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Flood events and their effects in a Himalayan mountain river: Geomorphological examples from the Buri Gandaki Valley, Nepal

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Abstract: This research examines flood events and related human interactions in the northwestern Himalayan Buri Gandaki Valley (Nepal). Past flood events that left traces at elevations between 3745 m to 780 m above sea level were investigated and reconstructed using morphometric and descriptive fluvial geomorphological analyses of historical flood markers and their related forms in the Buri Gandaki River system. Furthermore, the discharge of the Buri Gandaki River was measured, and infrastructure and permanent and temporary settlements potentially influenced by floods in the region due to their proximity to natural hazard areas were mapped. All reconstructed flood indicators have been documented with photographs that illustrate the evolution of the landscape over a short period in the Holocene. Moreover, satellite images have confirmed the morphological findings at the mesoscale and macroscale. An analysis of the flood levels showed that the high-water marks between 2160 m and 1710 m above sea level represented the highest reconstructed paleoflood stages.

An intense flood hazard was observed in the upper stream of the Buri Gandaki near the Birendra Kund glacial lake and Samagaun settlement (3520 m above sea level). Further conclusions may be drawn from the anthropogenic reactions to flooding, such as those of the ethnic groups in this valley, who have used their local knowledge of floods and high discharge events along the Buri Gandaki River to take safety precautions. Thus, local knowledge has reduced the social vulnerability in the settled areas of the valley. As a result of these local adaption strategies within the valley, we must rethink our implementation of protection and urbanisation strategies.

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Introduction

The recent glacier fluctuations and increasing ice melting processes in the mountains of the Himalaya and Karakoram (Meiners 1995; Achenbach 2011; Hewitt 2011; Iturrizaga 2011; Bolch et al. 2012; Kuhle 2014) influence the occurrence of the interrelated processes that trigger sudden flood events. Glacial lake outburst floods (GLOFs) are one such sudden flood process. Because of their high discharge energy, the fluvial dynamics of sudden GLOFs can flood and reshape the downstream mountain rivers and valleys (Cenderelli and Wohl 2003). Another type of flood event involves avalanches that cascade down the valley flank and accumulate on the riverbed; these processes alone can build temporary natural dams. These examples can be described as “natural hazards” (Hewitt 1997). In addition to the naturally triggered hazards, floods can also be induced by "technological hazards" (Hewitt 1997). For example, anthropogenic dam projects, which are employed as power stations, can intensify the risk of flooding, as evidenced by past dam failures in the Himalayan mountain range (Pradhan et al. 2007). Dam failure can destroy villages and infrastructure near the broken dam (Wohl 2010).

In order to determine the physiogeographical transformations and intensities of such flood events, including the triggering factors of floods in a mountain river, the paleoflood stages and forms in the riverbed (Baker 1994) were studied on the floodplain and on the bordering terraces in a particular watershed. Additionally, the perception strategies of the local people were considered to better understand their environmental behaviour and adaption strategies. These geomorphological observations and measurements were obtained in the remote Buri Gandaki Valley in the Nepalese Himalayan Mountains.

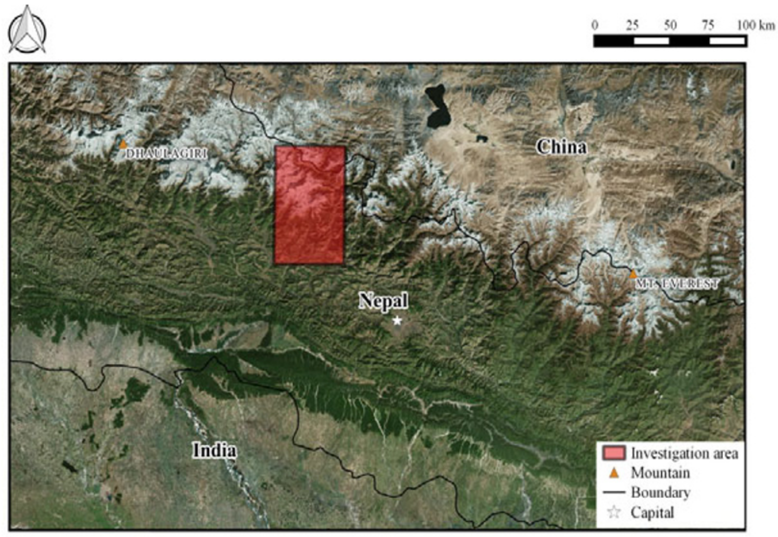


Figure 1 This map illustrates the location of the investigation area within the Himalayan mountains. The map is based on Esri World Imagery.

1 The Physiogeographic Conditions of the Study Area

The remote Buri Gandaki Valley (28°00' to 30°30' N latitude and 84°30' to 85°00' E longitude) lies in the northwest Nepalese High Himalaya, near Manaslu (8162 m a.s.l.), which is the focal point for many mountaineers (Figure 1). The valley is well defined by the Tibetan and Inner Himalayas (Hagen 1969). During past glacial periods (e.g., the Last Glacial Maximum, or LGM), the Buri Gandaki Valley floor experienced glacial processes that resulted in the formation of ground moraines, glacial polishing and subglacial potholes down to an elevation of 680 m (Kuhle 1998) or even as low as 500 m a.s.l. (Kuhle 2013). During the subsequent interglacial periods, the valley floor was influenced by fluvial erosional processes. Currently, these glacially and fluvially generated landforms are being reshaped by fluvial dynamics, which are primarily driven by the annual melting of glaciers and snow upvalley. Consequently, the riverbed of the Buri Gandaki has been influenced by different climatic cycles that underlie the evolutionary processes of landscape dynamics.

Glacial melting processes, primarily the melting of exposed snow, firn and ice surfaces at the terminus of the glacier (Klebelsberg 1949), feed the Buri Gandaki River system beneath the glacier tongues in the upper valley near the Samdo settlement (3858 m a.s.l.) and form sandur plains, proglacial plains, and streams, all of which are located in front of the glaciers (Church 1972; Church and Ryder 1972). This discharge flows downvalley from the upper reaches (3745 m a.s.l.) in a southeast direction to the middle reaches (780 m a.s.l.) near the Arughat Bazar settlement (Figure 2). Annual precipitation within the stream watershed of 3872 km² represents an additional stream source (Figure 2). In this study area, the average annual precipitation ranges between 1000 and 2000 mm (Chalise 1996; Bookhagen and Burbank 2006). During the monsoon season, the precipitation rises but is contained by the high flanks and ridges of the High Himalaya. Consequently, the monsoon intensity of the Inner Himalaya region is lower than that downvalley (Jacobsen 1990). Because of the diverse microclimate and morphology in the valley, the water line of all tributary streams follows a different pattern (Figure 2), which might result in different discharge influxes at different confluences with the mainstream Buri Gandaki. As a result of these influxes, the discharge and flood level stages of the Buri Gandaki stream change as well.

2 Research Methods

Empirical research and risk assessments were conducted during an expedition along the course of the Buri Gandaki River system (Manaslu-Himal) in April 2008 (Appendix 1, 2, 3, 4 and 5). By surveying the reaches (3745 m down to 780 m a.s.l.) of the Buri Gandaki and related glacial systems, it was possible to map the riverbed morphology and natural hazard areas and to measure the paleoflood stages, the river width and depth and flow velocity at different stream elevations at the microscale (Schumm 1991) of the stream. All of these findings have been documented with photography, including panoramas that identify the geomorphology of the river. Additionally, these photographs were used to validate the findings of the morphological research. To classify the survey sites within the catchment area, the river system was divided into different reaches. The survey sites within the highest reach of the river system were located between 3745 m and 1885 m a.s.l. and labelled the "upper reaches". Further downvalley, the survey sites between 1710 m a.s.l. and 780 m a.s.l. were labelled the "middle reaches". In both reaches of the stream, morphometric and descriptive geomorphological analyses were conducted at 12 cross-sectional survey sites. The flood level marks were measured with a folding yardstick by using the sum of the present river depth and the vertical distance between the water surface and the past flood level marks. For different reconstructed water levels whose margins are not clearly defined, the vertical distance between the upper and lower limit of the past high water marks was determined. These data were used to reconstruct an arithmetic average (Figure 3), which made it possible to compare this dataset with the width and depth along the river bed. High water levels have the potential to intensify the erosion and weathering effects on the boulders deposited on the floodplain. Furthermore, a well-developed floodplain and well-developed vegetation cover near the riverside indicate stable, low water levels over the last several years.

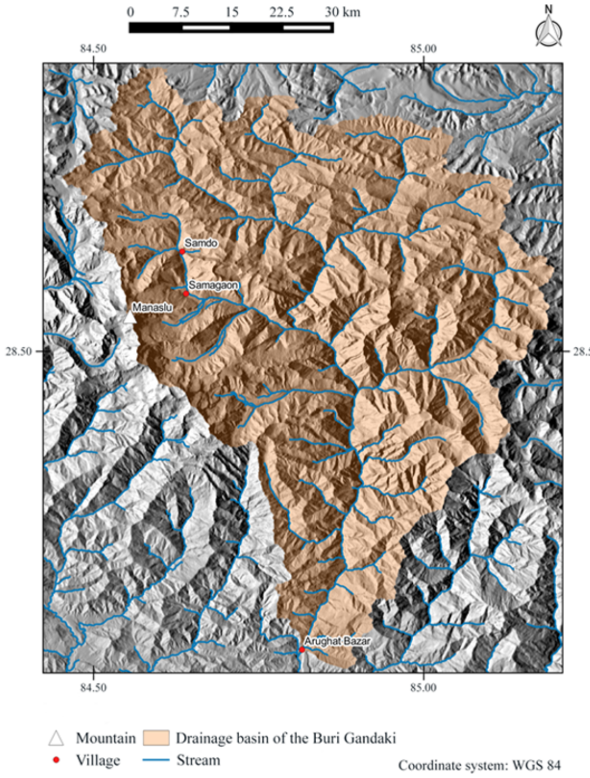


Figure 2 Buri Gandaki drainage basin covering an area of 3872 km². This basin is confined by the ridges of the High Himalaya. Based on SRTM digital elevation data and the software GRASS GIS (module: r.watershed), the river catchment area was modelled.

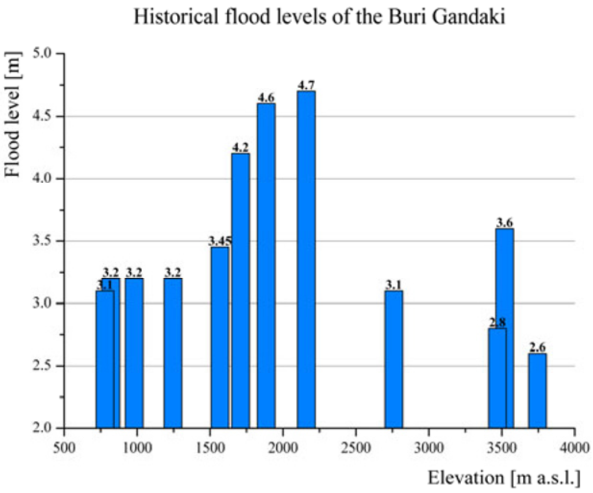


Figure 3 This bar chart illustrates the arithmetic average of measured flood stages at different elevations. These flood stages were measured with a folding yardstick at 12 cross-sectional survey sites in the upper- and middle-stream portions of the Buri Gandaki.

These measured marks provided us with information on the flood levels that occurred over the last several years during a portion of the

Holocene (Zalasiewicz et al. 2015). This short period of time is part of a longer development cycle of the stream and can be considered to represent recent and modern conditions, which depend on the hydrology, the hillslope morphology and the drainage network morphology (Schumm and Lichty 1965).

Furthermore, flow measurements were conducted with a buoy-like bag (which was filled with air and sinker) at each cross section of the survey sites. Due to the light-weight materials of the unfilled buoy-like bag, it was possible to transport it to the remotest reaches of the study area. The time required for this float-and-sinker device to travel a distance of 30 m when dropped into the absolute streamline was measured during the middle of the day when allowed by the expedition timetable and weather conditions. Repeated iterations of these measurements at each survey site, with subsequent averaging of these results, yielded information on the midday-dependent maximum flow velocity during the expedition in April 2008 (Figure 4). Combined with the data on the measured width and depth of the stream (Figure 5), the discharge could be calculated for each survey site cross section of the stream in the course of the expedition. These discharge data represent just a short time span during the premonsoon period in April 2008.

Supplementary digital SRTM datasets (http://www.viewfinderpanoramas.org/) were used in a geographic information system (GIS) environment to compile a digital elevational model (DEM) during the post analysis, which contextualized the field research data. This DEM was used to model the river catchment area of the Buri Gandaki (Geographic Resources Analysis Support System (GRASS GIS) module: r.watershed) and the stream order classification by Strahler and Horton (GRASS GIS module: r.stream.order). These datasets, along with satellite images (from Google Earth), provided additional information on the spatial distribution of morphology and morphometry at the mesoscale and macroscale (Schumm 1991) of the stream.

In addition to this geomorphological investigation, the infrastructure near the river system and the permanent and temporary settlements were mapped via GIS in 2014, and the measured distances between the stream and

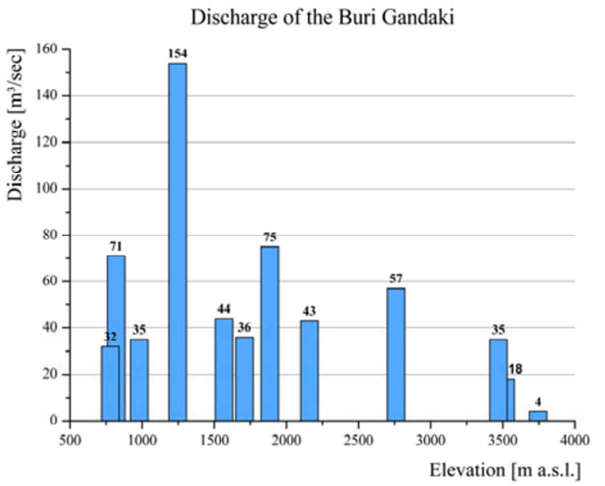


Figure 4 This bar chart illustrates the measured discharge at different elevations along the river during the expedition in April 2008. These measurements were conducted with a buoy-like bag as a float-and-sinker device at 12 cross-sectional survey sites in the upper- and middle-stream portions of the Buri Gandaki.

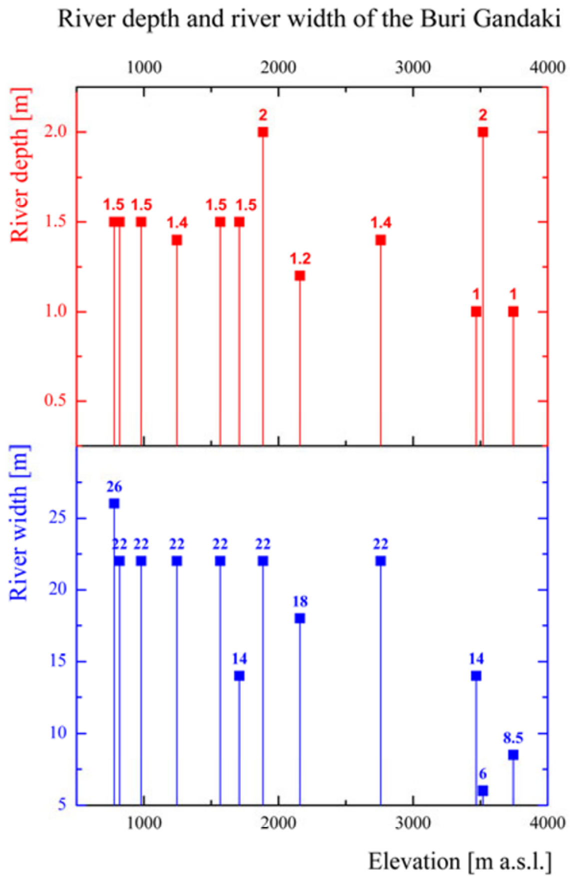


Figure 5 This chart illustrates the measured river depth and river width of the channel system at different elevations. The data were measured with a folding yardstick at 12 cross-sectional survey sites in the upper- and middle-stream portions of the Buri Gandaki.

settlements provided further insights into the stream morphology and its relevance to local infrastructure and human interactions.

3 Results of Historical Flood Level Measurements, Discharge Measurements, River Morphology and Human Behaviour

3.1 Survey of morphometric findings of historical flood levels and discharges

In the upper reach of the Buri Gandaki, flood level heights in the past were minor and the measured discharge was low. At an altitude of 3745 m a.s.l., the historical flood levels reached 2.6 m above the riverbed, and the measured discharge achieved a value of 4 m³/sec (Figures 3, 4 and measurement number 11 in Appendix 1). Further downstream, at an altitude of 3520 m a.s.l. near the Samagaun settlement, the flood level rose to 3.6 m above the riverbed (Figure 3; measurement number 9 in Appendix 1). This high flood level can be explained by the floods that occasionally occurred here during the field investigation and were induced by snow and ice avalanches falling into the Birendra Kund glacial lake. Consequently, these processes generated a surge that resulted in high water marks. Additionally, the small width (6 m and 8.5 m) and high depth (2 m and 1 m) of this river section create conditions for high flood water levels during a surge period (Figure 5). Nearly two hours after an avalanche, a discharge of 18 m³/sec was measured at this cross section (Figure 4).

The reconstructed historical flood level downstream at an altitude of 3470 m a.s.l. reached a value of 2.8 m (Figure 3 and measurement number 14 in Appendix 1). At this cross section, a river width of 14 m and a river depth of 1 m were measured (Figure 5 and measurement number 14 in Appendix 1). As a result of this morphology, the discharge rose and achieved a value of 35 m³/sec during the field studies (Figure 4). Further downstream, the paleoflood levels increased. At an altitude of 2760 m a.s.l., a flood level of 3.1 m and a discharge of 57 m³/sec were measured (Figures 3, 4 and measurement number 7 in Appendix 2). The highest flood levels in the Buri Gandaki stream were reconstructed between 2160 m and 1710 m a.s.l., and the values fluctuated between 4.2 m and 4.7 m (Figure 3 and measurement numbers 5, 6 and 16 in Appendix 2 and 3). As a result of the low river depth (1.5 m and 1.2 m) and narrow river width (14 m and 18 m) at two of these localities (Figure 5 and measurement numbers 5 and 16 in Appendix 2 and 3), the water level increased during high flood events.

The local flood level at measurement point 6, which is located between measurement numbers 5 and 16, was found to be 4.6 m (Figure 3). The discharge of the river at this cross section increases during monsoon events and through the upstream confluence with the Seran Khola River (ca. 28°30'37.69"N, 84°51'22.63"E; ca. 1963 m a.s.l.). Moreover, the measured discharge data show that the discharge at these localities increased first at 2160 m a.s.l. to 43 m³/sec then at 1885 m a.s.l. to 75 m³/sec. Downstream, it decreased at 1710 m a.s.l. to 36 m³/sec (Figure 4). Naturally, the highest measured discharge of 75 m³/sec could have arisen from the increasing river width (22 m) and depth (2.0 m) at this cross section (Figure 5). As a consequence of this cross-section morphology and the small floodplain, the paleoflood level of measurement point 6 could have occurred (Figure 3).

Further downstream, the paleoflood stage was found to be lower. At an elevation of 1568 m a.s.l., a flood level of 3.45 m (Figure 3 and measurement number 17 in Appendix 3) was reconstructed. This flood level may have resulted from additional

Figure 6 Photo 1 on April 27, 2008, at measurement point 17 at 1568 m a.s.l., facing the Buri Gandaki: Fluvial erosional processes on the boulder (---) and the sorted and relocated sediments on the floodplain (◌) illustrate the strength of past floods in this area. The riverbed morphology transitions from a plane bed (◆) into a pool-riffle pattern (○).

discharge associated with the confluence of tributaries with the Buri Gandaki further upvalley. At this survey site, the river channel widens (22 m; Figure 5). During the fieldwork, the measured discharge was 44 m^3/sec at this cross section (Figure 4). Additionally, widespread floodplains have filled the valley bottom of this V-shaped valley, thereby reducing the rapid-rise factor of the water level (Figure 6). Bankfull discharge is a typical feature of such a widespread floodplain with a plane bedform and evolving, meandering river patterns (Figure 6). The historical flood levels downstream between 1246 m and 780 m a.s.l. indicate that the river stages decreased to 3.2 m (Figure 3 and measurement numbers 4, 3 and 19 in Appendix 4 and 5). As a result of the broad floodplains and river widths (22 m; Figure 5) in these localities, the flood level could not rise as rapidly as in the upper river sections. On the other hand, the highest measured discharge obtained a value of 154 m^3/sec at 1246 m a.s.l. (Figure 4). This measured high value could be explained by the meandering riverbed dynamics at this cross section (measurement number 4 in Appendix 4) (see Section 3.2.5), which suggest changing discharge and water dynamics within this riverbed profile (Buffington and Montgomery 2013). Downstream of this cross section, the discharge was 35 m^3/sec (measurement number 3 in Appendix 4) at 980 m a.s.l. and 71 m^3/sec (measurement number 19 in Appendix 5) at 820 m a.s.l. (Figure 4). This increasing discharge is due to the confluence with the Macha Khola River.

Further downvalley, at an altitude of 780 m a.s.l., the historical water levels decreased to ca. 3.1 m (Figure 3 and measurement number 21 in Appendix 5) and the discharge achieved a value of 32 m^3/sec (Figure 4). In this wide river reach, the floodplain is well developed and the river is wider (26 m; Figure 5), lowering the risk of flooding.

3.2 Focused descriptive geomorphologic evidence of paleoflood stages

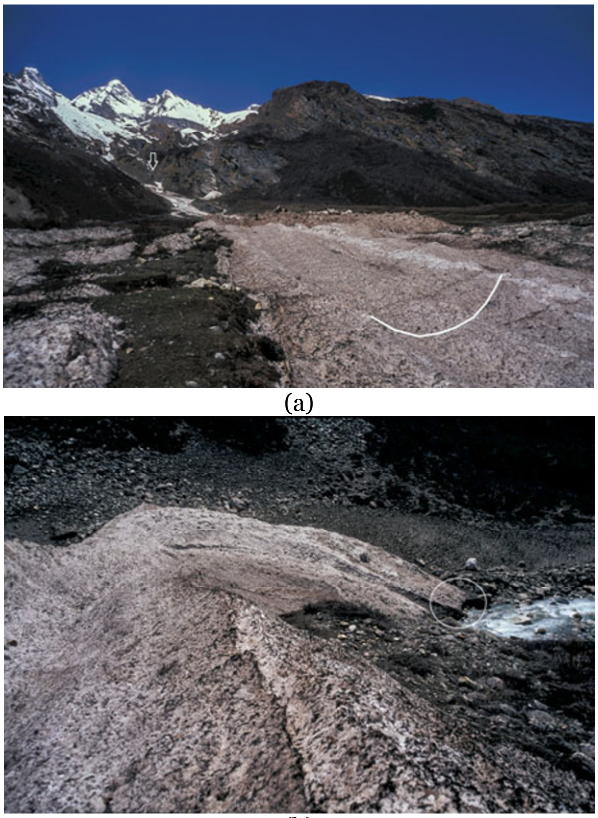
3.2.1 Natural hazards in the upper part of the headwater stream Larke Khola

At an altitude of 3770 m a.s.l. on the river-right side of the Larke Khola (Appendix 1), indications of an avalanche were visible. The accumulation of ice, snow and detritus from this avalanche crossed the Larke Khola headwater stream, which flows into the Buri Gandaki. This mass movement was induced above the thalweg on the river-right side (Figure 7). As a result of fluvial erosion processes, this superimposed river accumulation could be undercut. Consequently, the risks of dam development naturally decreased (Figure 7).

Figure 7 Photo 2 on April 21, 2008, at 3770 m a.s.l., facing west-southwest: The Larke Khola was invaded by an avalanche (◌), which initiated above the thalweg (⬇). However, the fluvial erosion reduced the development of a dam (○).

3.2.2 Natural hazards in the upper part of the Buri Gandaki near Samagaun

North of Samagaun on the river-right side of the Buri Gandaki upper valley at 3720 m a.s.l. (Appendix 1), the stream and a portion of the infrastructure were covered by an avalanche. The width of this avalanche was ca. 40 m (Figure 8a), and the observed avalanche slid down from the river-right slope. The accumulation consisted of firn, alluvium and boulders, and the historical slide path and frozen rock roll were clearly identifiable (Figure 8a). The bordering Buri Gandaki River was also covered by the ice and snow mass (Figure 8b). As a result of the river burial, the stream could have become dammed, which would have increased the risk and intensity of flooding within the upper Buri Gandaki system.



(a)

(b)

Figure 8 On April 21, 2008, south of measurement point 11 at 3720 m a.s.l. a) Photo 3 Facing west: The avalanche slid down from the orographic right slope (⬇) and built a ridge-like formation about 40 m wide (◡); b) Photo 4 Facing east: The Buri Gandaki River system (◯) and trekking path were covered by an avalanche.

Figure 9 Photo 5 on April 20, 2008, at 10:05 am on the river-left flank of the valley facing the Manaslu glacier: A snow and ice avalanche slumped from the Manaslu glacier into the glacial Birendra Kund Lake. The momentum produced a surge that was diverted into the Buri Gandaki stream and destroyed a nearby bridge.

Figure 10 Photo 6 on April 20, 2008, at measurement point 9 at 3520 m a.s.l., facing southeast: The bridge was destroyed by an avalanche surge on April 20, 2008. The weathering effects and erosional processes on the boulder (---) are indicative of past floods.

3.2.3 Flood risk and consequences for the Birendra Kund glacial lake

During field research on 20.04.08 at 10:05 am (Figure 9), a naturally triggered ice and snow avalanche that slid down from the Manaslu glacier to the glacial Birendra Kund Lake (Appendix 1) was observed. These high-energy dynamics induced a flood and pressure wave that spread out into the proglacial Birendra Kund Lake and the adjacent section of the river. These processes led to the destruction of a wooden bridge (Figure 10). Even after two hours, the flow dynamics and discharge of this cross profile were extremely turbulent (see Section 3.1).

These related flood effects could be directly observed at the end of the hanging Manaslu glacier tongue. Above the glacier snout, the longitudinal crevasses provided an indication of the steep glacial slope (Figure 11) and suggested that shear stress was dominant over shear strength (Winkler 2009). However, several crevasses were formed by the brittle behaviour of the ice in the shear surfaces (Figure 11). The steep glacial slope caused a section of glacial tongue to break off, creating a snow and ice avalanche. This material slid down the slope

Figure 11 Photo 7 on April 23, 2008, at ca. 4500 m a.s.l., facing south-southeast: Crevasses have formed along shear surfaces due to the plasticity of the ice (⬇). As a result of the steep glacial slope, a portion of the glacier tongue broke off (⬋), producing ice and snow avalanches.

(Figure 11) and fell directly into the glacial Birendra Kund Lake at an elevation of ca. 3636 m a.s.l. (ca. 28°35'47.11" N, 84°37'43.16" E; Figure 12 and 13). As a result of these accumulation processes, the water level of the proglacial lake rose and increased the discharge of the glacier stream. Even higher water levels in recent decades have been verified by paleoflood indications on the Birendra Kund glacial lakeshore (Figure 12 and 13) and along the proximal riverbed.

Therefore, flood events with similar or higher intensities can destroy downstream infrastructure, including bridges and trails (Figure 10). Such natural hazard events are characteristic of high mountain valleys (Hewitt 1997; Kuhle et al. 1998).

3.2.4 Past flood events and their consequences near the village of Deng

Narrow valleys, subglacial gorges and small channels without wide floodplains are several influential factors observed in the upper reach that could increase the risk of flooding. As a result, the river could spill over the river plains with a higher intensity. Naturally, the flooding events require a period of time to traverse the whole course of the Buri Gandaki, and paleoflood events beneath the village Deng (1885 m a.s.l.) (Appendix 3) provide an example: the floodplain at this cross profile was not well developed, and the accumulated rocks, which have a length of 6 m, increased the turbulent flow dynamics of this river reach. Because of flooding events, fluvial erosion has cut into the bedrock, and this feature is indicative of previous

Figure 12 Photo 8 on April 22, 2008, at 4450 m a.s.l., facing east: Ice and snow avalanches generated by the Manaslu glacier increase the risk of local floods (◌). However, the moraines protect the neighbouring regions from laterally induced flood waves.

Figure 13 Photo 9 on April 22, 2008, at 3618 m a.s.l., facing west: Ice and detritus accumulated 2 m above the recent glacial lake level of the Birendra Kund (○). This material slumped down from the Manaslu glacier (⬇) as an ice and snow avalanche (see Figure 9).

floods in this river reach (Figure 14). Furthermore, the vegetation cover at the riverside clarifies the limitation of past flood lines in recent decades (Figure 14). The high water levels are localised at approximately 2.40 m to 2.80 m above the recent water line (Figure 14). The sum of the recent water level during the field investigation (2 m) and the high water levels varies from 4.40 m to 4.80 m, with an arithmetic average of 4.60 m.

The paleoflood levels illustrate historical flood events in the Buri Gandaki at an altitude of 1885 m a.s.l., and the destroyed bridge (which was flooded in 2008 before the fieldwork occurred), accumulated cobbles on the right side of the river, and fluvial erosion of the boulders are all indicative of the significant discharge of past floods (Figure 14).

3.2.5 The meandering floodplain between the Dhoban and Jagat settlements

The river morphology of the valley between the Dhoban and Jagat settlements (1246 m a.s.l.) (Appendix 4) illustrates the well-developed floodplains of the meandering Buri Gandaki. The accumulated boulders within this riverbed were eroded during paleofloods (Figure 15). As a result of these past floods, cobbles and finer sediments accumulated on the riverbed floodplain, and the solid rock on river right became eroded (---) and weathered (Figure 16). These morphological features indicate evidence of paleoflood events. Therefore, the paleoflood level was likely approximately 1.6 m to 2 m above the existing water level (Figure 15). The sum of the observed

Figure 14 Photo 10 on April 26, 2008, at measurement point 6 at 1885 m a.s.l., facing upstream: The erosional effects on the boulder (--) and plant cover near the riverside (◌) are indicative of the Holocene river stages. The bridge was previously destroyed by flooding and was temporarily repaired.

Figure 16 Photo 12 on April 14, 2008, at measurement point 4 at 1246 m a.s.l., facing upstream along the Buri Gandaki: The Buri Gandaki deposits sand and gravel between previously deposited boulders (◌) during paleoflood events. The morphology of the riverbed illustrates the meandering patterns and pool-riffle sequences, which result from varying discharge. Rockslides have occurred on the orographic right side of the river (↓). In the past, these processes likely induced damming.

Figure 15 Photo 11 on April 14, 2008, at measurement point 4 at 1246 m a.s.l., facing downstream along the Buri Gandaki: Fluvial erosion marks on the boulder (◯) and accumulated sand and gravel above the recent water level (◌) illustrate the paleoflood levels attained during floods. The fluvially polished boulder (↓) indicates the minimum level of past flooding. The pool-riffle riverbed morphology is composed of detached step-pool formations (step: ■ pool: ●).

water level (here 1.4 m) and the paleoflood levels ranges between 3 m and 3.4 m. Consequently, the arithmetic average of 3.2 m represents the paleoflood stage. Furthermore, a meandering channel shape was observed. At the end of this valley, the meander-forming processes cease, and the valley becomes narrower, which increases the water level within this short river reach. Moreover, the relief results in rockfall that accumulates within the riverbed on the river-right side of the transition into this narrow valley. Consequently, these processes build a natural dam that can block the stream (Figure 16). The water level can rise at this survey site during higher discharge events. In the first step of these related processes, the floodplain minimises the risk of rising high water by serving as a flood buffer. However, if the water level continues to increase during such an event, the terraces bordering this river reach can be flooded. The accumulated and sorted sediments of these terraces testify to the strength of the paleoflood dynamics (Figure 15).

3.2.6 The river dynamics south of the Macha Khola settlement

South of the Macha Khola settlement (ca. 839 m a.s.l.), meanders and wide floodplains along the Buri Gandaki were investigated (Figure 17, Appendix 5). These meandering, pool-riffle and floodplain patterns depend on a high frequency of fluvial discharge and sedimentation changes (Buffington and Montgomery 2013), which illustrate the high-water dynamics of this river reach. During high-water events, which mostly occur during the monsoon season, the water levels of this river reach increase. Consequently, the bordering floodplain becomes submerged.

3.3 The response of local inhabitants and their adaptions to flooding in the Buri Gandaki Valley

During the monsoon season and the snow- and ice-melting season in summer, the water level of the Buri Gandaki can rise. Due to these annual floods, the local inhabitants in the upper and middle reaches of the Buri Gandaki primarily build their villages and houses far beyond the floodplains. Observations during fieldwork and houses mapped with the help of satellite image datasets confirm this practice and indicate that the ethnic groups primarily build their villages on the lower, middle and upper terraces (Figures 18,19 and 20, and 21 a, b, c, d). These plains are a type of natural platform that protects the houses from rising water levels during floods (Figures 18, 19 and 20). In contrast, rare, intense flood events outside of the normal range of floods, such as those triggered by natural hazards, e.g., high-intensity monsoon precipitation falling in the upper reach, earthquakes that cause snow and ice avalanches to cascade into a glacier lake (such as the Birendra Kund), or natural dam failures, are more likely to cause destruction within the Buri Gandaki Valley. Due to the variability in flood intensity, portions of local bridges and trails could be destroyed by intense or even normal flood events. However, the houses in the local villages in the upper reach are far beyond the areas that experience normal and/or intense flooding. Samagaun Village (3520 m a.s.l.), which is located approximately 600 m southeast of the Birendra Kund glacial lake and approximately 165 m from the shore of the Buri Gandaki, is built outside of the natural hazard zone. The local inhabitants of this village are aware that the temporary flood

Figure 17 Photo 13 on April 13, 2008, at ca. 820 m a.s.l., south of the Macha Khola settlement, facing downstream: In the non-monsoon season, the local people settle by the riverside of the Buri Gandaki and build a market stall and food stand for the transient porters and trekking tourists.

Figure 18 Satellite image of the Samagaun settlement and adjacent Buri Gandaki River (ca. 28°35'24.69'' N, 84°38'29.93'' E) at 3542 m a.s.l. The red line that starts at the riverside and ends at the centre of the circle represents the distance between the Samagaun settlement and the Buri Gandaki River, i.e., approximately 165 m. The approximately 80-m-high river-right Birendra Kund lateral moraine forms a natural dam. This glacial landform protects the adjacent valley, including Samagaun village, from splash waves generated in the lake. Therefore, the potential flood waves cannot flow southeastward, and the flow must follow the course of the river.

Figure 19 Satellite image of the riverbed adjacent to the Macha Khola settlement (ca. 28°13'44.31'' N, 84°52'27.99'' E) at 839 m a.s.l. The red line that starts at the riverside and ends at the centre of the circle represents the distance between the Macha Khola settlement and the Buri Gandaki River, i.e., approximately 130 m.

Figure 20 Satellite image of the meandering river and floodplain between the settlements Dhoban and Jagat (ca. 28°19'40.36'' N, 84°54'21.73'' E) at 1248 m a.s.l. The red line that begins at the riverside and ends at the centre of the circle represents the distance between the wooden huts and the Buri Gandaki stream, i.e., approximately 76 m.

waves generated in the Birendra Kund glacial lake can flood the adjacent river plain and can damage infrastructure (Figure 10). Consequently, they use the local landscape and landforms for protection against normal and intense flood events (Figure 18).

In a limited number of cases within the middle reach, the local people build their villages, such as the Macha Khola settlement (ca. 839 m a.s.l.), near small streams that flow directly into the Buri Gandaki (Figure 19 and Figure 22). These streams are used for irrigation of farmland and as a water source for grazing livestock. In this arrangement, the village is built above the floodplain, thereby protecting the villages from annual bankfull discharge events. However, during rare, intense flood events, a few farming and working houses built in detached peripheral areas of the settlements, such as those adjacent to the main settlement areas of Macha Khola, may be destroyed.

Outside of these mostly protected villages and houses, a few individual wooden huts and food stands may be destroyed even during annual normal flood events. Following the rainy season, the ethnic groups on the meandering floodplain between the settlements Dhoban and Jagat construct wooden huts and market stalls that are approximately 76 m away from the stream (Figure 20) on the river-left floodplain directly beside the summer trail, where they sell local and mass-produced food to porters and tourists (Figure 20; Figure 16). If the floods increased to a certain degree, these huts could be destroyed. As a result of the high-water dynamics, the ethnic groups in this narrow valley section built high-water trails on the river-left valley flank that can be used during the monsoon season. These types of adaption strategies were also observed downvalley from the Macha Khola settlement (ca. 839 m a.s.l.), where the settlers and merchants also built market stalls for the transient porters and trekking tourists (Figure 17). At the survey site, the wooden huts are taken apart and rebuilt on the river-right flank 24 m above the riverside when the rainy season begins and water level of the Buri Gandaki increases.

These observations demonstrate that the houses within the main settlement areas of the villages in this valley experience no risk of intense

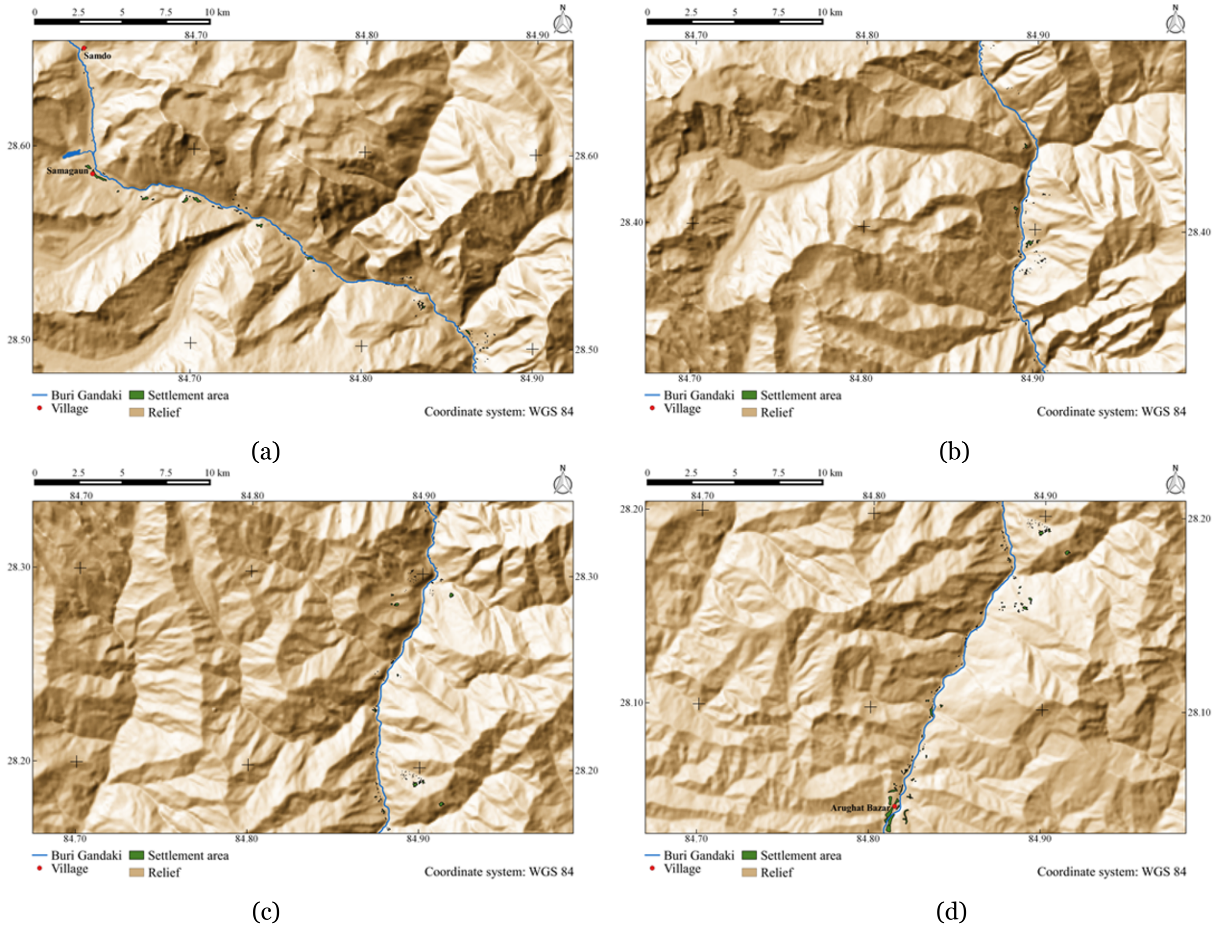


Figure 21 Map of the Buri Gandaki stream and settlement areas, which were mapped via GIS in 2014. The digital elevational model (DEM) is based on SRTM datasets.

flooding, even during rare intense flood events, due to the local knowledge of possible high-water patterns in this valley among the ethnic groups.

4 Summary of Flood Events and Their Consequences for Valley Residents

This research has shown that the highest historical flood levels and the lowest cross-sectional river width to depth of the Buri Gandaki occurred in the upper reach between 2160 and 1710 m a.s.l. The floods were mostly the result of seasonal fluctuations in the Buri Gandaki River dynamics. Moreover, glacial fluctuations and snow and ice avalanches can induce annual normal flood events with varying intensities in the upper Buri Gandaki watershed. These flood events can destroy bridges and summer trails downvalley. Consequently, the sources of these natural hazards are associated with glacial tongues and areas adjacent to zones of snow and ice avalanches within the upper part of the Buri Gandaki

Figure 22 Photo 14 on April 13, 2008, at measurement point 19 at 820 m a.s.l., facing the riverside of the Buri Gandaki: The vegetation cover near the floodplain (◯) indicates the maximum level of past flood events over the last several years. During rare intense flood events, the working hut could be destroyed.

(Appendix 1 and Figure 3). In contrast to the upper reach, lower flood level marks, higher cross-sectional river width to depth, and primarily well-developed floodplains were observed downvalley between elevations of 1710 and 780 m a.s.l. However, high flood levels can still be achieved in the middle reach in certain short river sections with narrow gorges, such as the river reach upvalley of the Dhoban settlement immediately downstream of the meandering patterns (Section 3.2.5). Additionally, the discharge data show that the discharge increases to the highest observed level of 154 m^3/sec within the meandering river section at 1246 m a.s.l. (Section 3.2.5). Downstream, the discharge decreases to values between 71 m^3/sec and 32 m^3/sec (Figure 4). Overall, the morphological river characteristics indicate a general decrease in the natural flooding of the middle reach downvalley. The discharge datasets confirm these morphological findings.

Further conclusions can be drawn by observing the anthropogenic reactions to these floods, which include the ethnic groups of this valley using their local knowledge to take safety precautions against floods and high discharge events on the Buri Gandaki. This phenomenon is exemplified by the settlements, which are located above the stream floodplains. Even during peak flooding in rare, intense flood events, only a few isolated farming houses and working huts built outside of the main settlements would be destroyed in the middle reach. Furthermore, the residents of this valley have built high water trails, which are used during flood events during monsoon season. During the non-rainy season, they build wooden huts on the floodplain to sell food. This type of human adaption, usage and transformation of local landforms is a typical phenomenon in remote mountain valleys (Iturrizaga 1996; Hewitt 1997). These circumstances are discussed in the literature as intersystem interference between human and environmental systems with numerous types of "feedbacks and interactions" (Harden 2012). Overall, the observations indicate that the vulnerability of the local ethnic groups to annually occurring natural hazards is reduced as a result of existing local knowledge and local safety precautions that protect against flooding.

5 Concluding Remarks: A Perspective on Changing Vulnerability at the Local Scale

Paradoxically, our implementation of protection strategies and technologies that should protect against "natural hazards" could increase the vulnerability of the ethnic groups in the remote mountain valley by affecting local knowledge and the perception of "natural hazards" (Hewitt 2013a, b). The implementation of protection is only the first step in our urbanisation and economic strategy (Hewitt 1995), which aims to achieve a pronounced economic and industrial society in remote valleys in the Himalayan Mountains.

In addition to this social influence, the natural balance between river morphology and river behaviour is being changed as well. On a global scale, urbanisation and economic strategies that promote engineering projects, such as dam building, river restoration, tourism and infrastructure building, change the overall river environment, especially the river morphology and sedimentation processes (Chin 2006) in the Himalaya. As a result of this urban development, "technological hazards" may increase. Due to these external human-triggered hazards, the vulnerability could also increase at the local scale.

Consequently, the expanding urbanisation in high mountain valleys, which begins with implementing protection strategies and technologies followed by a change in landscape processes through engineering projects, can cause a sharp increase in vulnerability. As a result of this externally instituted overexploitation, a collapse of ethnic groups (Diamond 2005) in mountain valleys may occur. Thus, an appropriate question is whether we should rethink our urban development strategy for the local societies in remote high mountain valleys, such as the Buri Gandaki Valley in the Himalaya, with respect to the near-future changes associated with the Anthropocene.

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