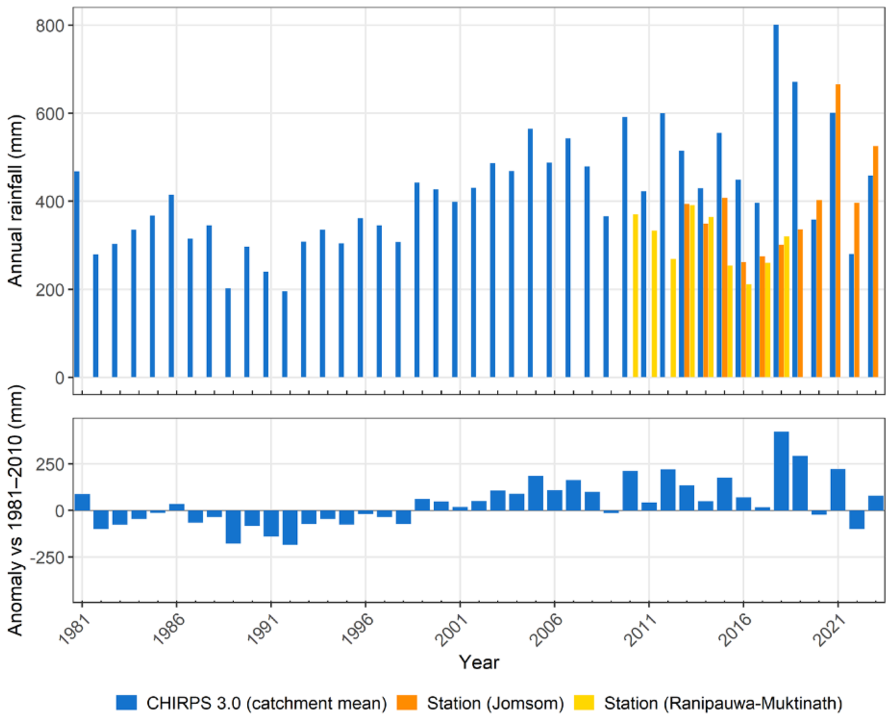



**Fig. 4 – Annual rainfall data of the studied area.**

Annual rainfall in Jhong Khola catchment (1981-2023, CHIRPS 3.0 data), Jomsom station (2013-2023) and Ranipauwa-Muktinath station (2010-2018). Anomaly of annual rainfall 1981-2023 compared to the average of 1981-2020 (CHIRPS 3.0 data). Source: CHIRPS 3.0: https://www.chc.ucsb.edu/data/chirps3; station data: GoN (Nepal Goverment), Dpt of Hydrology and Meteorology, www.hydrology.gov.np).

***Fig. 4 – Précipitations annuelles de la région d'étude.***

*Précipitations annuelles dans le bassin versant de la Jhong Khola (1981-2023, données CHIRPS 3.0), de la station de Jomsom (2013-2023) et de la station de Ranipauwa-Muktinath (2010-2018). Anomalie des précipitations annuelles pour la période 1981-2023 par rapport à la moyenne 1981-2020 (données CHIRPS 3.0). Source : CHIRPS 3.0 : https://www.chc.ucsb.edu/data/chirps3 ; données des stations : GoN (Gouvernement du Népal), Département d'Hydrologie et de Météorologie, www.hydrology.gov.np).*

Kagbeni settlement was established several centuries ago on the upper part of a large fan built up at the junction of the Kali Gandaki and the Jhong Khola (Khola means river in Nepali), a left bank, E-W oriented tributary (fig. 3). Kagbeni is famous for its temple built near the Kali Gandaki River as a stop for Hinduist pilgrims on their way up to Muktinath; it is also a node up to Upper Mustang, with the recently built (Feb. 2023) motor road along the « Kali Gandaki Corridor », as part of the BRI (Belt and Road Initiative) project, an annex of the new Chinese "Silk Roads" (Murton, 2019). The present-day village extends along both banks of the Jhong Khola, which has been channelised by concrete walls.

The Jhong Khola catchment (92.5 km$^2$) ranges from 2800 m (Kagbeni) up to the Yakwakang Peak (6482 m) and Khatungkang Peak (6484 m), respectively North and South of the Thorung Pass (5416 m) that connects the Manang (east) to Mustang (west) districts (fig. 2). The mean Jhong Khola catchment slope is 27° (Bell et al., 2021); it is characterized by a varied, highly contrasted topography (fig. 2, 3), controlled by the geology, its past and recent geomorphic evolution, and the present bio-climatic conditions.

Geologically, this catchment is located north of the South Detachment Fault above which the > 10 km thick, Northern Himalayan meta-sedimentary, folded series outcrop (Colchen et al., 1986; Godin, 2003). Mostly composed of Mesozoic Tethyan sedimentary rocks (fig. 5), there is a sharp morphological contrast between (*i*) the steep slopes and local narrow gorges upstream, cut into massive limestones of the Jomsom and Bagung formations (Colchen et al., 1986; Parsons et al., 2014), and (*ii*) the relatively gentle slopes developed in the Upper Jurassic, black Spiti shales (Colchen et al., 1986; Godin 2003), *e.g.*, the "Shaligram" series (Hagen, 1968), also called Lupra Formation (Parsons et al., 2014), prone to large, slow-moving landslides (see below).

Quaternary deposits, a legacy of the former glaciations, are composed of thick glacio-fluvial gravels overtopping older, indurated, limestone-rich till (derived from Muktinath and Purkung Himals) with a few remnants of recent morainic ridges on the top (3200 m) of the large glacio-fluvial terraces

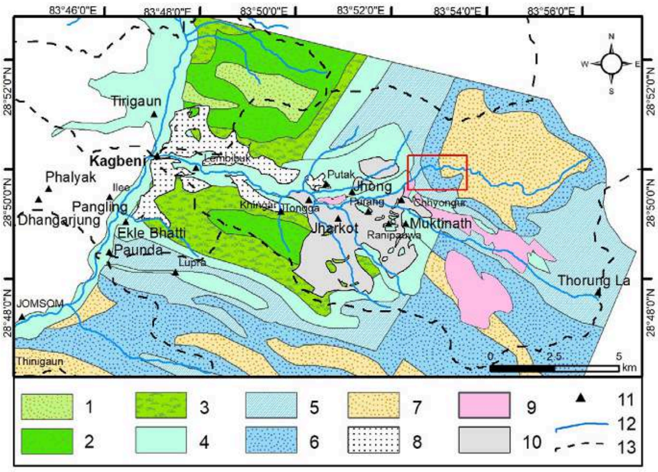



**Fig. 5 – Geological map of the Jhong khola catchment.**

1. Muding Unit: Black shale; 2. Kagbeni Unit: Greywacke, sandstone and conglomerate with volcaniclastic pebbles; 3. Chuck Unit: Sandstone and brown siltstone; 4. Lupra Formation: Black shale; 5. Bagung Formation: Bioclastic and micritic limestone; 6. Jomsom Formation: Oolitic and bioclastic limestone; 7. Thini Formation: Shale and limestone; 8. Late Quaternary and Holocene glacio-fluvial and fluvial gravels; 9. Late Quaternary and Holocene morainic material; 10. Recent and present slope instabilities; 11. Villages; 12. Hydrographic network; 13. Outlines of Jhong khola catchment and sub-catchments (adapted from Parsons et al., 2014, and completed by data from Fort, 1985).

***Fig. 5 – Carte Géologique du bassin versant de la Jhong khola.***

*1. Unité de Muding : Schistes noirs ; 2. Unité de Kagbeni : Greywacke, grès et conglomérats incluant des galets volcaniques ; 3. Unité de Chuc k : Grès et siltites brunes ; 4. Formation de Lupra : Schistes noirs ; 5. Formation de Bagung : Calcaires bioclastiques et micritiques ; 6. Formation de Jomsom : Calcaires oolitiques et bioclastiques ; 7. Formation de Thini : Schistes et calcaires ; 8. Dépôts glacio-fluviaux et alluviaux du Quaternaire tardif et de l'Holocène ; 9. Dépôts morainiques du Quaternaire Récent et de l'Holocène ; 10. Instabilités de versant récentes et actuelles ; 11. Villages ; 12. Réseau hydrographique ; 13. Délimitations des bassins versants de la Jhong khola et de ses affluents (adapté de Parsons et al., 2014, et complété par des données de Fort, 1985).*

culminating at about 3000 m above the Kali Gandaki and Kagbeni village (Fort, 1980; Iwata et al., 1982; Fort, 1985).

The present geomorphological processes of the Jhong Khola catchment are basically controlled by contrasts in elevation (Fort, 1985). At the highest altitudes (above 4800 m) there are still a few suspended glaciers, alternating with areas where periglacial processes and landforms are predominant (talus screes, rock glaciers). Below (4800-4000 m), slopes are snow-covered for about half of the year, with large talus screes that can be locally destabilized by tributaries of the Jhong Khola: depending on the substrate material (bedrock and/or surficial material): (*i*) local slumped areas have developed mostly along the south oriented, right bank of the Jhong Khola (as observed East of Dzong village), whereas (*ii*) the north oriented, shaly slopes are more and more subject to a large, earthflow type, slow-moving landsliding, as observed around the villages of Muktinath, Jharkot and Khingar (Fort, 1985, 1987b, 2000; Miehe and Weidinger, 2015; Etzelstorfer, 2020; Goetz et al., 2020; Bell et al., 2021).

Until recently (2000), the valley received mostly winter, dry snowfalls, that remained cold until spring, at least on its northern, upper rocky slopes and lower cultivated slopes. Now, meteorological conditions are marked by less snow and more rainfall, all changes observed and mentioned by the local people: *e.g.*, they report the absence of snow during the 2023 winter in Kagbeni. Therefore, the combination of a soft substrate (Spiti shales) and heavy rainstorms may have an immediate impact on slope stability, and subsequently on potential flood triggering.

## 3. Methods

Considering the hypothesis of two potential, combined triggers, *i.e.*, rainfall and landslides, we present below the methods (CHIRPS and InSAR coherence analysis) that were used to understand why this flood occurred. Then, we estimated the sediment volumes mobilized based on hydraulic geometry. Additional interviews with locals who witnessed and/or were affected by the flood completed the data collection.

### 3.1. Rainfall data

Precipitation data are mostly provided by the Department of Hydrology and Meteorology (DHM) of the Nepal Government. In Mustang, Jomsom station (2850 m, 10.7 km south of Kagbeni; fig. 2) is the most reliable as it was established in July 1957. Another station was located in Ranipauwa-Muktinath (3609 m), but it was only operational for a few years (Environment Statistics of Nepal, 2024), and since 2018, it has not been repaired (fig. 4).

For this reason, we used the rainfall estimates from rain gauges and satellite observations, run by CHIRPS (Climate Hazards group Infrared Precipitation with Stations). It combines station data, satellite observations (thermal infrared, microwave) and forecast models (Funk et al., 2015). The gridded rainfall dataset has a resolution of 0.05° x 0.05° (ca. 5 km x 5 km) and is available from 1981 to present. CHIRPS has proved able to detect extreme precipitation in mountainous areas of Nepal (*e.g.*, Singh et al., 2024; Subba et al., 2024). However, limitations and uncertainties exist: CHIRPS data could over/underestimate single extreme rainfall events – or miss smaller rainfall cells completely. We comparatively used CHIRPS 2.0 data (https://www.chc.ucsb.edu/data/chirps) as well as the recently published CHIRPS 3.0 data (https://www.chc.ucsb.edu/data/chirps3, Climate Hazards Center Infrared Precipitation with Stations version 3). CHIRPS analysis of the 2023 event includes *(i)* downloading of daily, monthly and annual CHIRPS 2.0 and 3.0 data from 1981-2023, *(ii)* extracting raster values from within the 5 km x 5 km cell containing the landslides most likely to have caused the landslide lake(s), *(iii)* extracting raster values for all cells covering the Jhong Khola catchment and calculating the mean daily, monthly and annual precipitation for the catchment, *(iv)* comparing daily, monthly and annual CHIRPS 2.0 and 3.0 data.

### 3.2. Existence of landslides

Sentinel-1 interferometric synthetic aperture radar (InSAR) satellite images were used to carry out coherence analysis over two slopes (Sites 1 & 2, fig. 6) identified as the potential source areas of landslides, located upstream of the Thangarghiu gorges (fig. 7; location study site 8, fig. 2). The landslides studied here failed too rapidly for the deformation to be measurable using differential InSAR techniques, but InSAR coherence analysis can be used to detect locations and timings of rapid landslides (Yun et al. 2015; Burrows et al., 2020; Deijns et al. 2022). After defining polygons for the potential landslide areas, we took the mean interferometric coherence within each polygon for every 12-, 24-, 36- and 48-day SAR image pair acquired during the period May-September 2023. We expect to see low coherence at all temporal baselines when and where rapid displacements occur at the Earth's surface.

Sentinel-1 images were downloaded from the Copernicus Dataspace ecosystem. The processing was done using SNAP software and had the following steps: (*i*) All images in the time series were co-registered to the first image in the time series (2023/05/05). (*ii*) SAR data were multi-looked by 5 in range and 1 in azimuth to obtain approximately square pixels. (iii) All possible 12-day, 24-day, 36-day and 48-day interferograms were calculated. Those with perpendicular baseline > 150 m were discarded following Deijns et al. (2022). (*iv*) Coherence maps were calculated using a 3 x 3 moving window (this gives the coherence map a resolution of 60 m x 66 m). (*v*) Coherence maps were converted from radar geometry to a geographic coordinate system. The mean coherence was calculated within each landslide polygon for every interferogram.

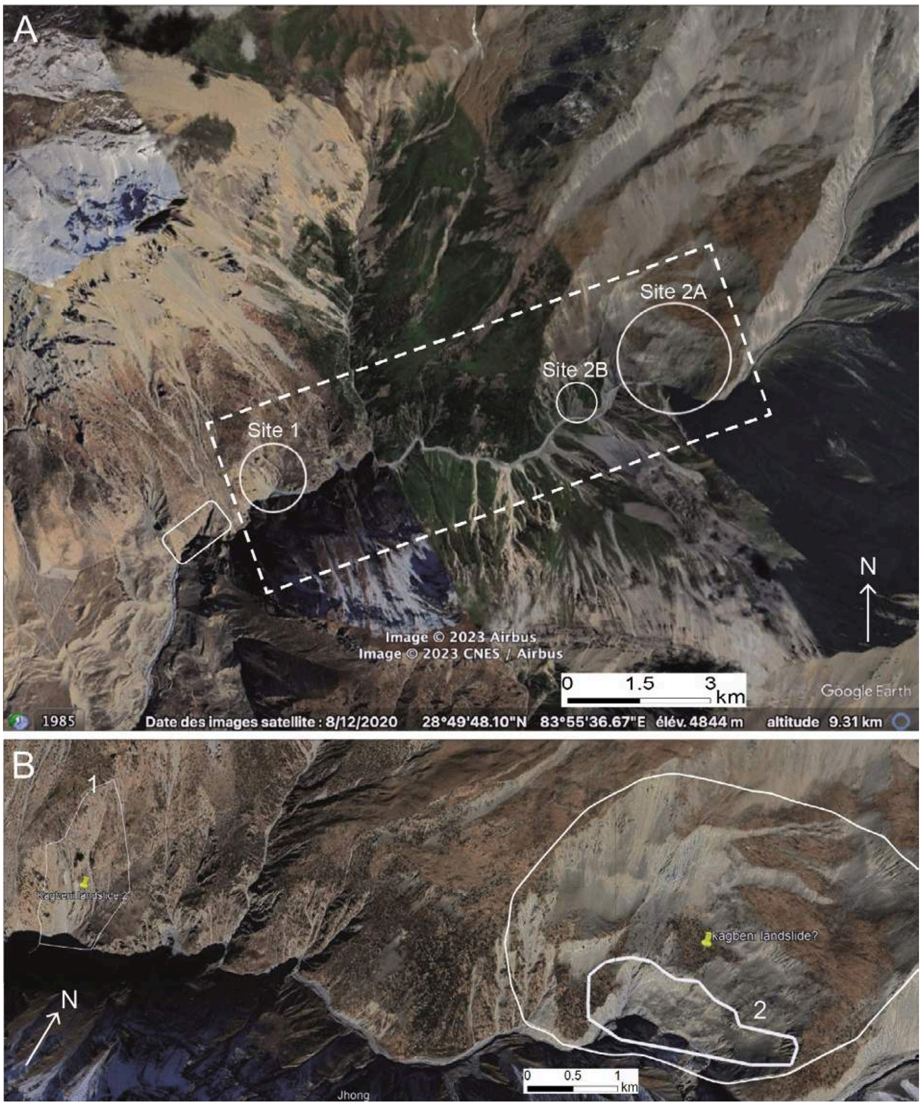



**Fig. 6 – Elements for landslide development in the upper Jhong Khola catchment.** A: satellite Image (2023 CNES Airbus) showing *(i)* the location of the gorges (rectangle) and *(ii)* the sites of potential landslides (circles); after detailed analysis, only Sites 1 and 2 were considered; B: detail of the Sentinel-1 Synthetic Aperture Radar showing the most likely site (2A) for the landslide dam (rotational slides in Thini formation). Location: fig. 2, site 9.

***Fig. 6 – Éléments de développement des glissements de terrain dans le bassin versant supérieur de la Jhong Khola.*** *A : image satellite (2023 CNES Airbus) montrant* (i) *la localisation des gorges (rectangle) et* (ii) *les sites de glissements potentiels (cercles) ; après une analyse détaillée, seuls les sites 1 et 2 ont été pris en compte ; B : détail de l'image radar à synthèse d'ouverture (SAR)Sentinel-1 montrant le site le plus probable (2A) du mouvement de terrain ayant bloqué le torrent (glissements rotationnels dans la formation de Thini). Localisation : fig. 2, site 9.*


**Fig. 7 – Thangarghiu gorge.**

The width of the gorge varies from about 8 to 10 m, and the potential water level reached during the flood was at least +6 meters (photo: Rainer Bell, 2020). Location: fig. 2, site 8.

***Fig. 7 – Gorge de Thangarghiu.***

*La largeur de la gorge varie d'environ 8 à 10 m, et le niveau d'eau potentiel atteint lors de la crue fut au moins de + 6 m (photo : Rainer Bell, 2020). Localisation : fig. 2, site 8.*

### 3.3. Quantifying the hydraulic geometry of the river and sediment volumes

Several methods were employed to measure the width of the riverbed (Yvrard, 2024). The first method involved using a laser rangefinder, measuring the distance from one bank to the other, while simultaneously recording the GPS coordinates of the measurement locations using the OsmAnd application (OpenStreetMap) (tab. 1). The second method utilized a decameter, with the GPS point also recorded on the same application (tab. 1). The third method involved measuring the riverbed width using Google Earth Pro, provided that the images were sufficiently recent (after the August 2023 flood event) and identifiable features, such as rocky outcrops, were visible.

It was not possible to directly measure the average thickness of the deposits everywhere on-site (see tab. 1 and fig. 2). Instead, estimates were made based on photographs taken in the field from elevated alluvial terraces. Additional photographs were captured from the active channel when accessible. Direct measurements were conducted in the village of Kagbeni, beginning at the confluence of the Jhong Khola and the Kali Gandaki, extending up to the road bridge (fig. 2, study sites 1 to 3). Further upstream, measurements were also taken from a broken metal suspension bridge connecting Jharkot and Dzong villages (fig. 2, study site 5), and all the way to the entrance of the Thangarghiu limestone gorges (sometimes referred to as Chhiongur gorges) (fig. 2, from study sites 7 to 8; fig. 7). When it could not be measured, the thickness of flood deposits was estimated based on observations upstream and downstream of a site. We interpreted our estimates based on our experience with riverbed dynamics.

The collected data were entered into a Geographic Information System (GIS) software package (QGIS), which enables comparisons of width based on location within the village. The base maps used varied, with the software providing an option to work with high-resolution Bing Satellite Imagery. However, since this imagery predated the August 2023 flood, Google Earth images were downloaded and georeferenced to allow for a comparison between the years 2022 and 2023, ensuring consistency with the measurements obtained. To estimate the volume of debris transported ($V_{dt}$) from slopes to the valley floor, the following calculation was performed:

$$V_{dt}\,(\text{in m}^3) = W_{ac} \times T_{fd} \times L_{rb} \qquad [1]$$

where $W_{ac}$ represents the active-channel width (in m), $T_{fd}$ denotes the average thickness of the flood deposits (in m), and $L_{rb}$ corresponds to the length of the riverbed (in m).

The volume of the debris fan at the Kali Gandaki junction was measured in two ways: the surface was calculated using post-flood Google Earth images, and the thickness was directly measured in the field (March 2024).

### 3.4. Interviews with local residents

We interviewed 14 residents, 10 in Kagbeni and 4 others in the upstream villages of Jarkhot and Chhyongur (see report in Yvrard, 2024) to find out their perception of the flood and to learn more about the exact damages (see the list of main questions, tab. 2). We also interviewed two members of the Rural Municipality of Varagung Muktichhetra. In addition to interviews, some residents shared photos and videos taken during the event with us, for which we are very grateful.

## 4. Results

Following our observations, measurements and interviews in the field, as well as analysis of rainfall data and satellite images (CHIRPS and InSAR data), we came to the interpretation that this unusual, debris-laden flood was generated by the combination of two potential triggers: (*i*) exceptional rainfall and (*ii*) landslides in the upper Jhong

**Table 1 – Approximate locations of width measurements taken along the Jhong Khola riverbed.**

***Table 1 – Localisation approximative des mesures de largeur faites le long du lit de la Jhong khola.***

| Number | Latitude | Longitude | Widht (m) | Approximate location | Downstream |
|---|---|---|---|---|---|
| 1 | 28.83720 | 83.78190 | 4.83 | | |
| 2 | 28.83721 | 83.78188 | 4.44 | | |
| 3 | 28.83710 | 83.78230 | 9.33 | | |
| 4 | 28.83706 | 83.78248 | 8.53 | | |
| 5 | 28.83722 | 83.78289 | 7.5 | Inside the village (dowstream motorway bridge) | |
| 6 | 28.83728 | 83.78381 | 7.6 | | |
| 7 | 28.83725 | 83.78406 | 8.2 | | |
| 8 | 28.83726 | 83.78470 | 8.48 | | |
| 9 | 28.83728 | 83.78471 | 10.66 | | |
| 10 | 28.83768 | 83.78841 | 25.5 | | |
| 11 | 28.83774 | 83.78871 | 54.3 | | |
| 12 | 28.83738 | 83.78559 | 6.41 | | |
| 13 | 28.83746 | 83.78660 | 18.7 | | |
| 14 | 28.83751 | 83.78727 | 19.8 | | |
| 15 | 28.83618 | 83.79390 | 16.25 | | |
| 16 | 28.83623 | 83.79412 | 23.01 | Upstream Kagbeni (from motorway bridge to old village's ruines) | |
| 17 | 28.83532 | 83.796447 | 11.45 | | |
| 18 | 28.83532 | 83.796447 | 31.65 | | |
| 19 | 28.83497 | 83.79970 | 37 | | |
| 20 | 28.82294 | 83.84999 | 32.7 | | |
| 21 | 28.82340 | 83.85107 | 24.5 | | |
| 22 | 28.82365 | 83.85183 | 23.09 | Broken bridge (Jhong) | |
| 23 | 28.82412 | 83.85468 | 18.25 | | |
| 24 | 28.82412 | 83.85468 | 18.25 | | |
| 25 | 28.82423 | 83.85503 | 21.69 | Between Jhong's bridge and the gorge's upstream section | |
| 26 | 28.82463 | 83.85537 | 23.42 | | |
| 27 | 28.82501 | 83.85660 | 22.46 | | |
| 28 | 28.82466 | 83.85836 | 21.94 | | |
| 29 | 28.82458 | 83.86106 | 16.96 | | |
| 30 | 28.82684 | 83.86902 | 37.13 | | |
| 31 | 28.82853 | 83.87061 | 8 | Gorge's section | |
| 32 | 28.83371 | 83.87744 | 2 | | Upstream |

Khola catchment, upstream from the gorges of the Thangarghiu Khola. Afterwards, we observed the effects of flood propagation from the exit of the gorge to the upstream section of Kagbeni then at the confluence with the Kali Gandaki, before presenting the impacts of the flood in the village of Kagbeni.

### 4.1. Triggers of the flood

#### *4.1.1 Rainfall trigger*

In recent years, all residents interviewed noted a trend towards increased rainfall during the summer-monsoon period, leading to the reactivation of landslides and/or causing flooding. But according to residents the Jhong Khola had never previously burst out of its channelized bed as it did in August 2023.

Daily CHIRPS 3.0 rainfall data from 1st June 2023 – 31 August 2023 (resolution: 5 km) shows the highest rainfall on 20 and 21 August *i.e.* after the flood event (fig. 8A). Rainfall based on the CHIRPS pixel in which the landslide(s) occurred are of a similar order of magnitude to the Jhong Khola catchment mean – sometimes only slightly higher. Cumulative rainfall indicates that landslides might have been triggered in July (16-20) – some weeks before the flood with the possibility of incipient formation of landslide-dammed lake(s). Subsequent rainfall (26 July – 11 August) might have filled the lake and finally a rainstorm on 12 and 13 August most probably triggered the burst out of the landslide(s) dammed lakes, both being at the origin of the sudden, hyper-concentrated flood. A resident from Jharkot described the rains of August 13, 2023 as a huge storm, with curtains of monsoon-like rain, that he had never seen before. However, CHIRPS 3.0 data may not have fully captured this rainfall event. Older CHIRPS 2.0 data also does not show significant rainfall on 13 August 2023. However, it shows more intense rainfall over a longer period, which could better explain the 2023 flood event (fig. 8B). Nevertheless, CHIRPS 3.0 data is more reliable for our study site than CHIRPS 2.0 data when considering annual rainfall from 1981 to 2023. The CHIRPS 3.0 data are within the range of typical annual rainfall totals in this dry area, as confirmed by station data from Jomsom and Ranipauwa-Muktinath. The CHIRPS 2.0 data overestimates annual rainfall totals by up to 100 % (fig. 8C).

#### *4.1.2. Landslides trigger*

According to some shepherds of Dzong and Chhiongur, who take their flocks to graze in the high valley of Thangarghiun, landslides can sometimes develop upstream, as they have experienced it before. Due to the difficult terrain and very bad weather, shepherds advised us not to go there because the path was too dangerous, making it impossible to visit the source area of the potential landslides when in the field (March 2024). This is why the coherence analysis of the Sentinel-1 InSAR images was carried out for the two potential landslide sites 1 and 2 (fig. 6A) for every 12-, 24-, 36- and 48-day SAR image pair acquired during the period May-September 2023. All interferograms that are formed from image pairs spanning the flood event on 13th August have a low coherence at Site 2A (within the white polygon in fig. 6B). This indicates a permanent change to the Earth's surface at this location, *i.e.* failure or erosion of the slope (Burrows et al. 2020; Cabré et al. 2020), making us more confident that this is the upper (eastern) landslide (fig. 6A, 6B,

**Table 2 – Main questions posed to residents and municipal officials during interviews.**

***Table 2 – Principales questions posées aux habitants et aux responsables municipaux lors des entretiens.***

| | |
|---|---|
| 1 | Were you present during the flood ? If yes, what was the sequence of events you observed ? |
| 2 | Do you have any idea of the causes of the flood ? What happened uptstream of Kagbeni ? |
| 3 | Do you have any idea of the origin of the debris, particularly the large boulders, that were transported to Kagbeni ? |
| 4 | What role did the bridges play ? |
| 5 | What was the situation at the confluence of the Jhong Khola and the Kali Gandaki river: was the course of the Kali Gandaki completely blocked during the flood ? |
| 6 | Had an event of similar magnitude ever occurred before ? And if so, did you witness it ? Or did the village elders tell you about it ? |
| 7 | Do you think climate change may have played a role in this event ? |
| 8 | What was the number and nature of buildings and bridges destroyed ? Do you think they could or should be rebuilt ? |
| 9 | Where have people who lost their homes gone ? |
| 10 | Have the villagers received any financial or structural assistance ? If so, where did it come from ? |

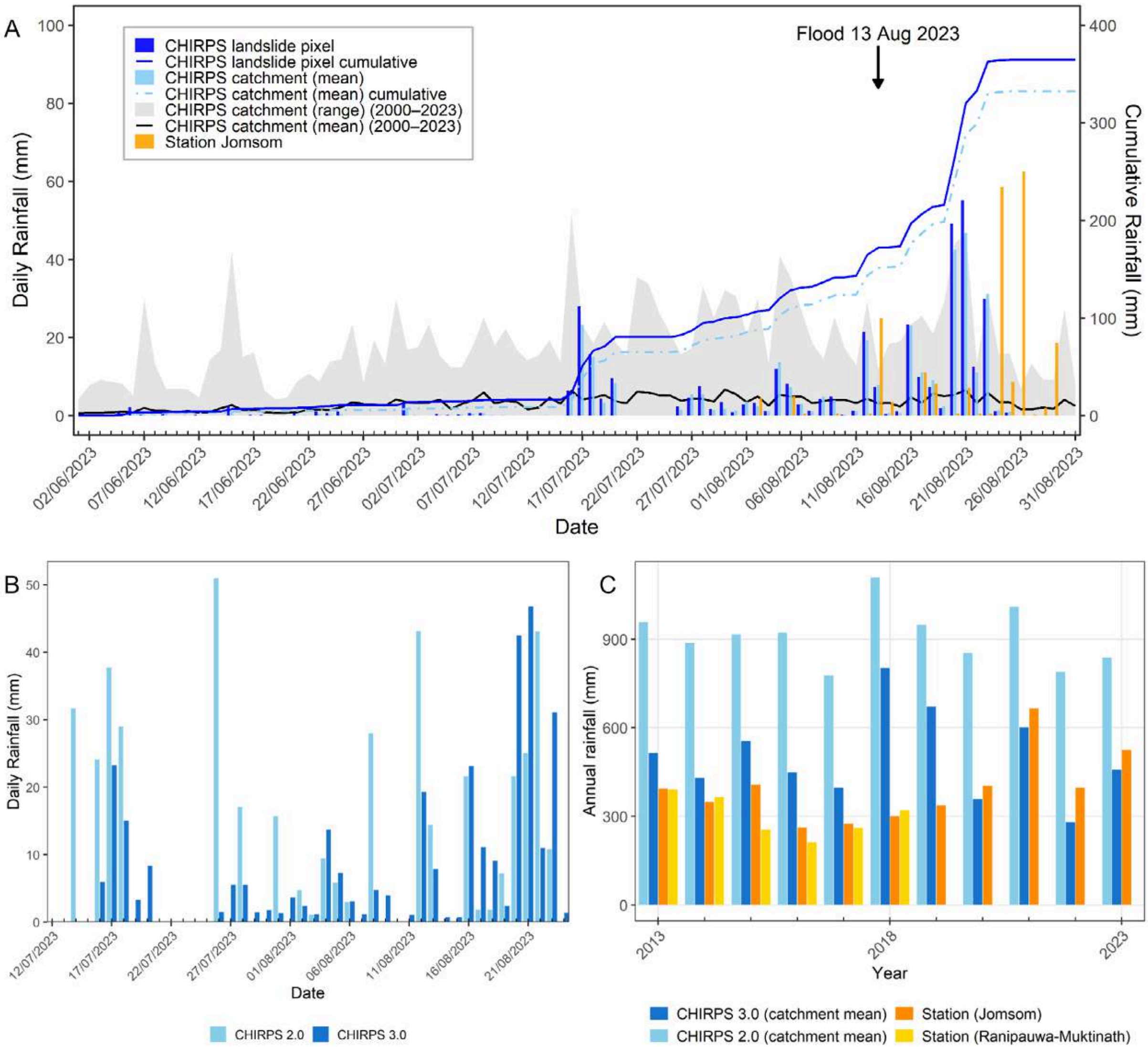



**Fig. 8 – Daily rainfall of June-August 2023 based on CHIRPS 3.0 and 2.0 as well as August 2023 rainfall registered at Jomsom station.** A: CHIRPS 3.0 daily and cumulative rainfall for the CHIRPS pixel including the landslide site as well as for the Jhong Khola catchment. In addition, mean daily rainfall and the range of daily rainfall is shown based on CHIRPS data. Daily rainfall for Jomsom station was only available for August 2023; B: comparison of CHIRPS 3.0 and 2.0 daily rainfall data (12/07-23/08/2023); C: comparison of annual rainfall data using CHIRPS 3.0 and 2.0 as well as station data

Sources: CHIRPS 2.0: http://chg.geog.ucsb.edu/data/chirps, CHIRPS 3.0: https://www.chc.ucsb.edu/data/chirps3, and station data: GoN, Dpt of Hydrology and Meteorology, www.hydrology.gov.np

***Fig. 8 – Pluies journalières de juin-août 2023 calculées avec CHIRPS 3.0 et 2.0, et pluies d'août 2023 enregistrées dans la station de Jomsom (orange).*** *A : précipitations journalières et cumulées CHIRPS 3.0 au niveau du pixel CHIRPS incluant le site du glissement de terrain ainsi que ceux du bassin versant de la Jhong Khola. De plus, les précipitations journalières moyennes et leur variation sont indiquées sur la base des données CHIRPS. Les précipitations journalières de la station de Jomsom n'étaient disponibles que pour le mois d'août 2023 ; B : comparaison des données de précipitations journalières CHIRPS 3.0 et 2.0 (12/07-23/08/2023) ; C : comparaison des données de précipitations annuelles à l'aide de CHIRPS 3.0 et 2.0 ainsi que des données de la station.*

*Sources : CHIRPS : http://chg.geog.ucsb.edu/data/chirps, et GoN, Dpt of Hydrology and Meteorology, www.hydrology.gov.np*

Site 2A) which has failed. The interpretation of this consistently low coherence at site 2A as landslide activity makes sense as the optical image displays a multi rotational-slumped area developed in the shaly Thini Formation (Parsons et al., 2014); this reinforces the possibility of a landslide blocking the valley bottom already in Late July 2023, at < 2.5 km upstream from the Thangarghiu gorges.

#### *4.1.3. Combined triggers of the flood*

From the videos taken by locals, and from discussions we had with them, the August 13 event appears as a sudden flood, with successive waves of hyper concentrated flows, that were triggered by heavy rains. Some people living at Jharkot or Chhiongur also mentioned the occurrence of landslides upstream. We therefore consider that the bursting out of the landslide dam, together with the bottleneck effect of the narrow Thangarghiu gorges (8-10 m width), favoured the rise of the water level upstream of the gorges (fig. 7) and, at the gorge exit, its sudden spread across the whole width of the valley near Chhiongur village (width varying between 35 m and 59 m).

### 4.2. Propagation of the flood downstream to Kagbeni

Downstream of the Thangarghiu gorges, the flood started at around 3:00 p.m., according to a villager from Chhiongur. Field observations, complemented by high-resolution imagery (Google Earth), allowed us to easily identify the passage of the flood thanks to the greyish deposits (either in the riverbed or as high water mud marks on top of preexisting low terraces). The greyish colour is linked to the local dark substrate (the Spiti shales) that provides most of the debris (coarse and fine) carried by the water. These greyish deposits differ markedly from the yellowish Quaternary deposits and light-coloured scree slopes that line much of the valley floor (fig. 9). Along its > 10 km longitudinal profile (downstream from the gorges to Kagbeni), the Jhong Khola eroded banks cut across material of varying resistance (white limestone or dark shaly bedrock, old, indurated, yellowish quaternary material, soft grey scree or alluvial material), so that the riverbed width is variable: narrower (25-30 m) across very localized, in-situ hard bedrock outcrops, and much wider (up to 60 m) where soft deposits outcrop and/or at junction with some rivulets or gullies. In addition, the


**Fig. 9 – Cascading impacts of the flood downstream the Jhong khola.**

From the highest terrace level (> 3100 m) located northwest of Khingar village, an overview of the Jhong Khola in its downstream section before the confluence with the Kali Gandaki (fig. 2, site 4). The river cuts through differentiated substrates: (*i*) bedrock (sandstones in the foreground, black shales in the middle ground, and glacio- and alluvial gravels in the background at Kagbeni), (*ii*) yellowish, slightly indurated Quaternary terrace and lacustrine deposits and (*iii*) slope debris. The light grey color of the valley floor and riverbed gives an idea of the variable height (3 to > 10 m) reached by the muddy flows of the flood in the meanders, splashing higher against vertical concave banks (as shown by white arrows) (photo: M. Fort, March 14, 2024).

***Fig. 9 – Impacts en cascade de la crue dans la partie aval de la Jhong khola.***

*Depuis le bord de la terrasse la plus élevée (> 3100 m) située au nord-ouest du village de Khingar, vue d'ensemble de la Jhong Khola dans sa partie aval avant la confluence avec la Kali Gandaki (fig. 2, site 4). La rivière traverse des substrats différenciés :* (i) *substrat rocheux (grès au premier plan, schistes noirs au milieu de la photo, et terrasses glacio-fluviales en arrière-plan à Kagbeni),* (ii) *dépôts quaternaires jaunâtres légèrement indurés de terrasses et sédiments lacustres, et* (iii) *dépôts de pente. La couleur gris clair du fond de la vallée et du lit de la rivière donne une idée de la hauteur variable (3 à > 10 m) atteinte par les eaux boueuses de la crue dans les méandres, éclaboussant plus haut les berges concaves verticales (flèches blanches) (photo : M. Fort, 14 mars 2024).*

meandering trajectory of the Jhong Khola was the cause of the variable height reached by the muddy, splashy waters, much higher (> 10 m) in the concave, rocky banks than in the convex banks (± 5 m).

*4.2.1. New deposits*

During the 2023 flood, the pre-existing low terraces (+5 m maximum) were overtopped by the muddy flood, and most of them have all been covered by thin veneers (up to 1 m thick) of greyish material. In the absence of pre-existing terraces, new deposits (minimum 3.5 m thick) have also been observed in several places: (*i*) downstream of the destroyed road bridge between Dzong and Chhiongur villages (fig. 10), or (*ii*) around the tilted suspended bridge linking Jarkhot to Dzong; fig. 11), to give a few examples.

More specifically, at the junction of Thangarghiu Khola and Thorung Khola, abundant fan-shaped debris was deposited by the Thangarghiu Khola (whose name becomes Jhong Khola downstream of this confluence), in contrast to the "clean" riverbed of the Thorung Khola. This supports the fact that the flood is only issued from the Thangarghiu Khola and argues even more in favour of the triggering role played by landslide dam outbursts in the development of the Jhong Khola flood, in addition to the rainstorm event.

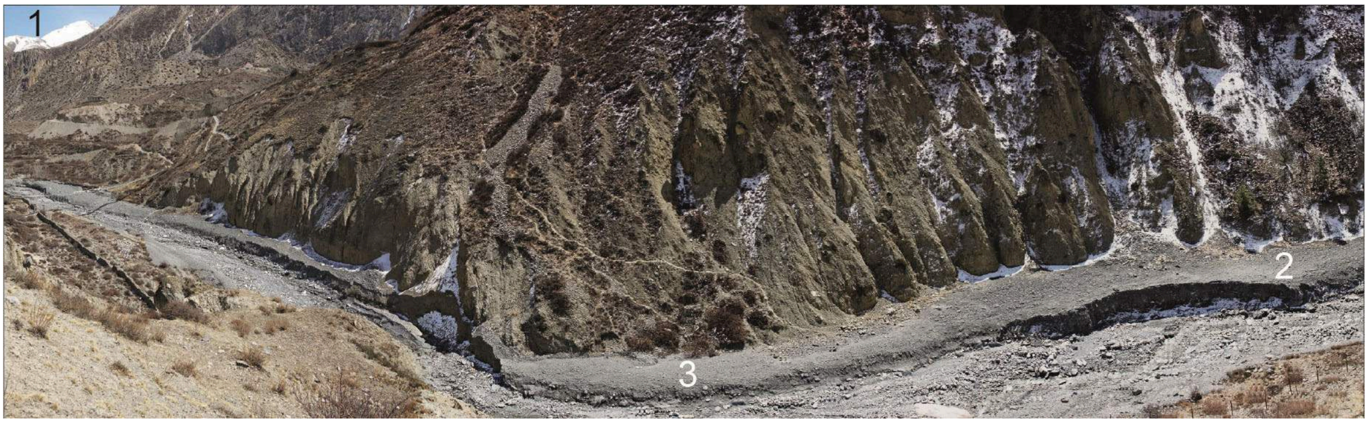



**Fig. 10 – Propagation of the flood downstream of the Thangarghiu gorges (fig. 2, sites 7 to 8).**

The gorges are on the left of the photo (1). Grey areas at the bottom of the valley reflect the increase in water discharge and correspond either to veneers on pre-existing terraces (2) or to new flood deposits (3) (fig. 2, sites 7 à 8). (photos: M. Fort, March 16, 2024).

***Fig. 10 – Propagation de la crue en aval des gorges de la Thangarghiu (fig. 2, sites 7 à 8).***

*Les gorges sont à gauche de la photo (1). Les zones grises au fond de la vallée reflètent l'augmentation du débit d'eau et correspondent soit à des placages sur des terrasses préexistantes (2) soit à de nouveaux dépôts de crue (3) (fig. 2, sites 7 à 8). (photos : M. Fort, 16 mars 2024).*

*4.2.2. Bank erosion and consequences on infrastructures*

At several sites, we observed landslide reactivation due to bank erosion, favoured by narrowing of the riverbed due to contrast in bedrock. Bank erosion was particularly evident along the left bank, along which the large landslide-earthflow complex of Khingar/Jharkot (Fort, 1985; Etzelstorfer, 2020; Goetz et al., 2020; Bell et al., 2021) provides additional fine sediments/mud to downstream flow hence increasing the density of the flow and making the flood even more destructive. Some sites clearly show this reactivation (fig. 12).

Several infrastructures were also affected. The small road bridge linking Dzong to Chhiongur villages was washed away and is still temporary replaced by a basic ford. Further downstream, the trail bridge (35 m long) linking Dzong to Jharkot was tilted; fig. 11B): a new, longer (75 m) and higher (+2 m) bridge was constructed by Kadoorie Agricultural Aid Association and is now operational (May 2025). Further downstream, at Kagbeni's entrance, the bridge deck of the motor road leading to Upper Mustang was washed away, carried downstream, and caused heavy damage to the village (see below 4.4.).

*4.2.3. Debris fan at the Kali Gandaki junction*

Impacts of the flood at the junction between Jhong Khola and Kali Gandaki River were particularly disastrous (fig. 13). Firstly, the debris and mud transported by the flood accumulated in a very large cone, leading to the formation of a temporary (2-3 days) lake developed up to the village of Tiri (2 km upstream). Even though the Kali Gandaki now flows through again, the width of the Kali Gandaki riverbed was still (18 months later) significantly reduced to 7-8 m, about one third of the previous riverbed (fig. 3, fig. 13B). From the situation observed in November 2023 (Google Earth satellite image), the volume of the fan has been estimated to be ≈ 17,000 $m^3$, so that its initial volume brought by the August flood sediments was probably at least ≈ 25,000 $m^3$. Secondly, the Hindu temple (where Hinduist visitors pay tribute to their relatives that have died during the past year) has been washed away; pilgrims now use temporary structures to pray and the temporary lake to perform ablutions (fig. 13B). Last, most trees (willows) along the left bank of the Kali Gandaki have been destroyed: this now endangers the stability of this left bank and, indirectly, threatens the buildings of the oldest, higher part of Kagbeni village.

### 4.3. Quantifying the hydraulic geometry of the river and sediment volumes

It was not always possible to observe the entire length of the Thangarghiu Khola, which becomes the Jhong Khola downstream of its junction with the Thorung Khola. However, we could access several sections (tab. 1): downstream from the gorges (between the


**Fig. 11 – Impacts of the flood across the large earthflow affecting the left bank of the Jhong Khola.** A: general view of the southern flank of the Jhong Khola affected by a large earthflow, with Thorung La (5300 m) in the background. The flood had several impacts on infrastructure and riverbed morphology; B: tilted bridge between Jharkot village (middle ground) and Dzong village (behind the picture); C: the minimum height of water reached during flooding can be identified by *(i)* a veneer of debris-flow facies overlying a pre-existing terrace, and by *(ii)* new deposits (fig. 2, site 5). (photos: M. Fort, March 17, 2024).

***Fig. 11 – Impacts de la crue au niveau de la grande coulée de terre affectant la rive gauche de la Jhong Khola.*** *A : vue générale du flanc sud de la Jhong Khola, affecté par un vaste glissement-coulée, avec le Thorung La (5300 m) en arrière-plan. La crue a eu avec plusieurs impacts sur les infrastructures et sur la morphologie du lit de la rivière ; B : pont basculé entre le village de Jharkot (au centre) et le village de Dzong (derrière l'image) ; C : la hauteur d'eau minimale atteinte pendant la crue peut être identifiée par* (i) *un placage de faciès de coulées de débris recouvrant une terrasse préexistante, et* (ii) *de nouveaux dépôts (fig. 2, site 5). (photos : M. Fort, 17 mars 2024).*

villages of Chhiongur and Dzong) (fig. 2, study sites 7 to 8), near the tilted steel truss bridge linking Jharkot and Dzong villages (fig. 2, study site 5), and around Kagbeni upstream from the road to Mustang down to the Kali Gandaki junction (Yvrard, 2024) (fig. 2, study sites 1 to 3). Additional data were collected from satellite images.

We estimated the landslides volume to be about 84,000 $m^3$. Considering the total length (L) of the Thangarghiu-Jhong Khola to be 15,294 m, with an average channel width (W) of 40 m and a minimum water height (H) of 3 m, we calculated the total volume of sediment transported to be of 647,000 $m^3$. As shown above from some studied sites (sites 3, 5, 6, 7 and 8 of fig. 2), we consider these values as minimum values. After the flood, the Jhong Khola rapidly re-incised across its former deposits, which represents an estimated volume of 215,000 $m^3$. Re-incision was much lower in the


**Fig. 12 – Landslide reactivation (Spiti shales bedrock) due to bank erosion by the flood.**

This landslide (3300 m), located between the villages of Chhiongur (3650 m) and Jarkhot (3550 m) (fig. 2, site 6), developed in the black shale substrate of the Lupra Formation (Parsons et al., 2014) (photo: M. Fort, March 17, 2024).

***Fig. 12 – Réactivation d'un glissement de terrain (schistes de Spiti) due à l'érosion de berges par la crue.***

*Ce glissement (3300 m), situé entre les villages de Chhiongur (3650 m) et de Jarkhot (3550 m) (fig. 2, site 6), s'est développé dans les schistes noirs de la formation de Lupra (Parsons et al., 2014) (photo : M. Fort, 17 mars 2024).*

downstream part of the catchment due to a gentler channel slope and to the volume of debris brought in by the flood so that it was therefore negligible at Kagbeni. In fact, the Kagbeni residents had to dig out and restore the previous Jhong Khola channel, which they could do efficiently thanks to the great support and help they received from the nearby villagers of Varagaon Municipality and others.

### 4.4. Impacts of the flood in the village of Kagbeni

The Jhong Khola started to increase in volume from about 4:00 pm, but the flow was still liquid water; then, suddenly at 7:00 p.m., a flow of mud and debris reached Kagbeni. It developed in several waves, up to nine according to several villagers, and lasted about 2 hours. The channeled Jhong Khola was immediately filled up, so that the flow spread out and rapidly invaded the adjacent areas (fig. 14A), including two streets (one leading from Community building to Korala hotel on the right bank, another one leading to the Yac Donalds hotel on the left bank) (fig. 14B). In fact, most buildings on the left bank of the Jhong Khola were affected, down to the Pilgrims house (close to the Kali Gandaki junction) (fig. 15).

In the following 5 to 10 minutes after the flood reached the village, 29 buildings of varying size were washed away (including hotels, dwellings, communal services, animal shelters, garden sheds, mills...), and other buildings (about 19) were damaged (fig. 14B, fig. 16). The muddy flow invaded ground floors of the houses and quite often their first floor as well, inducing ceiling collapses. Their inhabitants had to live temporarily elsewhere (in houses of relatives or friends, or in emergency shelters). Fortunately, there were no human losses because the residents of Kagbeni had been warned (1 to 3 hours in advance) by their relatives or friends living in the upstream villages (Dzong, Chhiongur, Jarkhot, Muktinath, Khingar) who were able to witness the occurrence of the dark flood rushing downstream. Given a river length of 15 km this would be a flow velocity of 15 km/h (> 4.2 m/s) if prevention time was < 1 h, or 5 km/h (= 1.4 m/s), if prevention time was about 3 hours.

The impacts of the upstream flood were amplified in the village by two important, aggravating factors: the destruction of the road bridge leading to Upper Mustang, and the recent changes in urbanization due to tourism development.

#### *4.4.1. The road bridge*

The muddy hyper-concentrated flow of the Jhong Khola (riverbed width: 54.3 m) was blocked by the narrow road bridge and its pillars (25.5 m), located upstream of the Kagbeni village. Additional jams across the bridge were caused by uprooted trees planted upstream of the bridge along small irrigation canals on both sides of the riverbed. Both caused a bottleneck effect: with the abrupt reduction of its section, the flow was forced to pass over and around the bridge deck, progressing in several waves, and flooding both banks of the Jhong Khola in the village, with its trajectory partly controlled by irrigation canals. The areas between the road bridge and the entrance bridge into the old city were devasted by a 1.5 m to > 2.5 m thick hyper-concentrated flow deposited over the ground floor of houses (fig. 14, 16), as observed and confirmed by the residents, like the owners of hotels on the left bank.

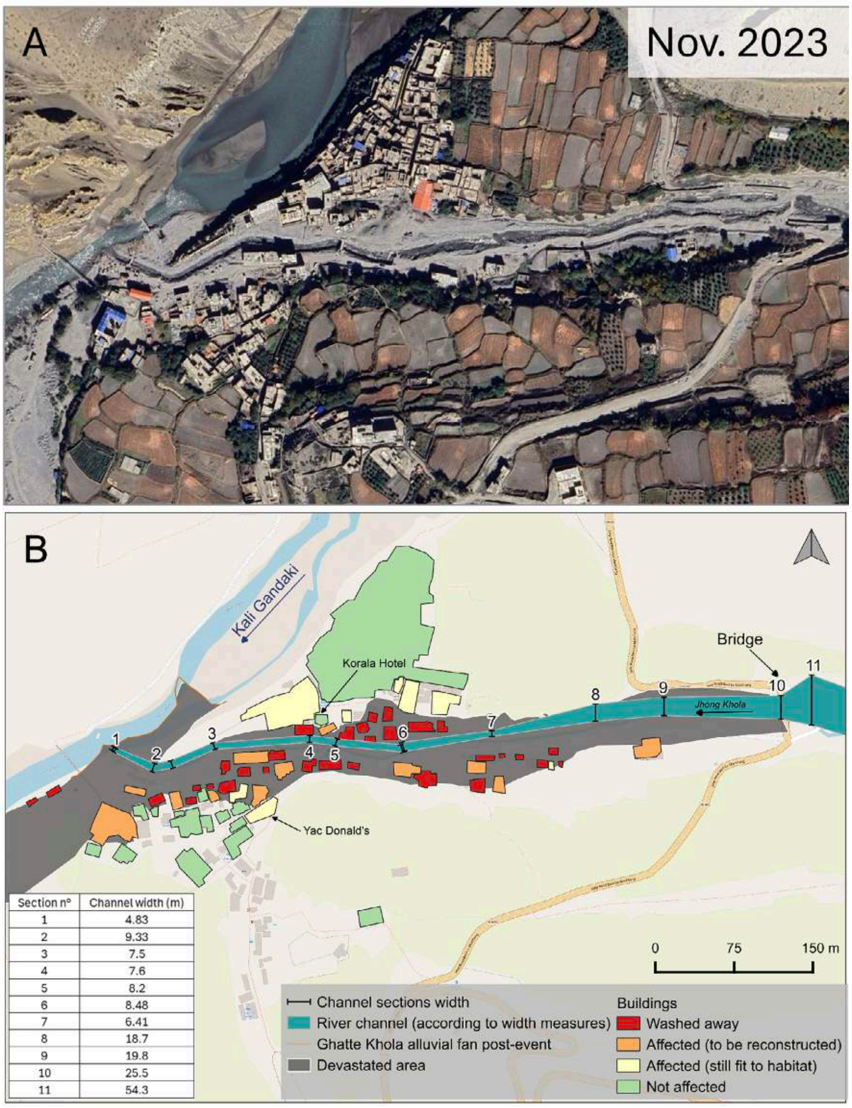
The collapse of the bridge's concrete deck was an aggravating factor (Section 10, fig. 14B). The increased volume and density of the water caused the deck to detach from its pillars, and it was swept away by the muddy flood downstream. Its zigzagging trajectory, from one bank to the other, was very destructive and explains the loss of so many buildings and various shelters, as well as 6 smaller bridges, trees and gardens, on both banks of the village (fig. 16). Cattle and vehicles were also washed away. Most of the houses closest to the riverbanks were destroyed, after having partially protected other houses located behind them: the Grand Hotel, or the private home of the Shangri-La Hotel owner. Although impacted, these two houses were later repaired (see below). Another older, narrower, motor bridge linking the left bank to the Red House (fig. 16) then to the old village (Section 6, fig. 14B) was also washed away: its deck was dragged down to the level of the Buddhist monastery and amplified the destruction on both banks caused by the deck of the major bridge.


**Fig. 13 – Kagbeni village and its confluence with the Kali Gandaki, view after the flood.** A: general northward view (from a left bank terrace) of the village, with the motor road going up to upper Mustang, and the Jhong Khola (noticeable with its light grey color) crossing the village (fig. 2, site 3). The Kali Gandaki River flows between the village and its cultivated land (foreground) and the rocky hillslope cut into the Mesozoic Chukh Formation (background on the left); B: remnants of the flood fan of the Jhong Khola and the still flat inundated riverbed of the Kali Gandaki (active riverbed width: 70 m in the foreground, 7-8 m in the middle ground), with the Nilgiri North peak (7061 m) in the background (fig. 2, site 1); C: the junction fan deposited during the 2023 flood event is now partly eroded, as observed from the right bank of the Kali Gandaki towards East (fig. 2, site 2). (photos: M. Fort, March 12, 2024).

***Fig. 13 – Village de Kagbeni et son confluent avec la Kali Gandaki, vue après la crue.*** *A : vue générale du village vers le nord (depuis une basse terrasse de rive gauche), avec la route qui monte vers le Haut Mustang, et la Jhong Khola (repérable par la couleur gris clair) qui traverse le village après l'inondation (Fig. 2, site 3). La rivière Kali Gandaki coule juste entre le village et ses terres cultivées (premier plan) et le versant rocheux taillé dans la formation mésozoïque de Chukh (arrière-plan à gauche) ; B : restes du cône de déjection de la crue de la Jhong Khola, avec le lit encore inondé de la Kali Gandaki (largeur du lit actif : 70 m au premier plan, 7-8 m au second plan), avec le pic Nilgiri Nord (7061 m) en arrière-plan (fig. 2, site 3) ; C : le cône de confluence formé lors de la crue de 2023 est maintenant en partie érodé, comme on l'observe depuis la rive droite de la Kali Gandaki (vue vers l'est) (fig. 2, site 2). (photos : M. Fort, 12 mars 2024).*

### *4.4.2. Canalized Jhong Khola across Kagbeni*

Changes in width of sections of the Jhong Khola (table of fig. 14B) amplified the damage in the village. Before the 1970's, the left bank of the river and lower terraces were only cultivated lands or meadows, while the traditional village was built on the right bank terrace ≈ 10 m higher than the present riverbed around the Buddhist monastery (5 centuries old, the second oldest of the Mustang district) and its prayer walls. But the opening of the Annapurna trekking Tour in 1977 has stimulated the building of lodges in Kagbeni along the unoccupied left bank of the Jhong Khola and, indirectly, their progressive development closer to the attractive riverside. Therefore, the section widths of the Jhong Khola were progressively reduced and canalized (width varying from ≈ 10 m to < 5 m): they are now nearly 6 times less compared to their




| Section n° | Channel width (m) |
|---|---|
| 1 | 4.83 |
| 2 | 9.33 |
| 3 | 7.5 |
| 4 | 7.6 |
| 5 | 8.2 |
| 6 | 8.48 |
| 7 | 6.41 |
| 8 | 18.7 |
| 9 | 19.8 |
| 10 | 25.5 |
| 11 | 54.3 |

**Fig. 14 – Impacts of the flood in the village of Kagbeni.** A: Google Earth Image (November 2023) showing all the flooded areas (in grey); B: map showing the devastated areas by the flood and the different degree of damage on the buildings; the table (left) confirms the drastic reduction in the width of the Jhong Khola canal in the village, downstream of the upper Mustang Road bridge (data collected and map drawn by P. Yvrard, 2024).

***Fig. 14 – Impacts de l'inondation dans le village de Kagbeni.*** *A : Image Google Earth (novembre 2023), montrant toutes les zones inondées (en gris) ; B : carte montrant les zones dévastées par l'inondation et les différents niveaux de dégâts ayant affecté les bâtiments ; le tableau (à gauche) confirme la réduction drastique de la largeur du chenal de la Jhong Khola dans le village, en aval du pont supérieur de la route du Haut Mustang (données collectées et carte dessinée par P. Yvrard, 2024).*


**Fig. 15 – Impacts of the Jhong khola flood at the junction with the Kali Gandaki.**

View taken the day after the flood, from the right bank terrace (+5 m) of the Jhong Khola, near the prayers wall leading to the Buddhist Monastery. Debris carried by the flood invaded the ground floor of the Pilgrims Hostel and impacted the first floor. The width of the Kali Gandaki was reduced, while the suspension bridge was severely damaged. It has since been repaired by Kadoorie AAA (photo: N. Gurung, August 14, 2023).

***Fig. 15 – Impacts de l'inondation de la Jhong Khola à la confluence avec la Kali Gandaki.***

*Vue prise le lendemain de l'inondation, depuis la terrasse de la rive droite (+5 m) de la Jhong Khola, près du mur de prières menant au monastère bouddhiste. Les débris charriés par l'inondation ont envahi le rez-de-chaussée de l'auberge des pèlerins et ont endommagé le premier étage. La largeur de la Kali Gandaki a été réduite, tandis que le pont suspendu a été gravement endommagé. Il a depuis été réparé par Kadoorie AAA (photo : N. Gurung, 14 août 2023).*

initial natural width (tab. 1), as observed upstream from the road bridge and on the 1970 Corona satellite images (see below the discussion).

As mentioned above, the canal was entirely filled with debris and mud, so that the flow invaded easily the adjacent areas. The case of the Johnny Cash Hotel and Restaurant is particularly illustrative as it was built very close to the channelized riverbed, and the flood reached the 2nd floor of the building. The next morning (Aug. 14, 2023), the Jhong Khola channel was still not visible (fig. 17A), as the whole area was buried by flood debris of various sizes, including large blocks (> 1 $m^3$) and dark mud (provided by the Spiti shales eroded from upstream). A few days after the flood, the Jhong Khola channel was cleaned off by locals,


**Fig. 16 – Impacts of the flood in Kagbeni.**

View taken from the left bank terrace (+10 m) of the Jhong Khola, the next day after the flood (between sections 5 and 6, fig. 14B). The channel of the river is totally invisible: mud and coarse debris are spread over the former active flood plain. The lower floor of the community building has been very impacted as part of the flow passed by behind the trees. Further downstream, two buildings (with stars) have been destroyed, yet their position protected the houses situated behind them, which could be repaired: their owners are now living here again. The pilar of an old bridge (white arrow) is still present (photo: N. Gurung, August 14, 2023).

***Fig. 16 – Impacts de la crue à Kagbeni.***

*Vue prise depuis la terrasse de rive gauche (+10 m) de la Jhong Khola, le lendemain de la crue (entre les sections 5 et 6, fig. 14B). Le chenal de la rivière torrentielle est totalement invisible : de la boue et des débris grossiers ont recouvert toute l'ancienne plaine d'inondation active. L'étage inférieur du bâtiment communautaire a été très affecté, une partie du flot boueux étant passé derrière les arbres. Plus en aval, deux bâtiments (avec des étoiles) ont été détruits, mais leur position a protégé les maisons situées derrière eux, qui ont pu être réparées : leurs propriétaires y vivent à nouveau. Le pilier d'un ancien pont (flèche blanche) est encore présent (photo : N. Gurung, 14 août 2023).*

retaining the same cross-section as before the flood (fig. 17B). It took more than a year to restore and reopen the Hotel-restaurant (fig. 18), even though it still overlooks the channel directly, with its foundations placed right in the riverbed, exactly as it was before the flood.

Close to the Johnny Cash Hotel, the less affected Lhasa hotel (left) was more rapidly repaired (in a few months; fig. 18A, B). Meanwhile, in March 2025, another building totally washed away in 2023 is being rebuilt in the same location, just in front of Lhasa hotel (fig. 18C).

## 5. Discussion: How to manage disaster risk?

The Kagbeni flood is one of many examples illustrating how current global warming is affecting geomorphological and sedimentary processes in the entire Himalayan Range and generating more natural hazards. These processes often interact and develop as cascading hazards when progressing downstream due to local extreme topographic gradients and to alternating morphologies of river valley bottoms (deep, steep gorges vs. wider, flatter areas) in relation to bedrock contrasts. Heavy rainfall over a short period and flash-flood-like disasters are becoming a real trend in the mountain regions in Nepal, on both the monsoon and rain-shadow sides of the Higher Range (Krishnan et al., 2019).

### 5.1. Rainfall data recording

In the rain-shadow zone of Mustang, former studies have shown that there is a slight increase in temperature, creating periods of droughts and disruptions in precipitation patterns (Bhadra et al., 2021; Meier et al., 2022). In addition, the strong northerly winds blowing up the Kali Gandaki valley favor the expansion of moist monsoon air masses on the northern slopes of the Himalayas, so that rainfall is gradually taking the place of snowfall. Furthermore, this "rain-shadow" zone over Mustang is particularly sensitive to the warming climate because of its substrate (large areas underlain by Spiti shales), so that heavy rainfall has an immediate impact, firstly because there is little soil and nearly no vegetation to absorb this unusual influx of water and, secondly, because drought favors desiccation cracks and thus water penetration at depth, a major factor for triggering landslides. Consequently, we consider that the gradual rise in temperatures over the last few decades and the resulting change in the nature and intensity of precipitation could be the source of both intense rainfall and landslide-dam failures at the origin of the Kagbeni 2023 flood.

The study region was much wetter in 2018 than in 2023 (fig. 4). Geomorphic processes triggered in 2018 are described in Bell et al. (2021). We therefore examined the rainfall in the Jhong Khola catchment from June to August in 2018 using CHIRPS 3.0 data. This shows that, during the monsoon months, about twice as much rain fell in 2018 (700 mm) than in 2023 (350 mm), with much more intense periods of rainfall in 2018 (fig. 19). Given the giant landslide complex in Thangargiu Khola, reactivation was more likely in 2018 than in 2023, yet nothing similar to what happened in 2023 occurred.

Since landslides can be triggered by extreme rainfall events, it is possible that the CHIRPS data did not capture the extreme rainfall that triggered either the landslide or the landslide lake outburst flood. Statements by local inhabitants regarding the rainfall on 13 August 2023 may provide insight into whether CHIRPS underestimated the rainfall, particularly on that day. However, it is highly likely that a landslide or progressive landsliding was triggered in July 2023. There may have been important internal processes within the slope, making it increasingly unstable over time, so that smaller rainfalls could trigger the initial landslide(s), whereas much stronger previous rainfalls were unable to do so. Subsequent rainfall filled the lake until the water level exceeded the height of the dam, causing the outburst flood.

The slope may have returned to a more stable phase; consequently,


**Fig. 17 – Impacts of the flood near the Johnny Cash hotel and restaurant, eastward and upstream view from the right bank.** A: the situation the morning after the flood shows how the volume of debris has totally filled up the Jhong Khola channel and favored the flood spreading in adjacent street (see arrow behind the restaurant). The size of transported debris and blocks confirms the high density of the flow, and mud marks indicate the level reached by the flows (photo: Tenzin Dhoka Gurung, Aug. 14, 2023); B: some months later, the situation appears "normal": the channelized Jhong Khola is visible again with its former cross section, part of the excavated debris has been deposited to re-create a lower terrace again, but the restaurant was still under repair (photo: P. Yvrard, March 12, 2024).

***Fig. 17 – Impacts de l'inondation près de l'hôtel-restaurant Johnny Cash, vue vers l'est et l'amont depuis la rive droite.*** *A : la situation le lendemain matin de l'inondation montre comment le volume de débris a totalement rempli le canal de la Jhong Khola et favorisé la propagation de la crue dans la rue adjacente (voir la flèche derrière le restaurant). La taille des débris et des blocs transportés confirme la forte densité de l'écoulement, et les placages de boue matérialisent le niveau atteint par les écoulements (Photo : Tenzin Dhoka Gurung, 14 août 2023) ; B : quelques mois plus tard, la situation semble « normale » : la Jhong Khola canalisée est à nouveau visible avec son ancienne section transversale, une partie des débris dégagés ont été étalés pour recréer une terrasse inférieure, mais le restaurant était toujours en réparation (photo : P. Yvrard, 12 mars 2024).*

stronger post-event rainfall did not trigger new landslides. Clearly, the post-event rainfall itself, without the landslide-dammed lake and subsequent outburst flood, was not sufficient to trigger a significant flood.

However, while there is a clear link between climate change and the triggering of natural hazards, human activities, like the expansion of settlements and infrastructures in exposed and potentially dangerous places, should now be directly questioned, so that the right mitigation measures can be taken to avoid more disasters.

### 5.2. How to control and/or avoid floods?

#### *5.2.1. Perception of local people*

According to some interviews of Kagbeni villagers, their elders have not seen flood of this magnitude in the last 100 years, and if large floods (filling all the canal, but without overflowing) have happened before, they are rare. This is why they consider the Aug. 13, 2023, flood as an exceptional one, which will not happen again soon. For them, people build along the river because it is attractive: it is a place of passage for pilgrims and tourists, ideal for business. They are not conscious of future likelihood of disasters, and so are not considering moving away, even if they live in vulnerable areas. For instance, the owner of the New Tibet Guest House, located on the lower left bank of the village (100 m upstream the Pilgrims Hostel), on the edge of the convex fan slope, has no plans to move, even though the site she occupies has become more dangerous. Before the flood, the riverbed was about 5-6 meters deeper, and so the New Tibet Guest House was higher than the river level, whereas today the Guest House is at about the same level as the river with the current embankments, due to the deposition of new sediments during the 2023 flood (the Kali Gandaki junction is only 130 m away; fig. 15).

However, some residents are conscious that the orientation of recent buildings vs. the flow direction may either amplify the damage (if perpendicular) or reduce them (if parallel). Some of them also consider that the trees should not be replanted because they represent a danger during such events, as they prevent the "peaceful" flow of the watercourse. But they have no knowledge of the natural behavior of a torrential river like the Jhong Khola, and of its functional space.

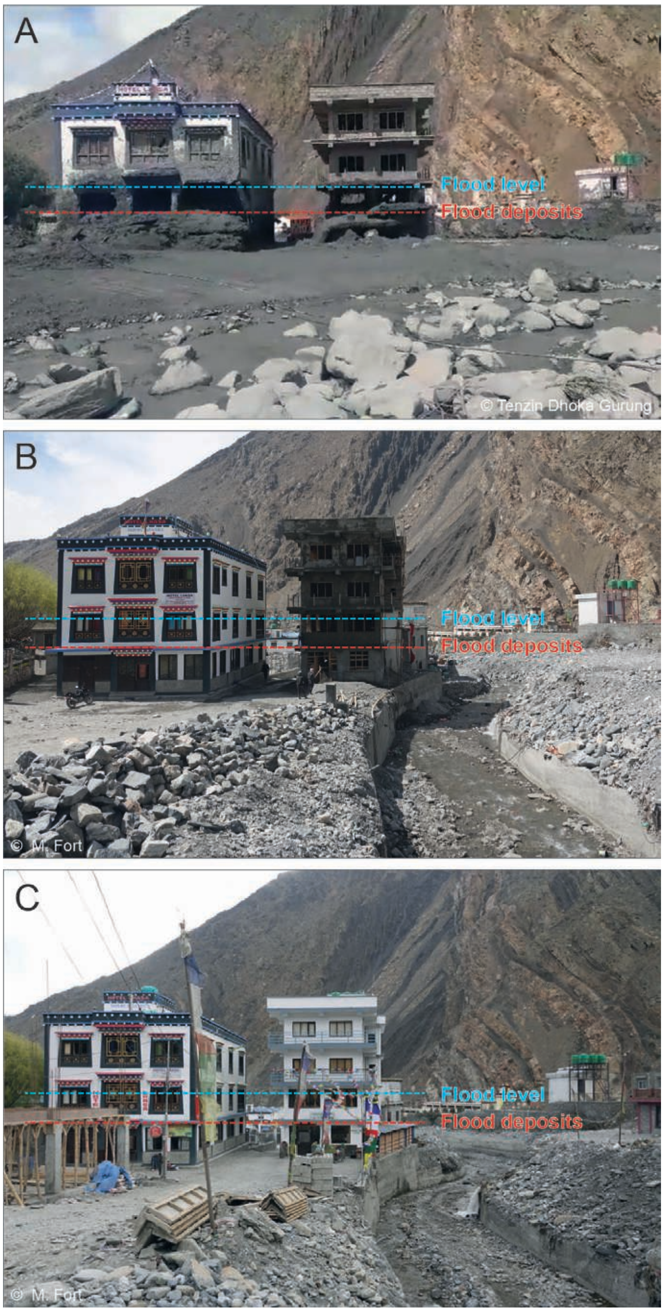



**Fig. 18 – Post flood repair and reconstruction in Kagbeni village.** A: the Lhasa Hotel and Johnny Cash Hotel and Restaurant, the next morning after the flood, without any Jhong Khola channel (photo: Tenzin Dhoka Gurung, Aug. 14, 2023); B: same view six months later, with the channelized riverbanks of Jhong Khola (discharge < 1 $m^3$/s), and part of dug out debris remaining on both sides (photo: M. Fort, March 9, 2024); C: the Johnny Cash Hotel and Restaurant is re-opened, whereas a new building (washed away in August 2023) is under re-construction in front of the Lhasa Hotel (photo: M. Fort, March 13, 2025).

***Fig. 18 – Réparation et reconstruction après l'inondation dans le village de Kagbeni.*** *A : l'hôtel Lhasa et l'hôtel-restaurant Johnny Cash, le lendemain matin de l'inondation, sans le canal de la Jhong Khola (photo : Tenzin Dhoka Gurung, 14 août 2023) ; B : même vue six mois plus tard, avec les berges canalisées de la Jhong Khola (débit < 1 $m^3$/s), et une partie des débris enlevés restant sur les bords (photo : M. Fort, 9 mars 2024) ; C : l'hôtel-restaurant Johnny Cash est rouvert, tandis qu'un nouveau bâtiment (emporté par les eaux en Août 2023) est en cours de reconstruction devant l'hôtel Lhasa (photo : M. Fort, 13 mars 2025).*

#### *5.2.2. Application of the "functional space of a river" concept*

The concept of « river functional flooding space » or « freedom space » (Malavoi et al., 1998; Arnaud-Fassetta et al., 2009; Biron et al., 2014) should be applied to manage this flood risk sustainably, as suggested by the comparison of the Jhong Khola floodway in 1970, 2018 and 2023 satellite images (fig. 20). But this concept is unknown in Nepal and has only been referred to occasionally for two case studies (Gurung et al., 2020; Gurung et al., 2021).

In 1970 (fig. 20A), the active channel of the Jhong Khola was wide (> 50 m), similar to the width of the 2023 flood observed upstream of the road in 2018 and 2023. In 1970, the Jhong Khola could change its course within its own floodway from year to year: there was no obstacle and bank erosion was a possible way of adjustment. The opening of Upper Mustang to foreigners has changed the situation, first in 1977 when the Annapurna Tour was launched, then in Autumn 1992 when Upper Mustang, the famous "lost Tibetan Kingdom" (Peissel, 1968) could be visited. Kagbeni became a mandatory overnight stop, and lodges and restaurants started to develop further because the prestigious Dhaulagiri peak (8167 m) could be observed very nearby from the Kali Gandaki riverside and its terraces. Hinduist pilgrims also took advantage of this development. This is why, in the absence of damaging flood, hotels were progressively built on the lower "terraces" (in fact formerly deposited during high floods) (fig. 20B). However, everything has changed following the 2023 flood (fig. 20C): the Jhong Khola suddenly expanded its course and reoccupied its former active channel as it was in 1970. This argues in favor of the practical application of the "functional space" concept, and indirectly suggests the need for relocation of inhabitants.

The Rural Municipality of Varagaun was asked to widen the river, in agreement with some residents, by 3 meters on each side; but 18 months after the flood, it does not seem to be done. In fact, the Rural Municipality cannot ask residents to move, due to a real problem in the distribution of titles of property by the federal government. If a Nepali citizen does not own land, he/she may be given a piece of land by the government. In contrast, the landowners who have money are buying more and more along the most vulnerable river side, as one of them said "I need my land". According to R.N. Gurung (chairman of the Rural Municipality), the Municipality has no right to force residents to leave their land, because it is beyond their jurisdiction. They can only recommend against building anything permanent on land near the river, leaving the decision up to each individual.

In fact, as mentioned above, most residents will not accept relocation. Some of them have already started rebuilding houses damaged by 2023 flood (fig. 18C) and continue to live in the potentially threatened zone, in the planned "freedom space" of the river (fig. 20C), even though the local government will not provide them any financial assistance. Changing national/regional regulations and laws would be essential to adapt to climate change and ensure sustainable and resilient development.

### 5.3. How best to design the bridge?

Eighteen months after the flood, the motor road bridge of the Kali Gandaki corridor (BRI) is still not rebuilt, and vehicles cross the river directly, which is quite easy when the flow is low (most of the year).

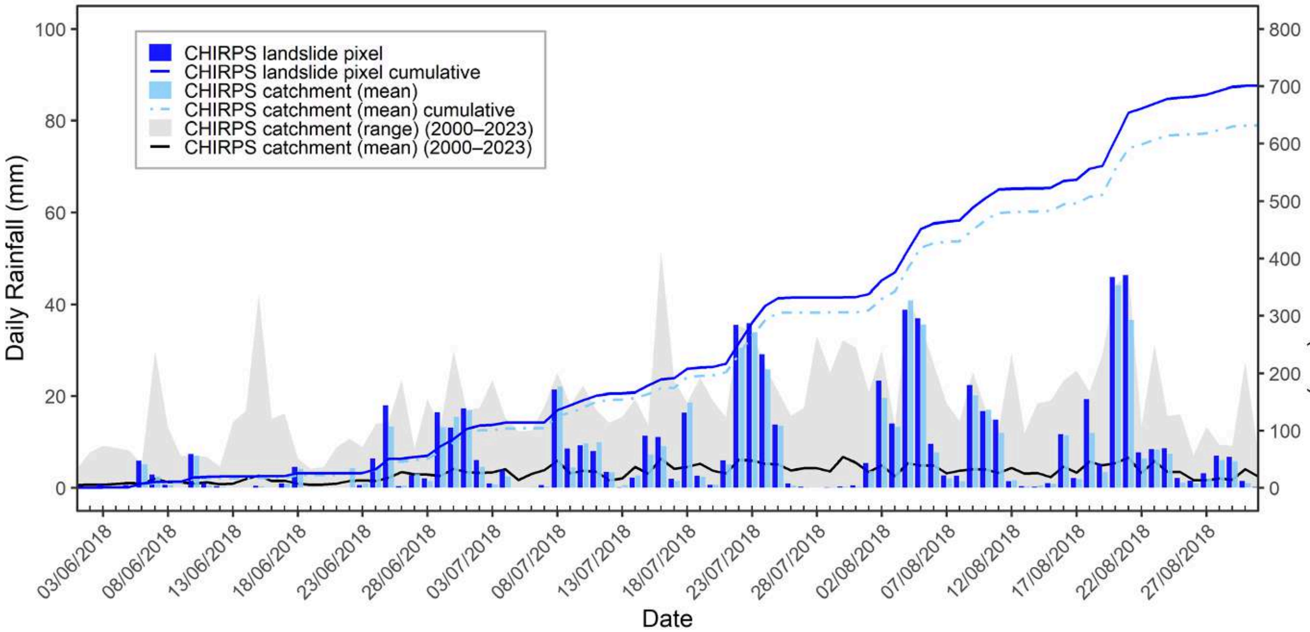



**Fig. 19 – Daily rainfall of June-August 2018 based on CHIRPS 3.0 data.**

CHIRPS 3.0 daily and cumulative rainfall for the CHIRPS pixel including the landslide site of 2023 as well as for the Jhong Khola catchment. In addition, mean daily rainfall and the range of daily rainfall (2000-2023) is shown based on CHIRPS data. Sources: CHIRPS 3.0: https://www.chc.ucsb.edu/data/chirps3

***Fig. 19 – Précipitations journalières de juin à août 2018 d'après les données CHIRPS 3.0.***

*Précipitations quotidiennes et cumulées CHIRPS 3.0 pour le pixel CHIRPS incluant le site du glissement de terrain de 2023 ainsi que pour le bassin versant de la Jhong Khola. De plus, les précipitations quotidiennes moyennes et l'ampleur de la variabilité des précipitations journalières (2000-2023) sont indiquées sur la base des données CHIRPS. Sources: CHIRPS 3.0:* https://www.chc.ucsb.edu/data/chirps3

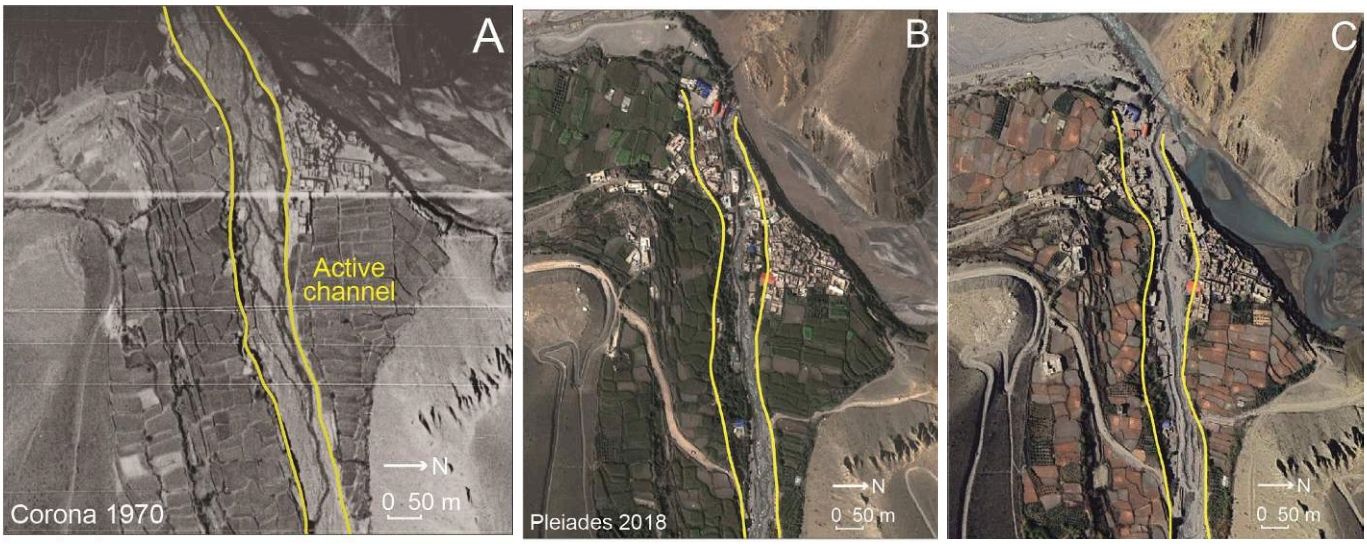



**Fig. 20. Evolution (1970-2023) of the active floodplain of the Jhong Khola across Kagbeni.** A: the traditional Kagbeni village is only developed on the nortern edge of the junction with the Kali Gandaki: in 1970, the Jhong Khola has an active flood plain (outlined by yellow lines), with intermittent flows and transient gravel bars, all bounded by cultivated, lower terraces (source: Corona satellite images, Center for Advanced Spatial Technologies, University of Arkansas/U.S. Geological Survey); B: nearly fifty years later, the village has expanded mostly along the left bank of the Jhong Khola (source Pleiades), largely encroaching on the former active floodplain, especially close to the Kali Gandaki River junction where the dry road coming from the south ends (source: Pleiades satellite imagery, 2018); C: taken 3 months after the flood, this image clearly shows that during the flood the Jhong Khola reoccupied its natural, functional flooding space (source: Google Earth, Nov. 2023).

***Fig. 20 – Évolution (1970-2023) de la plaine d'inondation active de la Jhong Khola à travers Kagbeni.*** *A : le village de Kagbeni traditionnel n'est développé que sur la partie nord de la confluence avec la Kali Gandaki : en 1970, la Jhong Khola a une plaine d'inondation active (délimitée par les lignes jaunes), avec des écoulements intermittents et des bancs de galets mobiless, le tout étant bordé par des basses terrasses cultivées (source : Corona satellite images, Center for Advanced Spatial Technologies, University of Arkansas/U.S. Geological Survey) ; B : près de cinquante ans plus tard, le village s'est étendu principalement le long de sa rive gauche (source : Pléiades), avec des bancs de gravier transitoires : Près de cinquante ans plus tard, le village s'est étendu principalement le long de sa rive gauche, empiétant largement sur son ancienne plaine d'inondation active, en particulier près de la jonction de la rivière Kali Gandaki, où se termine la route non goudronnée en provenance du sud (source : images satellite Pleiades, 2018) ; C : prise 3 mois après l'inondation, cette image montre clairement que lors de sa crue, la Jhong Khola a réoccupé son espace naturel et fonctionnel en cas de hautes eaux (source : Google Earth, Nov. 2023).*

The decision to rebuild the bridge has not been taken yet: it is a federal project, financed by the Nepal Government and by China.

Two points must be considered: (*i*) The destroyed bridge was 25 m long, whereas the riverbed was almost 55 m wide further upstream (fig. 14B): this means that if the bridge were to be rebuilt, it would have to be twice as long to allow the passage of a future flood without its deck being washed away again. (*ii*) At the site of the bridge, the banks of the Jhong Khola are carved out of loose alluvial material, so we can imagine the technical and financial constraints that this may pose for the re-construction of a sustainable bridge.

And so, the question arises as to whether to rebuild a bridge or build a ford (Gurung et al., 2020)? Given the cost of a bridge, and the low flow of the Jhong Khola most of the year, a concrete ford would probably be a better solution, with two options: either a ford with a concrete road surface (the simplest one), or a concrete ford with culverts (to evacuate increased flow during snowmelt period or after a rainy spell). In both cases, the ford would have to be cleaned off after a flood event.

## 6. Conclusions

The possibility of flash floods reoccurring at Kagbeni in the future remains high, given the effect and evolution of climate change in a catchment with fragile geology, and the ongoing anthropogenic activities (tourism and agriculture). In this study, we have observed natural processes and their cascading effects (substrate erosion and debris deposition) and their impacts all along this deeply entrenched, meandering river, which have damaged homes and infra-structure (roads, bridges) located > 10 km downstream.

Furthermore, this example of a landslide-flood event whose origin is in a remote, upper valley highlights the utility of applying new independent techniques (CHIRPS rainfall data and InSAR data) in studying hazard triggers and their cascade events, particularly those that occur during the monsoon season when multi-spectral satellite images are often obscured by cloud cover and involve landslide activity in inaccessible parts of the landscape.

More generally, the 2023 Kagbeni flood illustrates well the fact that climate change can no longer be denied, particularly in the dry, northern Himalaya. This flood shows that the « rain shadow » effect is progressively disappearing along these N/S oriented river valleys like the Kali Gandaki, allowing extensive penetration of moisture north of the orogen, so that rainfall becomes more frequent, while snowfall less so. Geomorphologically, these short-lived events exert a decisive control over slope dynamics and sediment transport processes, resulting in disastrous impacts on inhabited areas located quite far downstream, with no real possibility of forecasting for the inhabitants.

Another point worth mentioning is the quality of communication we (as scientists) had with residents (including hotel managers and owners) and representatives of the Rural Municipality of Varagaon, which was very fruitful. This communication should be extended to engineers, stakeholders and politicians, to help them better understand the impacts of flood chain-reactions and make the right decisions.

For example, some specific actions would be highly recommended. (*i*) In view of climate change, the number of high-altitude weather stations should be increased, and these must properly be maintained to get continuous rainfall monitoring. (*ii*) Setting up flood monitoring would also be a positive step, providing a better understanding of the evolution over time of discharge fluctuations of the Jhong Khola. (*iii*) Another priority would be to develop the concept of Functional Space of a river: a real tool for reducing and managing flood risk. This means delimiting and maintaining the natural "freedom space" of rivers and streams and keeping them free of construction. It also means reconsidering the way sustainable bridges and infrastructures must be designed, a real challenge for Nepal's development.

In other words, anticipating and preparing for future disasters is always a better option than responding and repairing the damage once the disaster has occurred. This is certainly the strategy that should be adopted by the National Platform for Disaster Risk Reduction (NPDRR) of Nepal.

## Acknowledgements

This study was carried out without any funding, as part of a Master1 thesis by one of the co-authors. We would like to extend our warmest thanks to all residents who kindly gave us their time during the interviews, especially Rabindra Bhujet (manager of The Red House), Chhinphura and Yangmento Gurung (owner of the badly affected Blue House, right bank of Jhong khola), Dhawa Dorje Gurung (owner of Mustang Purple Haze), Korchung Gurung (owner of Mount Everest Hotel), Kunsang Gurung (owner of Hotel Grand), Laxmi Gurung (owner of YacDonalds hotel), Tenzin Dhoka Gurung (owner of New Tibet Guest House), Tsepten Gurung (owner of Shangri-La hotel), Kunga Lhundupi (monk at the monastery), Dawa Thapa (owner of the Karnali Hotel), Karma Thakuri (owner of Singhi hotel), Chhuki Gurung (Chhiongur village), Palgen Gurung (Himali Hotel, Jharkot village). We also deeply appreciated a meeting with two members of the Rural Municipality of Varagaon: Hom Bahadur Thapa Magar (Chief Administrative Officer) and Rinzin Namgyal Gurung (Chairman). Special thanks go to the two anonymous reviewers whose insightful suggestions help improve the manuscript.

## References

**Adhikari T.R., Baniya B., Tang Q., Talchabhadel R., Gouli M.R., Budhathoki, AwasthiR.P. (2023)** – Evaluation of post extreme floods in high mountain region: A case study of the Melamchi flood 2021 at the Koshi River Basin in Nepal. Natural Hazards Research 3, 437–446. https://doi.org/10.1016/j.nhres.2023.07.001

**Allen S.K., Rastner P., Arora M., Huggel C., Stoffel M. (2016)** – Lake outburst and debris flow disaster at Kedarnath, June 2013: hydrometeorological triggering and topographic predisposition. Landslides, 13(6), 1479–1491. https://doi.org/10.1007/s10346-015-0584-3

**Arnaud-Fassetta G., Astrade L., Bardou E., Corbonnois J., Delahaye D., Fort M., Gautier E., Jacob N., Peiry J.L., Piégay H. (2009)** – Hydrogeomorphological contribution to flood-hazard analysis in fluvial-risk management. Géomorphologie : relief, processus, environnement, 2, 109–128. DOI : 10.4000/geomorphologie.7554

**Bajracharya S.R., Maharjan S.B., Shrestha F., Sherpa T.C., Wagle N., Shrestha A.B. (2020)** – Inventory of glacial lakes and identification of potentially dangerous glacial lakes in the Koshi, Gandaki, and Karnali River Basins of Nepal, the Tibet autonomous Region of

China, and India. Research Report, ICIMOD and UNDP, 54 p. Available on: www.icimod.org/himaldoc

**Bell R., Fort M., Götz J., Bernsteiner H., Andermann C., Etzlstorfer J., Posch E., Gurung N., Gurung S. (2021)** – Major geomorphic events and natural hazards during monsoonal precipitation 2018 in the Kali Gandaki Valley, Nepal Himalaya. Geomorphology. 372, 107451. Available online 3 october 2020. https://doi.org/10.1016/j.geomorph.2020.107451

**Bhadra R., Neupane B., Khadka U.R. (2021)** – Induced Impacts of Climate Change on Livelihood and Migration in Upper Himalayas: A Case of Mustang, Nepal. In: Luetz J.M., Ayal D. eds Handbook of Climate Change Management. Springer, Cham. https://doi.org/10.1007/978-3-030-57281-5_303

**Biron P.M., Buffin-Bélanger T., Larocque M., Choné G., Cloutier C.-A., Ouellet M.A., Demers S., Olsen T., Desjarlais C., Eyquem J. (2014)** – Freedom Space for Rivers: A Sustainable Management Approach to Enhance River Resilience. Environmental Management 54, 1056–1073. DOI 10.1007/s00267-014-1366-z

**Böhner J., Miehe G., Miehe S., Nagy L. (2015)** – Climate and Weather. Ch. 4 in Miehe G., Pendry C.A., Chaudhary R. Eds, Nepal - An introduction to the natural history, ecology and human environment of the Himalayas. A companion to the Flora of Nepal. Royal Botanic Garden Edinburgh. 23–90. DOI : 10.1017/S096042861700021X

**Bookhagen B., Thiede R.C., Strecker M.R. (2005)** – Abnormal monsoon years and their control on erosion and sediment fluxes in the high, arid northwest Himalaya. Earth Planetary Science Letters 231, 131–146. https://doi.org/10.1016/j.epsl.2004.11.014

**Burrows, K., Walters, R.J., Milledge, D. and Densmore, A.L. (2020)** – A systematic exploration of satellite radar coherence methods for rapid landslide detection. Natural Hazards and Earth System Sciences, 20(11), 3197–3214. https://doi.org/10.5194/nhess-20-3197-2020

**Byers A.C., Rounce D.R., Shugar D.H., Lal J.M., Byers E.A., Regmi D. (2018)** – A rock-fall induced glacial lake outburst flood, Upper Barun valley, Nepal (2018). Landslides, 167:533–549. https://doi.org/10.1007/s10346-018-1079-9

**Cabré, A., Remy, D., Aguilar, G., Carretier, S. and Riquelme, R. (2020)** – Mapping rainstorm erosion associated with an individual storm from InSAR coherence loss validated by field evidence for the Atacama Desert. Earth Surface Processes and Landforms, 45(9), 2091–2106. https://doi.org/10.1002/esp.4868

**Chen C.M., Hollingsworth J., Clark M.K., Chamlagain D., Bista S., Zekkos D., Siwakoti A., West A.J. (2025)** – Erosional cascade during the 2021 Melamchi flood. Nature Geoscience, 18, 32–36. https://doi.org/10.1038/s41561-024-01596-x

**Climate Hazards Center Infrared Precipitation with Stations version 3 (2025)** – CHIRPS3 Data Repository https://doi.org/10.15780/G2JQ0P. Data was accessed on 25/07/2025

**Colchen M., Le Fort P., Pêcher A. (1986)** – Recherches géologiques dans l'Himalaya du Népal, Annapurna, Manaslu, Ganesh Himal. Ed. du CNRS, Paris, 363 p.

**Cook K.L., Andermann C., Gimbert F., Adhikari B.R., Hovius N. (2018)** – Glacial lake outburst floods as drivers of fluvial erosion in the Himalayas, Science 362, 53–57. https://doi.org/10.1126/science.aat4981

**Cook K.L., Shrestha D., Brun F., Berthier E., Charrier L. (2025)** – The 2024 Thame GLOF, Khumbu Nepal - causes, consequences, and dynamics. EGU General Assembly 2025, Vienna, Austria, 27 Apr-2 May 2025, Abstract EGU25-12752. https://doi.org/10.5194/egusphere-egu25-12752

**Deijns A.A., Dewitte O., Thiery W., d'Oreye N., Malet J.-P., Kervyn F. (2022)** – Timing landslide and flash flood events from SAR satellite: a regionally applicable methodology illustrated in African cloud-covered tropical environments. Nat. Hazards Earth Syst. Sci., 22, 3679–3700. https://doi.org/10.5194/nhess-22-3679-2022

**Dobremez J.F. (1976)** – Le Népal. Écologie et Biogéographie, Ed. du CNRS, Paris, 136 p.

**Dobremez J.F., Jest C. (1976)** – Carte écologique du Népal, 3 – 1/250 000e. Ed. du CNRS, Paris.

**Duwadi S., Adhikari D.P., Dhital M.R., Parajuli N. (2024)** – Assessment of the 2021 debris flow and flood related loss and damage in Melamchi Watershed of Central Nepal. Journal of Nepal Hydrogeological Association, v.1, 107–134. ISSN: 3059-9725. https://doi.org/10.3126/jnha.v1i1.78226

**Etzelstorfer J. (2020)** – Die Gromassenbewegung bei Muktinath (Nepal) – Systembeschreibung und rezente Dynamik. MSc.thesis, Fachbereich Geographie und Geologie, Naturwissenschaftliche Fakultät, Paris-Lodron-Universität Salzburg, Salzburg. https://www.researchgate.net/publication/342354183.

**Environment Statistics of Nepal (2024)** – National Statistics Office, Government of Nepal, Kathmandu. 311 p.

**Fischer M., Brettin J., Roessner S., Walz A., Fort M., Korup O. (2022)** – Rare flood scenarios for a rapidly growing high-mountain city: Pokhara, Nepal. In Natural Hazards Earth System Science, Special issue "Estimating and predicting natural hazards and vulnerabilities in the Himalayan region" (Guest editors: A. Agarwal, K. Cook, U. Öztürk, W. Schwanghart, R. Shukla, and S. Fuchs), 22, 3105–3123. https://doi.org/10.5194/nhess-22-3105-2022

**Fort M. (1980)** – Les formations quaternaires lacustres de la basse Thakkhola (Himalaya du Népal) : intérêt paléogéographique, néotectonique et chronologique. C-R. Acad. Sciences Paris, 290(D), 171–174.

**Fort M. (1985)** – Contribution of sedimentary and geomorphic data to the knowledge of paleoclimates in Nepal Himalayas. in: Climate and Geology in Kashmir and Central Asia: The Last Four Million Years, D.P. Agrawal ed., Today and Tomorrow's Publ., New Delhi, 159–189.

**Fort M. (1987a)** – Sporadic morphogenesis in a continental subduction setting: an example from the Annapurna Range, Nepal Himalaya. Zeit. f. Geomorph., Suppl.-Bd 63, 9–36.

**Fort M. (1987b)** – Geomorphic and Hazards mapping in the dry, continental Himalaya: 1:50,000 maps of Mustang District, Nepal. Mountain Research and Development, Boulder, 7, 3, 222–238. https://doi.org/10.2307/3673198

**Fort M. (2000)** – Physical conditions and constraints for irrigation in the dry Himalaya: an example from Upper Mustang (Nepal). In Water in Asia (H. Kreutzmann ed.). Oxford University Press, Karachi, 239–258.

**Fort M. (2015)** – Natural hazards vs climate change and their potential impacts in the dry, northern Himalayas: focus on the Upper Kali Gandaki (Mustang District, Nepal). Environmental Earth Sciences Special Issue: Sustainable Water Management in Central Asia. DOI : 10.1007/s12665-014-3087-y

**Fort M., Adhikari B.R., Rimal B. (2018)** – Pokhara (Central Nepal): A Dramatic Yet Geomorphologically Active Environment Versus a

Dynamic, Rapidly Developing City. In: Mary J. Thornbush, Casey D. Allen (Eds) «Urban Geomorphology: Landforms and Processes in Cities», Ch. 12, Elsevier S&T Books. 225–252. http://dx.doi.org/10.1016/B978-0-12-811951-8.00012-6.

**Funk, C., Peterson P., Landsfeld M., Pedreros D., Verdin J., Shukla S., Husak G.J., Rowland J., Harrison L., Hoelt A., Machaelsen J. (2015)** – The Climate Hazards Infrared Precipitation with Stations-A New Environmental Record for Monitoring Extremes. Scientific Data, 2: 150066. https://doi.org/10.1038/sdata.2015.66

**Godin L. (2003)** – Structural evolution of the Tethyan sedimentary sequence in the Annapurna area, central Nepal Himalaya. J. Asian Earth Science, 22, 307–328. https://doi.org/10.1016/S1367-9120(03)00066-X

**Goetz J., Etzlstorfer J., Bernsteiner H., Bell R., Griesebner G., Fort M. (2020)** – Monsoon-driven landslide dynamics in Nepal – the complex mass movement system in the Muktinath Valley. EGU General Assembly, Abstract EGU2020-19597. https://doi.org/10.5194/egusphere-egu2020-10597

**Gurung N., Fort M., Bell R., Arnaud-Fassetta G. (2024)** – The Kagbeni flood event (August 13, 2023), Mustang District (Nepal): A rapid, polygenic event with processes and sediment cascades exacerbated by recent infrastructure development not taking the risk equation into account. European Geophysical Union meeting, Geophysical Research Abstracts, EGU24-2563-2. https://doi.org/10.5194/egusphere-egu24-2563

**Gurung N., Fort M., Arnaud-Fassetta G., Bell R., Sherchan B. (2020)** – Bridge construction vs. natural dynamics of a debris flows prone catchment in central Nepal, Myagdi District. Géomorphologie : Relief, Processus, Environnement. vol. 26, n° 3, 195–215. DOI :10.4000/geomorphologie.14777

**Gurung N., Fort M., Bell R., Arnaud-Fassetta G., Maharjan N.R. (2021)** – Hydro-torrential hazard vs. anthropogenic activities along the Seti valley, Kaski, Nepal: Assessment and recommendations from a risk perspective. Journal of Nepal Geological Society. 62, 61–90. https://doi.org/10.3126/jngs.v62i0.38695

**Hagen T. (1968)** – Report on the Geological Survey of Nepal, vol. 2: Geology of the Thakkhola. Reprinted in 2014 by the Nepal Geological Society, Kathmandu, Nepal. 152 p.

**Hille M., Mark E., Strouth A., Sharma K., Dixit A., Zubrycky S., Scheip C., Carter R. (2025)** – Field insights from the August 16, 2024 Thame glacial lake outburst flood in Nepal: how geomorphology can affect a cascading hazard chain. EGU General Assembly 2025, Vienna, Austria, 27 Apr-2 May 2025, EGU25-14809, https://doi.org/10.5194/egusphere- egu25-14809, 2025.

**ICIMOD, Media Advisory (2024, 18 Aug.)** – GLOF from Thyanbo glacial lake sweeps away Thame Village.

**Immerzeel W.W., van Beek L.P.H., Bierkens M.F.P. (2010)** – Climate Change will affect the Asian Water Towers. Science, 328, 11 June. https://doi.org/10.1126/science.1183188

**Iwata S., Yamanaka H., Yoshida M. (1982)** – Glacial landforms and river terraces in the Thakkhola region, Central Nepal. J. of Nepal Geological Society, v.2 Sp. Issue, 81–94.

**Krishnan R., Shrestha A.B., Ren G., Rajbhandari R., Saeed S., Sanjay J., Syed M.A., Vellore R., Xu Y., Youi Q., Ren Y. (2019)** – Unravelling Climate Change in the Hindu Kush Himalaya: Rapid Warming in the Mountains and Increasing Extremes. Ch.3, in Wester P., Mishra A., Mukherji A., Shrestha A.B. (Eds): "The Hindu Kush Himalaya Assessment. Mountains, Climate Change, Sustainability and People". Springer Nature Switzerland AG, Cham. 57–96. https://doi.org/10.1007/978-3-319-92288-1_3

**Lamichhane K., Biswakarma K?n Acharya B., Karki S., KC Rajan, Subedi M., Sharma K. (2025)** – Preliminary assessment of September 2024 extreme rainfall-induced landslides in Central Nepal. Landslides. DOI : 10.1007/s10346-025-02577-w

**Lutz A.F., Immerzeel W.W., Shrestha A.B., Bierkens K.S. (2014)** – Consistent increase in High Asia's runoff due to increasing glacier melt and precipitation. Nature Climate Change, 4 (7), 587–592. DOI : 10.1038/NCLIMATE2237

**Maharjan S.B., Steiner J.F., Shrestha A.B., Maharjan A., Nepal S., Shrestha M.S., Bajracharya B., Rasul G., Shrestha M., Jackson M., Gupta N. (2021)** – The Melamchi flood disaster. HimalDoc, ICIMOD, 21 p. https://lib.icimod.org/record/35284

**Maharjan S.B., Sherpa T.C., Shrestha A.B., Strouth A., Mark E., Bam A.K. (2025)** – The 2024 GLOF disaster in Thame valley: causes, impacts and pathways for future risk reduction. Journal of Nepal Geological Society, vol. 68, p. 97 (Sp. Issue, Abstract vol. 11th Nepal Geological Congress, March 10-11, 2025). ISSN: 2676-1378.

**Malavoi J.-R., Bravard J.-P., Piégay H., Héroin E., Ramez P. (1998)** – Détermination de l'espace de liberté des cours d'eau. Guide Technique n°2, Bassin du Rhône Méditerranée Corse, DIREN Rhône-Alpes, 40 p.

**Meier W.J-H., Pohle P., Grissinger J. (2022)** – Climate Change and New Markets: Multi-Factorial Drivers of Recent Land-Use Change in the Semi-Arid Trans-Himalaya, Nepal. Land, 11, 1567. https://doi.org/10.3390/land11091567

**Miehe G., Weidinger J.T. (2015)** – Himalayan Landforms and Processes. Ch. 6, in Miehe G., Pendry C.A., Chaudhary R. Eds, Nepal - An introduction to the natural history, ecology and human environment of the Himalayas. A companion to the Flora of Nepal. Royal Botanic Garden Edinburgh, 103–124. DOI : 10.1017/S096042861700021X

**Murton G. (2019)** – Facing the fence: The production and performance of a Himalayan border in global contexts. Political Geography, 72, 13–42. https://doi.org/10.1016/j.polgeo.2019.03.001

**NDRRMA (National Disaster Risk Reduction and Management Authority) (2024)** – Preliminary Loss and Damage Assessment of Flood and Landslide/ Report, MHO (Ministry of Home Affairs, Government of Nepal), 28 Oct. 2024. 45 p.

**Parsons A.J., Law R.D., Searle M.P., Phillips R.J., Lloyd G.E. (2014)** – Geology of the Dhaulagiri-Annapurna-Manaslu Himalaya, Western Region, Nepal. 1:200,000. Journal of Maps. https://doi.org/10.1080/17445647.2014.984784

**Peissel M. (1968)** – Mustang: A Lost Tibetan Kingdom. HarperCollins Distribution Services, 288 p.

**Petley D. (2024)** – The Landslide Blog. https://eos.org/thelandslideblog/the-impact-of-the-26-to-28-september-2024-rainfall-event-in-kavre-

**Piégay H., Darby S.E., Mosselman E., Surian N. (2005)** – A review of techniques available for delimiting the erodible river corridor: a sustainable approach to managing bank erosion. River Research and Applications, 21(7), 773–789. DOI :10.1002/rra.881.

**Sattar A., Cook K.L, Rai S.K. and 29 more co-authors (2025)** – The Sikkim flood of October 2023: Drivers, causes, and impacts of a multihazard cascade. Science, 387 (6740). DOI : 10.1126/science.ads2659

**Singh R., Koch A., LeGrande A.N., Tsigaridis K., Ramos R.D., Ludlow F., Aleinov I., Ruedy R., Kaplan J.O. (2024)** – Modelling framework for asynchronous land-atmosphere coupling using NASA GISS ModelE and LPJ-LMfire: Design, application and evaluation for the 2.5ka period. Geosci. Model Dev., submitted, doi:10.5194/gmd-2024-219.

**Sharma E., Molden D., Rahman A., Khatiwada Y.R., Zhang L., Singh S.P., Wester P. (2019)** –Introduction to the Hindu Kush Himalaya Assessment. Ch. 1, in: Wester P., Mishra A., Mukherji A., Shrestha A.B. Eds (2019): "The Hindu Kush Himalaya Assessment Mountain, Climate Change, Sustainability and people". Springer Nature Switzerland AG, Cham https://doi.org/10.1007/978-3-319-92288-1_1

**Shugar D.H., Jacquemarty M., Shean D. and 50 more co-authors (2021)** – A massive rock and ice avalanche caused the disaster at Chamoli, Indian Himalaya. Science, 373 (6552). DOI : 10.1126/science.abh4455

**Subba S., Ma Y.M., Ma W.Q., Han C.B. (2024)** – Extreme precipitation detection ability of four high-resolution precipitation product datasets in hilly area: a case study in Nepal. Advances in Climate Change Research, 5, 3, 390–405. https://doi.org/10.1016/j.accre.2024.05.005

**Tamta M.K., Joshi J. (2019)** – Geomorphic processes, topographical changes and disasters: A study from the Mandakhini river basin, Uttarakhand. Intern. Journal of Basic and Applied Research, 9(6), 887–898.

**The Kathmandu Post (2024, Aug.16)** – Flood in Solukhumbu destroys 12 houses. https://kathmandupost.com/national/2024/08/16/flood-in-solukhumbu-destroys-12-houses

**Thakuri S., Dahal S., Shrestha D., Guyennon N., Romano E., Columbo N., Salerno F. (2019)** – Elevation-dependent warming of maximum air temperature in Nepal during 1976-2015. Atm. Res. 228, 261–269. https://doi.org/10.1016/j.atmosres.2019.06.006

**Yun, S.H., Hudnut, K., Owen, S., Webb, F., Simons, M., Sacco, P., Gurrola, E., Manipon, G., Liang, C., Fielding, E. and Milillo, P. (2015)** – Rapid damage mapping for the 2015 M w 7.8 Gorkha earthquake using synthetic aperture radar data from COSMO–SkyMed and ALOS-2 Satellites. Seismological Research Letters, 86(6), 1549–1556.

**Yvrard P. (2024)** – Étude de la perception des inondations et des mouvements de terrain par les habitants de la vallée de la Kali Gandaki (Népal). Approche réflexive de la forte exposition de la population et des infrastructures face aux changements globaux. Master 1 GAED – DYNARISK, Université Paris Cité, 112 p.

## *Version abrégée en français*

Au nord de l'Himalaya népalais, dans la zone continentale sèche (< 300 mm/an) protégée de la mousson, le village de Kagbeni (2810 m, 420 habitants), situé à la confluence de la Jhong Khola et de la Kali Gandaki (fig. 1-3), a été affecté par une crue hyper-concentrée dévastatrice et inhabituelle dans la soirée du 13 août 2023. Cette crue a causé d'importants dégâts aux biens et aux infrastructures (coût ≈ 7,4 millions USD, 39 bâtiments emportés dont 19 habitations ou bâtiments officiels, des abris de bétail). Heureusement, il n'y eut aucune perte en vies humaines grâce aux alertes téléphoniques envoyées par les habitants des villages situés en amont, témoins non directement affectés par la crue.

Depuis plusieurs années, la station de Jomsom (2720 m, 12 km au sud de Kagbeni) a enregistré une augmentation des précipitations (fig. 4), une tendance confirmée par les habitants de la région. Cependant, en août 2023, aucun événement pluvieux extrême n'a été enregistré – ni à la station de Jomsom, ni dans les données pluviométriques CHIRPS analysées pour la vallée de Jhong Khola – qui aurait pu déclencher l'inondation.

Vu le contexte géomorphologique, nous avons émis l'hypothèse que cette crue fut probablement déclenchée par la rupture d'un lac de barrage formé à la suite d'un glissement de terrain récent. Le site ayant été inaccessible lors de la mission de terrain (conditions météorologiques défavorables), l'existence du glissement de terrain et sa localisation (en amont des gorges de Chhiongur) furent confirmées par l'analyse des séries temporelles de cohérence d'images du satellite Sentinel-1 InSAR (fig. 6, 7). En aval des gorges, l'inondation s'est propagée dans le fond de vallée plus ou moins sinueux, comme en témoignent localement de nouveaux dépôts (Fig. 10), des érosions de berge et la réactivation de glissements de terrain (fig. 12), ceux-ci fournissant une charge solide supplémentaire rendant l'inondation encore plus destructrice vers l'aval (ponts, bâtiments, bétail, vergers…). Le volume de débris transportés a été estimé à 647 000 m$^3$, suivi d'une ré-incision rapide après l'inondation (215 000 m3).

Les habitants de Kagbeni ont indirectement contribué à cette catastrophe car, installés sur les très basses terrasses, ils empiètent ainsi sur la plaine d'inondation de la rivière Jhong Khola, qui a été étroitement canalisée (fig. 14). De plus, situé en amont du village, le pont de la route menant au Haut Mustang a amplifié les dégâts par un effet de goulot d'étranglement : son tablier en béton a été emporté, puis transporté vers le village, causant de graves dégâts plus en aval. À la confluence avec la Kali Gandaki, la charge solide transportée a été en partie déposée (fig. 13, 15), formant un large cône qui a bloqué pendant près de trois jours la Kali Gandaki, transformée en lac temporaire qui a notamment dévasté des installations religieuses très fréquentées.

Compte tenu de la tendance générale au réchauffement climatique, la possibilité que se reproduisent dans le futur de telles crues brutales à Kagbeni reste non négligeable, et pourtant, certains habitants ont reconstruit leurs maisons à l'identique et continuent de s'installer dans le lit inondable potentiellement menacé (fig. 17, 18).

Au terme de notre analyse, et à la suite de l'observation de l'accroissement des zones habitées depuis 1970 (impacts du tourisme international et de plus en plus domestique), nous suggérons quelques mesures pour prévenir les risques de futures inondations. Dans un contexte de développement de l'urbanisation, il faudrait désormais tenir compte du concept d'espace de liberté (ou fonctionnel) de la rivière pour éviter l'empiètement du lit majeur de la rivière par les activités anthropogéniques (bâtiments, ponts) (fig. 20). Par ailleurs, plutôt que reconstruire un pont mal calibré le long de la Route du Haut Mustang, il vaudrait mieux mettre en place une structure de type gué en béton, plus économique et plus facile à entretenir ; mais cela ne semble pas être la solution qui ait été retenue. Plus généralement, une réglementation sur la prévention des risques naturels devrait être mise en œuvre à l'échelle de l'ensemble du Népal.