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The Pokhara May 5th flood disaster: A last warning sign sent by nature?

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ABSTRACT

The flood disaster of May 5th, 2012 in Pokhara Valley, Nepal, taking the life of at least 72 people, is explained by a so-called sturzstrom. It developed from a huge rockfall onto a glacier in a high-mountain depression and then transformed into a subsequent debris flow/hyper-concentrated flow devastating the upper reaches of Seti Khola Valley. Apparently, the same processes have formed the smooth terrace landform of Pokhara Valley during Holocene times: two gigantic debris-flow events were identified and dated to have occurred about 12,000 and 750 years ago. Both epochs were associated with global warming processes. During these debris-flow events the whole valley was filled by 3-5 km^3 of debris transported from the same huge high-mountain depression called Sabche Cirque where the recent debris flow came from. A new catastrophe of similar size would have an apocalyptic impact: about half a million people live in the valley today. A detailed investigation of the circumstances of the disaster on May 5th, especially the possible influence of global warming on the trigger of the disaster, and a reliable forecast of a potential recurrence of similar events or of even much greater scope, are urgently required. For this, the thorough understanding of the conditions, triggers and mechanisms of the huge flows in the past to compare it with the recent flood is indispensable as well.

Key words: Pokhara Valley, May 5, 2012 disaster, Holocene giant debris flows

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INTRODUCTION

Geological background

The beauty of Pokhara Valley in Western Nepal with its nearby high-mountain Annapurna range (Fig. 1) is world-famous. The smooth landscape of the valley floor and the lovely Lake Phewa are, however, the results of at least two gigantic debris-flow events (Yamanaka et al. 1982; Fort 1987). One took place 12,000 ± 1000 B.P., at the end of the last glaciation (Koirala and Rimal 1996; Koirala et al. 1998), and led to the so-called Ghachok Formation; it filled the valley with an up to 60 m thick cover of debris which consists of well-cemented (and meanwhile karstified) matrix-supported conglomerates with grain sizes ranging between silt and huge boulders. The source area of the (originally) glacial sediment masses has been identified to be a large high-mountain depression northeast of Machapuchre peak (Fig. 2), the so-called Sabche Cirque (Yamanaka et al. 1982; Fort 1987).

The second event of similar size and nature occurred 750 ± 50 B.P. (Koirala et al. 1998; Hanisch and Koirala 2010) and resulted in the "Pokhara Formation"; several km^3 of mud and debris of all sizes were transported by debris flows to fill the Pokhara Valley again to a level of up to 60 m (Yamanaka et al. 1982; Fort 1987). All tributary valleys were blocked and lakes quickly have formed three of which are still existent today; all others were filled with lake sediments from which most of the datable material originates. The flat gently inclined surface of these debris-flow sediments and the terraces carved into them form the basis of the densely populated Pokhara Valley (Koirala et al. 1996).

Debris flow/flash flood of Seti Khola on May 5th, 2012

In the morning of May 5th, 2012 the people living in the northwest of Pokhara got frightened by a strange thunder which quickly approached. Some of the village inhabitants nearby the Seti Khola (meaning "White River" in Nepali) understood the warning sign and ran to higher areas; many others were swept away by the first surge of a fast-flowing debris flow/flash flood/hyper-concentrated flow (Fig. 3). First speculations of the origin of the flood to come from the burst

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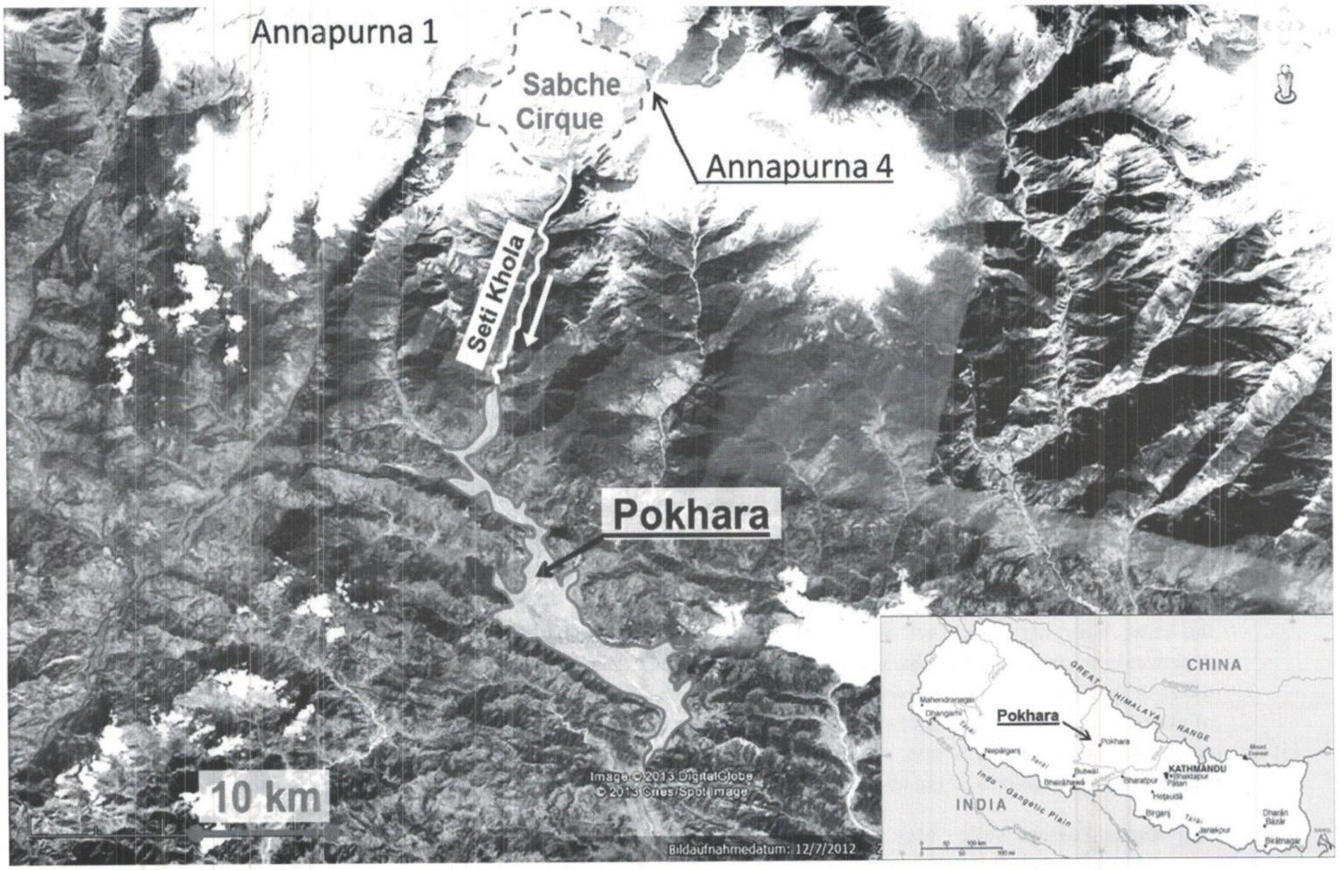

Fig. 1: Google Earth view of Pokhara Valley with Annapurna Range in Nepal. Path of debris flows along Seti Khola (blank) from Sabche Cirque down to Pokhara Valley filled with debris from former events (light grey).

of a glacier lake (GLOF) were rejected by ICIMOD (2012); instead a temporary blocking of the river by a landslide was proposed to have been the cause of the disaster. Only when a video was published taken by Capt. Maximov of Avia Club Nepal (2012) during a regular sightseeing flight, it became obvious that the source area lies high in the mountains in the Sabche Cirque (Fig. 2) northeast of Machapuchre peak (Petley 2012a; 2012b).

A huge light brown cloud is visible on the video taken by Capt. Maximov during the relative video time from 2:03 through 2:19 minutes (Fig. 4). On an earlier turn of this flight no such cloud is present in the video until video time 0:52. The initiation of the cloud formation has therefore been dated in between these two relative time marks (Petley 2012b). From the data analysis of the global seismic network, Colin Stark and Goeran Ekstroem of Lamont-Doherty Earth Observatory at Columbia University, New York, USA, spotted a big rockslide in the upper reaches of Seti Khola in the morning of May 5, 2012 (Petley and Stark 2012). This earthquake was also recorded by several stations in Nepal (Duvadi and Sapkota 2012). Putting these data together they concluded that the flood was triggered by a major rockfall from one of the western steep slopes of Annapurna IV (7525 m). Through a comparison of the satellite images of April 20th and May 6th 2012 (Fig. 5) Petley and Stark (2012) found that a major slab of rock is missing at the crest line in the picture of May 6th. The volume of this slab was calculated to be about 22 million m^3. According to their seismic analysis the impact of the rockfall was at 9:09:56 a.m. local Nepal time (9:09:44.51 a.m., Duvadi and Sapkota 2012). The impact should have happened between the relative video times 0:52 and 2:03, the short interval of just 71 seconds between the picture of 0:52 where no cloud is visible, and 2:03 with the full development of the cloud (Fig. 4).

Capt. Maximov immediately understood that this cloud was something absolutely beyond normal snow avalanches, turned back and observed a fast running flood rushing down the Seti River. He sent a warning to the airport tower in Pokhara from where, after some discussions, it was distributed via VHF; many lives certainly were saved by this brave action (Dixit 2012). For the people living near

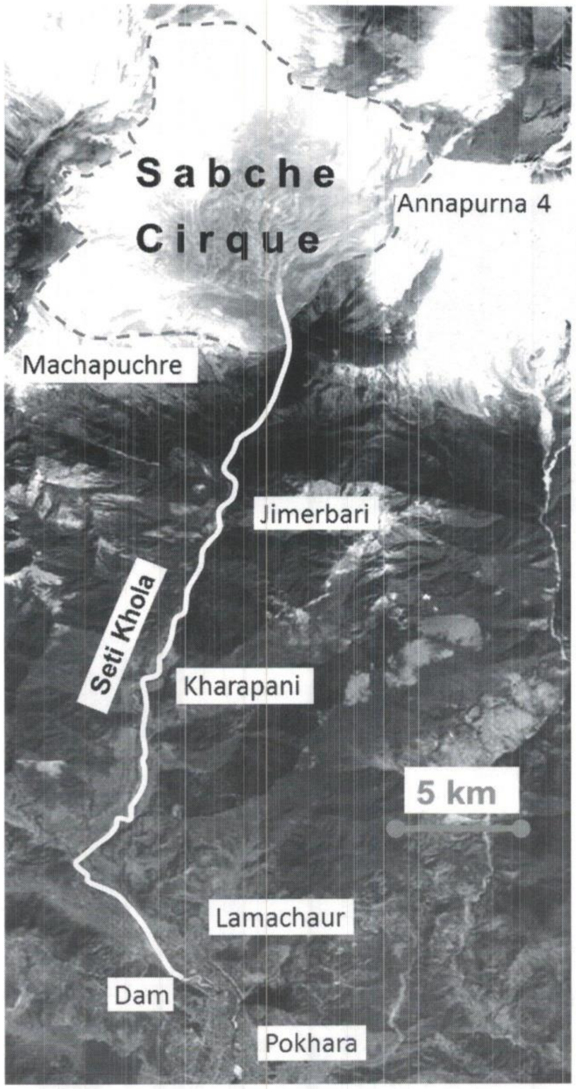

Fig. 2: Google Earth view of upper Seti reaches with high-mountain depression Sabche Cirque. Path of debris flows along Seti Khola from Sabche Cirque down to the irrigation dam near Lamachaur.

the river in Kharapani this warning unfortunately came too late (Fig. 3) when the first surge of the flood arrived at 9:38. The next time mark of the front was recorded at 10:35 near the irrigation dam about 20 km downstream of Kharapani (Bhandary et al. 2012). Near Kharapani the front of the first surge was described to have been as high as 30 m (Bhandary et al. 2012; Shrestha et al. 2012). The number of surges (roll waves) of the debris flow/hyper-concentrated flow is reported to have been between 8 and 27.

DISCUSSION AND SYNTHESIS OF EXISTING DATA

Analysis of published details of the disaster

The course of events of the disaster can be reconstructed from the close analysis of satellite images, the published aerial photos, and the observations published in internet.

(i) There is now a general accordance that the disaster was initiated by a huge rockfall from the steep western slope of Annapurna IV hitting on the flatter area at the toe of the slope; the impact generated an earthquake of 4.3 on the Richter scale (Petley and Stark 2012; Bhandary et al. 2012; Dwivedi and Neupane 2012).

(ii) The volume of the rockfall of 22 million m^3 calculated by Petley and Stark (2012) is, however, over-estimated because the scale given on the satellite images (Fig. 5) is not correct: instead of the 2 km indicated it should be 1 km. Bhandary et al. (2012) calculated the top area of the missing slab to be 32,000 m^2. This points to a volume of 10 to 15 million m^3 of rock which detached from the slope.

(iii) Petley (2012b) concluded from the satellite image taken on May 6th (Fig. 5b), on which large brown patches are visible at the toe of the slope, that these patches represent

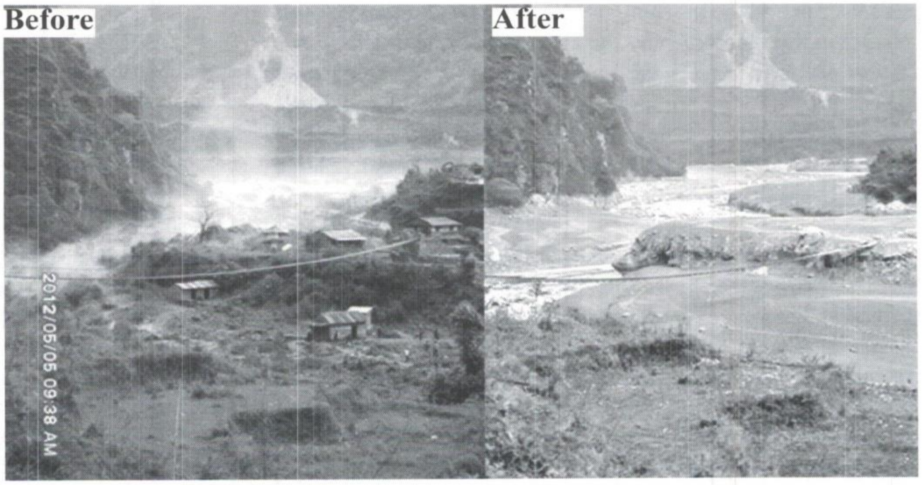

Fig. 3: The disaster near Kharapani village: first surge to the left killing numerous people, and the situation after the disaster (Photos: Milan Thapa, courtesy Kunda Dixit (2012).

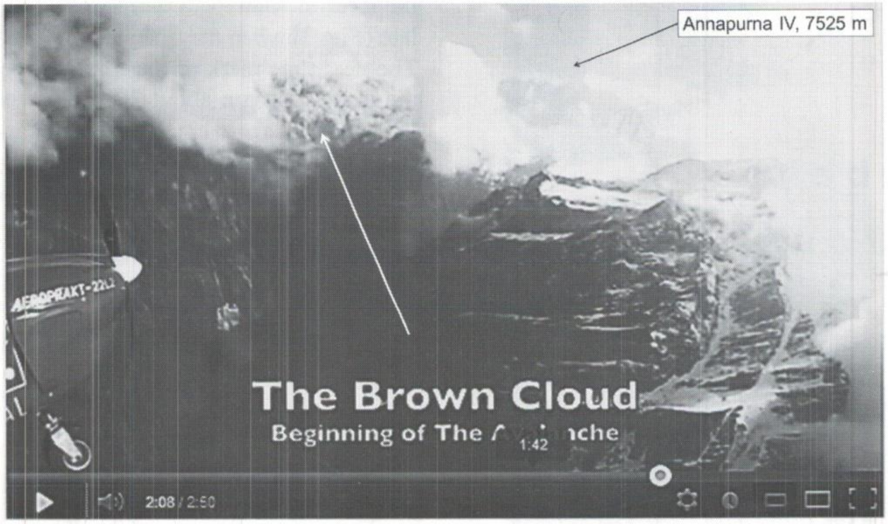

Fig. 4: Aerial video photo taken by Capt. Maximov on May 5th, 2012 at about 9:11 a.m. from the high-mountain Seti Khola gorge showing a huge brown cloud (partly covered by rock and clouds). Annapurna IV in the background to the right, video time 2:08. Courtesy: Avia Club Nepal.

landslide debris (or of debris flows) created by the rockfall on May 5th. The brown area of 1.5 x 1.3 km north of it is interpreted to be wind-blown dust from this event. The large area of light-brown colour in the centre of Sabche Cirque (Fig. 5b) is astonishingly ignored in this view. An open question arises from Petley's interpretation: how did the main part of the rockslide/avalanche reach the deep central part of the Sabche Cirque to run out from there down the Seti Khola gorge? Petley (2012b) speculated that some narrow gorges might have been the channels to lead the debris flow down to the centre of the depression and to the exit of the huge depression (Fig. 6).

(iv) A close view on the images of Fig. 5b reveals, however, that the large patches of landslide debris and dust identified by Petley (2012b) are lying upon a thin layer of fresh snow which must have fallen between the main event on May 5th and the morning of May 6th (the abundant clouds visible in the video of May 5th can corroborate this finding). The fresh snow covers the sediments left by the avalanche/debris flow of May 5th above the altitude of about 4000 m. The brown patches on the May 6th image (Fig. 5b) therefore should be the result of a later smaller event; usually, large rockfalls are followed by smaller secondary events.

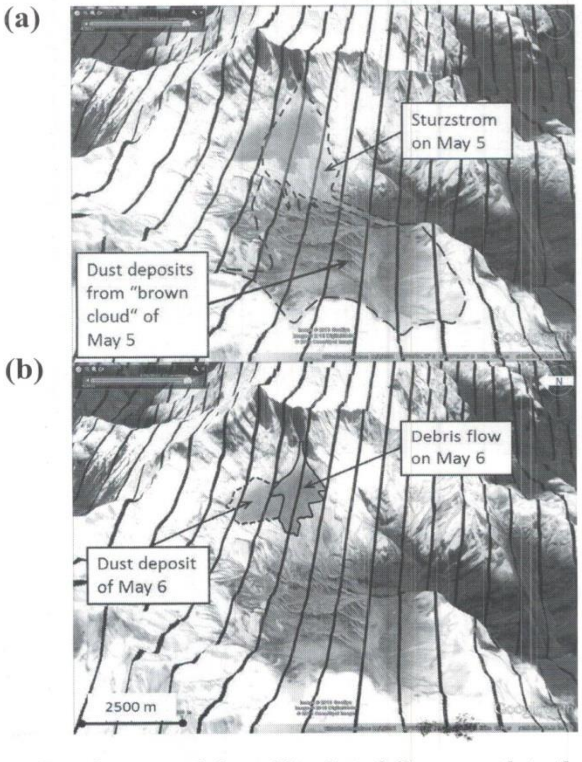

Fig. 5: Satellite images of Sabche Cirque of May 6, 2012 (black stripes from partial satellite data failure, north to the left). (a) Upper picture shows the situation before the event, the lower one day later (black stripes from partial satellite data failures). The event happened on May 5. The central part of Sabche Cirque on May 6 is covered by similarly coloured material like in the eastern area ("landslide debris", "dust"). West boundary of deposits in the shape of lobes seems to indicate the ends of debris flows (Petley 2012b). (b) On lower picture fresh snow is present just west of the areas of "landslide debris" and "dust" thus certainly also underlying these deposits. The snow covers the brown colours of the first big event of May 5; the snow therefore must have fallen after the main rockfall event. This signifies that the lobe-shaped patches and the "dust" should originate from a (smaller) later event between May 5 and 6. Images: Petley (2012b).

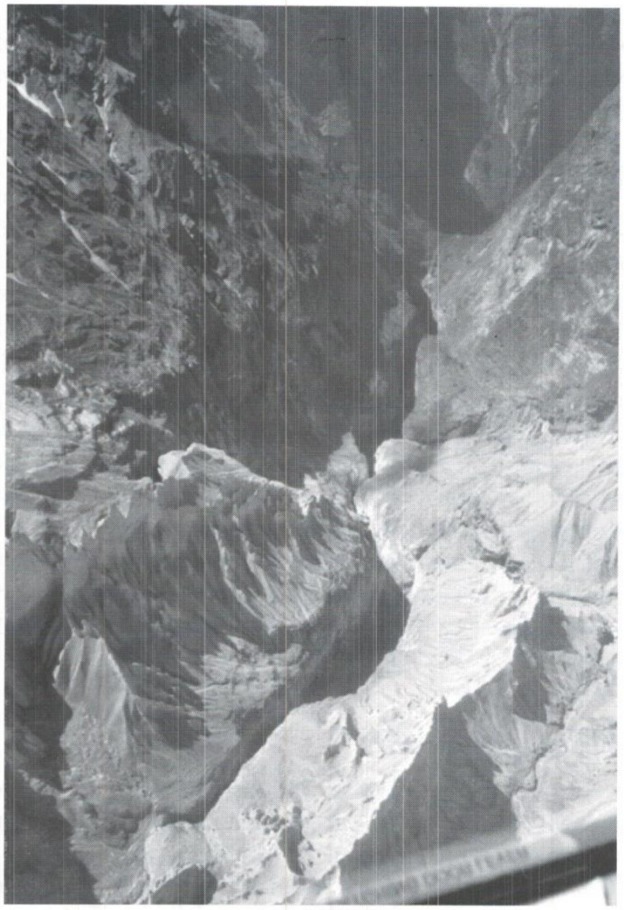

Fig. 6: Photo from helicopter of entrance area of extremely narrow Seti Gorge, the spillway of Sabche Cirque showing light-grey fine sediments (lake sediments or glacial flour) and light-coloured dust cover to the middle right. Courtesy: Arun Shrestha, ICIMOD, May 20, 2012.

(v) The aerial photo of the area in question, taken by Capt. Maximov on May 20th (Fig. 7) demonstrates unequivocally that the rock avalanche/debris flow (or what so ever it was) rushed continuously from the impact area at the foot of the rock slope down to the centre of Sabche Cirque. The path had a width of up to 2 km (Fig. 8).

(vi) The recent high-resolution Google Earth images of the area (Fig. 8) before and after the event do not leave any space for a different interpretation: the flow of May 5 vigorously rushed down to the bottom of Sabche Cirque eroding all kinds of loose debris and vegetation. Also, the extremely rugged glacier crevasse surface seen in the picture of March 23, 2012 (Fig. 9) was smoothed-either grinded by erosion or the deep cracks and trenches were filled by debris (or both).

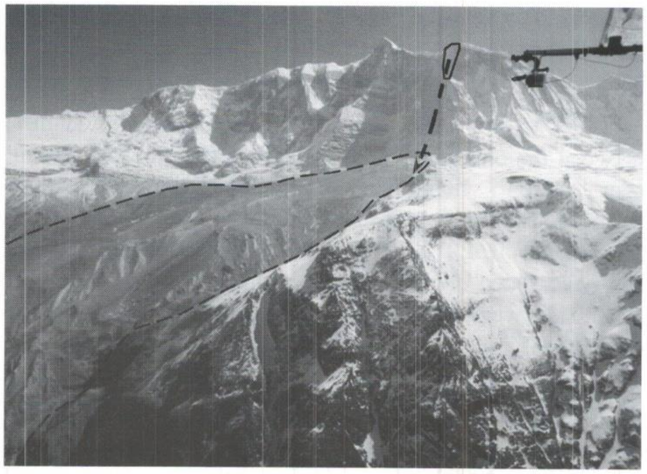

Fig. 7: Aerial photo of taken by Capt. Maximov on May 7, 2012 showing Annapurna IV peak (7525 m), the detachment slope of rockfall and the wide area overrun by the sturzstrom (dashed line) which was created by the rockfall and impact at the foot of the slope. Courtesy: Avia Club Nepal (2012).

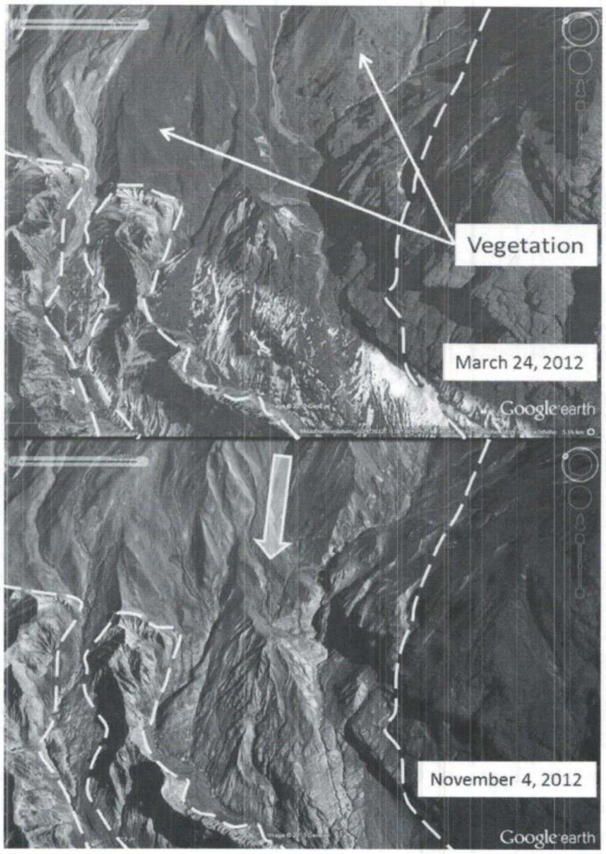

Fig 8: Pair of Google Earth high-resolution 3D images of March 24, 2012 and November 4, 2012.

(vii) The events of May 5 and 6 that have taken place in the Sabche Cirque are summarized in Fig. 10. The events of May 5 and 6 are summarised in Fig. 10.

(viii) Most of the debris flow/hyper-concentrated flow between the entrance of the Seti gorge (Fig. 6) and its end near Jimerbari village (Fig. 2) remains in the dark because the gorge is extremely deep and narrow (Regmi et al. 2012, Shrestha et al. 2012). For this reason the Sabche Cirque has never been climbed before and the crew of Regmi et al. (2012) were the first to touch ground of the Sabche depression.

(ix) The next time mark is a breath-taking picture (Fig. 3) showing the huge front of a debris flow/flash flood/hyper-concentrated flow reaching the area of Kharapani village (Dahal et al. 2012) which is dated 9:38 a.m. Houses and several farmers can be seen there seconds before they were swept away by the flood. Provided that the clock of the camera registered the correct local time (we are aware of that this time mark is crucial for all the further calculations but it has been used as reference time in all investigations hitherto), the picture should have been taken between 9:38:00 and 9:38:59 a.m. (as no seconds were recorded). The average value of this timing is 9:38:30. That means the travel time of the sturzstrom and the subsequent debris flow from the impact area at the toe of Annapurna IV to Kharapani was T = 9:38:30-9:09:56 min.± 30 sec.=29:26 min. ± 30 sec.=1766 ± 30 seconds. Considering all windings of the river bed and the difference in altitude of about 4,500 m, the length of the travel path from the impact zone till Kharapani was 23.5 km (Fig. 11). This results in an average velocity of about 13.3 m/s or 48 km/h (which is at the upper limit of debris flows).

(xi) The last time mark comes from photos taken at the irrigation dam southeast of Lamachaur: there the first wave reached the dam at 10:35 (Dwivedi and Neupane 2012). The distance between Kharapani and the dam is about 20 km signifying that the flow had an average velocity of 5.8 m/s (Fig. 11). This is in accordance with the impressions taken from the many videos of the flood published in the internet where it can be observed that the front was considerably faster than the flowing river water.

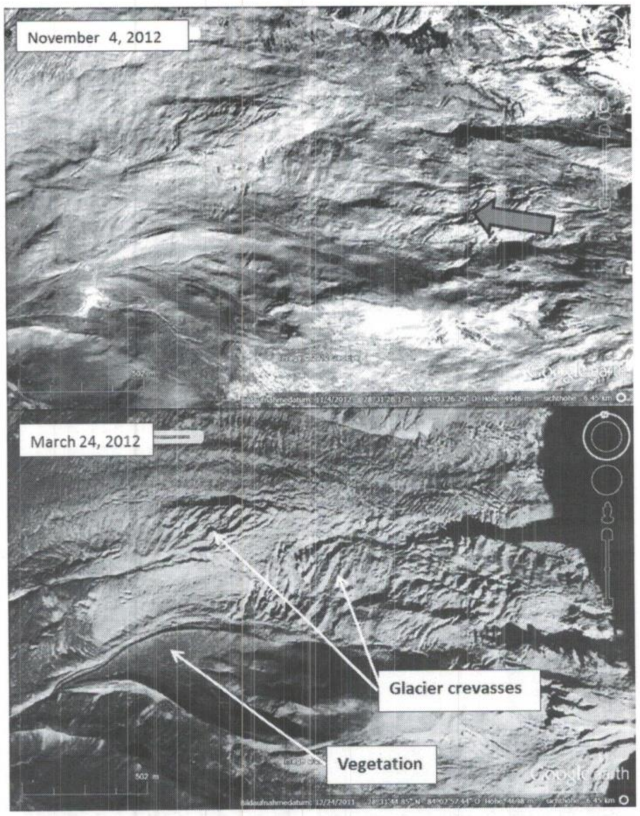

Fig. 9: Pair of Google Earth high-resolution images of March 24, 2012 and November 4, 2012 showing the extremely rugged glacier crevasse surface before and the smoothed surface after the sturzstrom event just west of the toe of the failed rock slope of Annapurna IV; flow was from right to left.

Summary of the events

In the morning of May 5th, 2012, a major wedge of rock with some snow cover detached from one of the steep western slopes of Annapurna IV. The almost free fall of, say, 1000 m (1500 m according to Bhandary et al. 2012) should have lasted 14 seconds; the impact velocity according to this model was 140 m/s. The impact at the foot of the slope at about 5,500 m altitude occurred at 9:09:56 a.m. local Nepal time. As a result of the heavy impact, the falling rock mass must have been totally disintegrated or even pulverized. It has certainly removed substantial ice masses from the glacier at the bottom (Dwivedi and Neupane 2012, cf. Huggel et al. 2005). A kind of rock/ice avalanche (sturzstrom) developed together with a huge cloud. The sturzstrom is likely to have consisted of rock fragments, pulverized rock, snow, pulverized glacier ice, and water from melting by the impact. It moved towards the bottom of Sabche Cirque along an up to 2 km wide path (Figs. 7, 8, and 9) which is 15o to 30o steep and reached the mouth of the Seti gorge (Fig. 6). There, by an up to date unknown process, the sturzstrom transformed into a debris flow/hyper-concentrated flow and entered the narrow gorge of upper Seti Khola leaving plenty of trunks (Bhandary et al. 2012), rock, and ice behind (according to Capt. Maximov in Dixit 2012).

The brown cloud which developed during the rockfall and from the impact took a somewhat different path: after having moved with the sturzstrom to the centre of the depression, it continued moving toward the southwest and apparently run up the eastern slopes of Machapuchre (Fig.

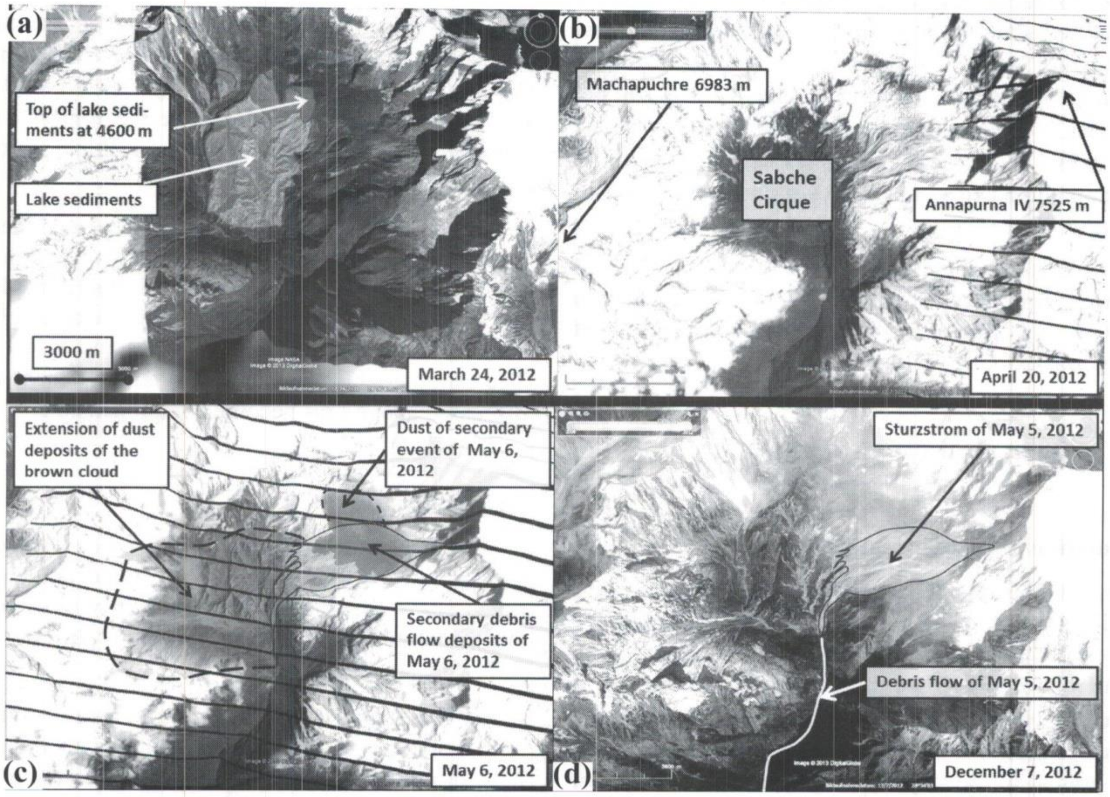

Fig. 10: Summary of the events in Sabche Cirque documented by the Google Earth images of March 24, April 20, Mai 6, and December 7, 2012. Figure 10a shows the distribution of lake sediments (or glacier flour) with flat top of the sequence at about 4600 m. Stripes in Figs. 10b and 10c from partial satellite data lack.

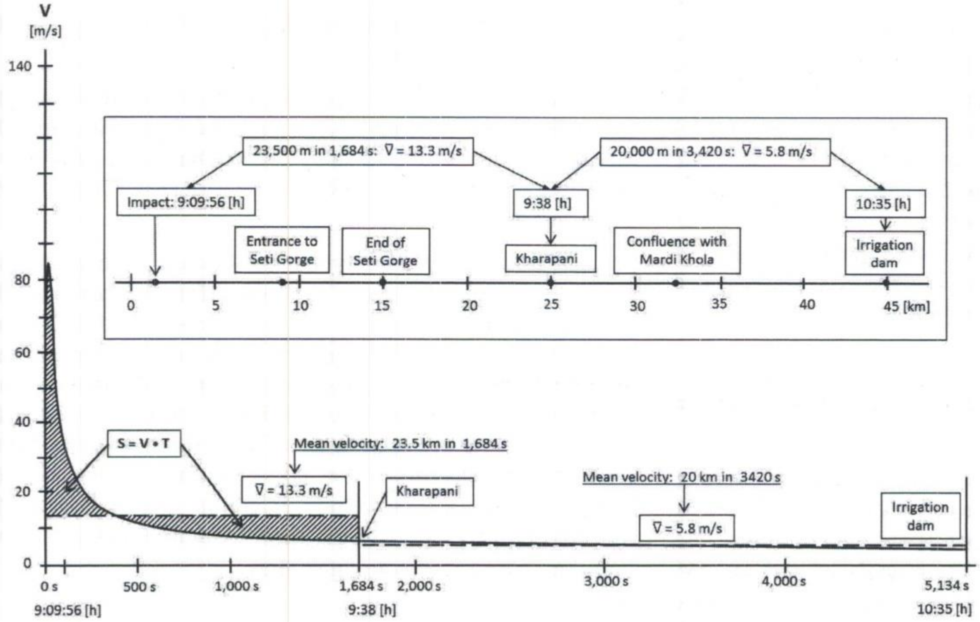

Fig. 11: Velocity versus time diagram with inferred velocity distribution from impact area in Sabche Cirque till Kharapani village and the irrigation dam (cf. Fig. 2). Given a calculated average velocity the areas above and below the average line must be equal. Length of travel path in insert diagram includes all river windings and the differences in altitude of about 5,500 m.

10). There considerable masses of snow were removed up to an altitude of about 4200 m from (Capt. Maximov, pers. comm.). In the Sabche Cirque the area covered by dust (Figs. 5b and 10) is about 20 km^2. According to results of the first field visit by Regmi et al. (2012), the thickness of this dust layer was 1 to 5 cm. That signifies that the volume of fines which precipitated from the brown cloud was between 200,000 and 1,000,000 m^3 (!).

The movements of the sturzstrom and the cloud happened in the narrow time span of max. 71 seconds (see above) meaning that the velocity of the sturzstrom and the cloud must have been extremely high.

REMAINING QUESTIONS

Transformation of rockfalls into sturzstroms

In general, the transformation of rockfalls into sturzstroms with subsequent debris flows is still an enigmatic process (e.g. Plafker and Ericksen 1978; Huggel et al. 2005). The role of glacier ice in fast running sturzstroms is emphasised by Haeberli et al. (2004), Huggel et al. (2005), and Schneider (2011). Furthermore, the presence of glacier ice at the bottom of the slopes beneath the impact zones of the rockfalls seems to be a pre-requisite for the formation of such sturzstroms (Hanisch and Schulze 2012). According to all available images of Google Earth the impact area at the foot of the western slopes of Annapurna IV peak is covered by glaciers. The kinetic energy of perhaps 15 million m^3 of almost free falling rock (roughly 35 million tons at a velocity of 140 m/s) is calculated to be 245 billion kJ. During the impact, even at an angle of only 45°, a lot of this energy was probably consumed by the disintegration of the rock mass up to its pulverisation, the melting of snow, and by the removal of glacier ice in the impact zone as it was in the comparable case of Karmadon in Caucasus in 2002 (Huggel et al. 2005). There up to 90 million m^3 of glacier ice was removed from the bottom; the ice was shattered (Huggel et al. 2005), pulverized, melted, or possibly even transformed into steam (Hanisch and Schulze 2012).

Velocity distribution of sturzstrom and debris flow in upper Seti River reach

As inferred above, the impact velocity should have been about 140 m/s. Up to now, there is no way to estimate how much of the speed has been preserved and deviated into the sturzstrom after the impact at an angle of perhaps 45°. The slope west of the impact area at the toe of the slope of Annapurna IV is between 15° and 30° steep (Dwivedi and Neupane 2012); this should have led to an additional acceleration from gravity forces (for discussion see Huggel et al. 2005, Schneider 2011, Hanisch and Schulze 2012). Goeran Ekstroem (in Petley and Stark 2012) - from the seismic waves recorded after the impact - inferred a considerable acceleration which is well in accordance with this constellation.

In Fig. 11 an attempt is made to balance the velocities during the flow: for the average velocity of 13.3 m/s from the impact area to Kharapani and for 5.8 m/s from Kharapani to the irrigation dam it is necessary that the areas of $S = V \bullet T$ above the lines of average velocities and below are equal. The extremely high velocities within the Sabche depression discussed above thus become comprehensible.

Origin of water

Another unsolved enigma of sturzstroms and subsequent debris flows is the origin of the huge amount of water necessary to generate such low-viscosity flows (see Plafker and Ericksen 1978). In the present case, we expect the following sources:

(i) The snow cover of the summit area of Annapurna IV which apparently fell down together with the rock could have provided 0.6 million m^3 water considering the area of 32,000 m^2 and a snow thickness of 40 m (from Google Earth images),

(ii) A second smaller part could stem from the snow lying at the toe of the rock slope between about 5,500 and 4,000 meters (Bhandary et al. 2012),

(iii) A third (totally unknown) part from removed glacier ice as discussed above.

(iv) According to the reports of the pilots of the ultra-light aircrafts, "a lot of snow" was removed from the opposite slopes at the eastern foot slopes of Machapuchre peak (n.b., this area was only reached by the "brown cloud" and not by the sturzstrom).

All this is however by far not enough to explain the origin of water volumes necessary for the perhaps 20 surges reported during the day of the disaster; Jeff Kargel estimated 250,000 m^3 for the first surge only (in Shrestha et al. 2012). Therefore, a considerable part of the debris-flow water should have come from different sources: Shrestha et al. (2012) proposed the release of huge water volumes from hidden karst caverns in the upper reaches of Seti Khola. Regmi et al. (2012) found indications for a temporary damming of the Seti Gorge. Both assumptions have to be verified during forthcoming studies.

The role of river water overrun by the debris flow

The water runoff of Seti Khola near Kharapani village is estimated to be 10 m^3/s during non-monsoon times (Bhandary et al. 2012). The average runoff between Sabche Cirque and Kharapani, therefore, in a preliminary approach, can be estimated to be about 9 m^3/s. The flow velocity of such rivers usually is about 3 m/s as an average in comparable river sections considered here. The volume of 9 m^3/s of water running at 3 m/s needs a mean river cross section of 3 m^2. It follows that the volume of water flowing in the river channel at a length of 16 km (Fig. 11) between the entrance of the Seti Gorge and Kharapani is $V = 16{,}000\ m \cdot 3\ m^2 = 48{,}000\ m^3$.

The debris flow is calculated to have run at a mean velocity of 13.3 m/s from the impact area to Kharapani. As the velocity was much higher inside Sabche Cirque (see above and Fig. 11), the mean velocity between the gorge entrance and Kharapani must have been lower. According to the model developed in Figs. 10 and 11, the time of entering into the gorge should have been 130 seconds after impact; the velocity could have been then around 25 m/s (Fig. 11). From this estimation a mean velocity of about 10 m/s results within the gorge. The debris flow thus should have needed a time of $T = 16{,}000\ m \div 10\ m/s = 1{,}600\ s$ to get from the entrance of the gorge to Kharapani. Within this time span, the volume of about 10,800 m3 (9 $m^3/s \cdot 1{,}600\ s$) should have escaped by the normal run-off process. This signifies that about 37,000 m^3 (48,000-10,800 m^3) of surplus water was available to feed the first debris-flow surge. Similar quantities consequently were available for the numerous surges which followed with time.

IMPLICATIONS FOR FUTURE RISK ASSESSMENTS

As discussed above, the last gigantic debris-flow disaster happened about 750 years ago during the medieval climate optimum. We are undoubtedly experiencing a phase of rapid climatic warming. The thorough investigation of the reasons and the mechanisms which have initiated the disaster 750 years ago and the flood of May 5th is therefore urgently required. The stability of the rock slopes surrounding the Sabche Cirque, the types of sediments lying in this depression, glacial flour (Bhandary et al. 2012) or lake sediments (Regmi et al. 2012, Shrestha et al. 2012), need to be investigated thoroughly (Fig. 10a). In case of the sediments stemming from a former lake, the circumstances of the formation of such a big high-mountain lake (glacier lake, landslide damming?) have to be found out. Last not least, the possibility that the disaster of 750 B.P. had to do something with the first recorded heavy earthquake in Nepal in 1255 AD should be considered as well (Amod Dixit, pers. comm.).

Based on these findings, a reliable prognosis for possible future events (potentially much bigger than that of May 5, 2012) must be developed. A reliable warning system will be necessary in any case. In addition to remote sensing techniques the on-site investigation under the harsh high-mountain conditions is of crucial importance.

In an even wider scope, the circumstances and the trigger and flow mechanisms of the abundant pre-historic huge debris flows along Marsyangdi Khola, Madi Khola, Modi Khola and Kali Gandaki, all with apparent origin in the high-mountain environment of Annapurna Range (Hormann 1974; Yamanaka and Iwata 1982) should be included in the investigations.

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