Unraveling the spatio-temporal debris-flow activity on a forested cone in the Kyrgyz Range: implications for hazard assessment

Vitalii Zaginaev[1]; **Juan Antonio Ballesteros Canovas, PhD.**[2]; Markus Stoffel, Prof. Dr.[2,3]; Sergei Erokhin[1]

ABSTRACT

Ongoing climate change has recently resulted in an increase of risks related with glacial lake outburst flows (GLOFs) and debris flows in Northern Tien Shan, Kyrgyzstan. In this communication, we analyze recent process activity by applying tree-ring analysis to contribute to a better understanding of the past debris-flow activity. Based on the analysis of 96 disturbed trees, we reconstruct spatio-temporal patterns of events going back to 1877. A total of 26 events have been reconstructed, revealing high activity in the 1960s and 1970s. Our results are in agreement with the existing, but very fragmentary historical records, and can be used as a baseline for both risk assessment and for the understanding of glacier-climate-debris flow linkages in the region.

KEYWORDS

debris flow, glacial lake outburst flows, GLOFs, tree-rings, Northern Tien Shan

INTRODUCTION

Debris flows are rapid mass movements in which a combination of loose soil, rock, organic matter, air, and water mobilize as slurry flows downslope. This natural process is considered one of the most common natural hazards in mountain environments and is often responsible for large damage to infrastructure and even loss of life. Especially powerful events are the so-called glacial lake outburst flows (GLOFs), which are formed through the breaching of moraine dammed or supraglacial lakes or subglacial reservoirs as a consequence of glacier dynamics. These extreme events shape debris cones in the Tien Shan Mountains of Central Asia and produce intense changes in depositional forms, affecting long distances downstream of fans and thereby disrupting inhabited valleys (Erochin et al., 2009a).

The creation of new unstable glacier lakes in many high mountain environments and the destabilization of the cryosphere is explained by changes in extreme precipitation and temperature patterns (Stoffel and Huggel, 2012). Given the projected temperature increase in Northern Tien Shan, one can expect these processes to become an even greater challenge for local authorities and populations in the next future.

1 Institute of water problems and hydropower, National Academy of Science, Bishkek, KYRGYZSTAN

2 Dendrolab.ch, Institute of Geological Sciences, University of Berne, SWITZERLAND juan.ballesteros@dendrolab.ch

3 Climatic Change and Climate Impacts, Institute for Environmental Sciences, University of Geneva, SWITZERLAND

In this communication, we contribute to the understanding of past spatio-temporal occurrences of GLOFs at a case-study site in northern Tien Shan. We use tree-ring data to provide the longest annually-resolved GLOF record existing to date. Results are expected to be useful to re-define debris-flow hazard at the level of the cone level where touristic activities become increasingly important as well as provide findings about long-term changes in debris-flow frequency.

METHODS

Study site

The study site is located on the Aksay cone (42˚33´*N*; 74˚29´*E*; Figure 1). This is the largest debris-flow cone of northern Tien Shan (Kyrgyz Mountain Range). Catchment size is 28.3 km^2 with a relief of 2645 m. There are two glaciers systems located in the accumulation area on the western slopes of Semenov Tianshanskiy (4895 m asl) and Korona (4691 m asl) peaks, respectively. Vegetation on the cone is formed by Picea abies and Betula sp.. The mean annual precipitation is 517 mm (ranging between 18.1 mm in January and 87.1 mm in May), mean annual temperature is 6.5 °C. Snow is present from September to April. At this site, debris-flow (GLOF) activity has been observed in the recent past; generally during the summer season (Erochin et al., 2009a). Archival records from the Kyrgyz Hydrometeorological Survey and State Agency of Geology contains data on nine debris flows triggered by GLOFs and one event triggered by rainfall between 1960 and 1999 (Erochin et al., 2009b).

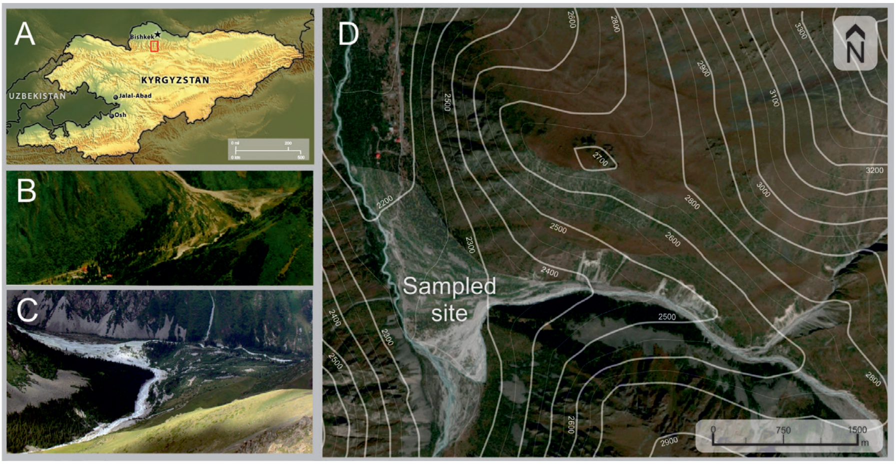

Figure 1: A. Location of study area, North slope of Kyrgyz range, National Ala-Archa park, Aksay valley. B. View on cone from west to east. C. View on cone from east to west. D. Sampled site on satellite image (2014).

METHODOLOGICAL STEPS

Initially, a geomorphic description combining both aerial images interpretation (from 1960, 1971, 1978, 2014) and field surveys was carried out to characterize past and current debris-flow channels, as well as the main depositional areas and forest cover. Then, all disturbed trees located on the fan were sampled following standard dendrogeomorphic procedures (Stoffel and Corona, 2014). At least two increment cores were extracted per tree. Additionally, undisturbed trees were sampled on adjacent, unaffected sites to build a reference chronology to identify pointer years for cross-dating.

Samples were prepared and measured following standard dendrochronological procedures. Tree rings were first counted and then measured with a precision of 0.01mm using a digital LINTAB positioning table connected to a Leica stereomicroscope and TSAPWin Scientific software. Growth disturbance (GD) related with past debris flow activity were then identified on the increment cores and included injuries, callus tissue, compression wood, abrupt growth increase and/or growth suppression. In samples from Picea abies, the occurrence of tangential rows of traumatic resin ducts (TRD) was used as an indirect indicator of scars (Stoffel, 2008).

Debris-flow definition was based on the weighted index value (Wit) developed by Kogelnig-Mayer et al. (2011). This index considers the number and the intensity of GDs within each tree-ring series and the total number of trees available for the reconstruction. We applied detection thresholds based on previous experience form debris flow in Alps (Schneuwly-Bollschweiler et al., 2013). The criteria here used for debris flow definition was: if Wit > 1,2; then we considered a sure event; if 1,2>Wit>0,8 then we considered a potential event; if Wit < 0,8, then we reject the possibility of event. During this process, a visual analysis based on the spatial distribution of affected trees on the fan was also performed to detect potential incongruences. The representation and visualization of disturbed trees during specific debris-flow events also allows interpretation of spatial patterns of past events in the current and past channels. During this analysis we exclusively focused on the location of breakout sites, the extension of affected areas, and the dynamic of existing channels.

RESULTS

Eleven past debris flow channels as well as the main fan deposits and the forest cover evolution were identified based on aerial pictures (Figures 2 and 3). In the field, very large deposits with boulder sizes of up to 10-14 m in diameter were found at the cone apex. Most affected areas were located in the central and southern parts of the cone, where the forest cover was completely removed on older images (this site now bears a 20-30-yr old forest). By contrast, the northern part of the cone was less affected.

A total of 320 GD were identified in the 156 samples from 96 P. abies trees affected by past debris-flow activity. Based on tree-ring analysis, the older trees date back to AD 1850 and are located in the northern part of cone, whereas the youngest trees grow next to the channel and in southern part of the cone. Our tree-ring data reveals that the 6% of the analyzed GDs corresponded to injuries, 25% of the reactions were strong, 33% medium, and 36% weak.

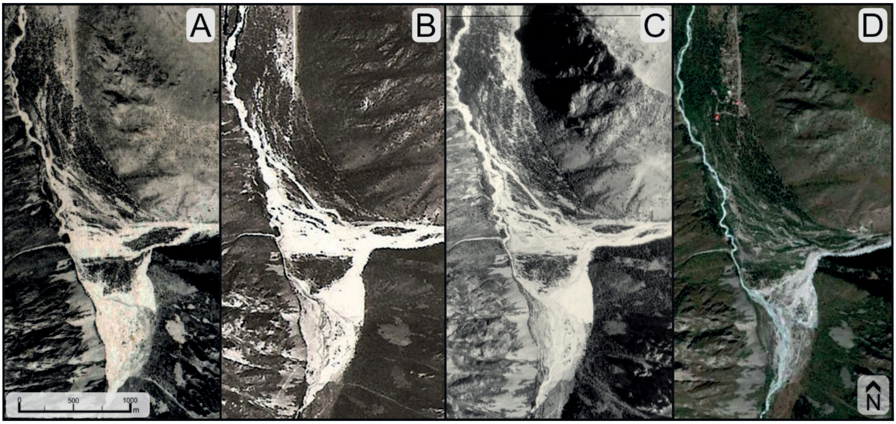

Figure 2: Aksay debris cone changes. A. aerial image 11.08.1960; B. aerial image 01.09.1971; C. aerial image 08.08.1978; D satellite image 30.08.2014

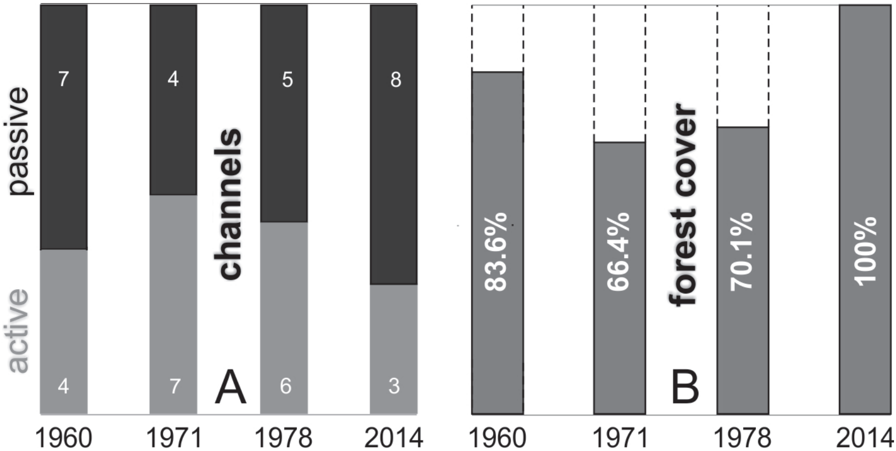

Figure 3: Number of debris flow channels. For each aerial image counted a number of active and passive channels. B. Forest cover for each year, area in 2014 – 100%

Based on this dataset, the temporal reconstruction of debris-flow events at Aksay cone is presented in Figure 4. The oldest reconstructed event was in 1877, whereas the more recent event took place in 1999. Based on historical records, nine dated debris flow events were related with lake outbursts floods being transformed into debris flows (1960, 1961, 1965, 1966, 1968, 1969, 1970, 1975, and 1980), and only in one case, the dated event was related with intense rainfall (i.e. 1999). Higher Wit indexes were observed for the events recorded in 1980 (Wit=22,3), 1969 (Wit=10,6), 1960 (Wit=12,8) as well as for the newly documented events in 1928 (Wit=15,6), 1936 (Wit=9,1), and 1950 (Wit=11,8). The more recent events were, by contrast, characterized by lower Wit indices (e.g. in 1993 – Wit=1,42, and 1999 –

Wit=2,12). The most recent event occurred on 23 and 25 July 2015, i.e. during our fieldwork for this study, but did not yet leave evidence (GD) in the tree-ring series. Our results show increased debris-flow activity on the cone between the 1960 and 1970 (0.54 event/year; i.e. 1960, 1961, 1965, 1968, 1969, and 1970), and a significant decrease from 1970s to the end of the 20th century (0.16 event/year: 1973, 1975, 1977, 1980, 1993 and 1999).

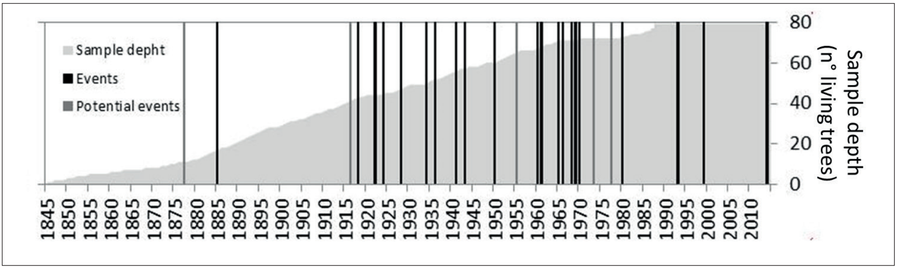

Figure 4: Reconstructed frequency of debris flows on the Aksay debris cone.

Spatial analysis of the positions of disturbed trees shows that channels 1, 2, 3, and 6 have been repeatedly active during past events (up to 13 events). The most recent events in channels 3 and 8 were dated to 1999 and observed in 2015 (23 and 25 July). In contrast, less activity (only 3 events) was recorded in channel 9, with a last event in 1969. Based on these observations, we identify two main spatial patterns at Aksay cone (Figure 5):

Pattern A.

Debris flows affecting the entire cone: Reconstructed events in 1885, 1922, 1928, 1936, 1950, 1955, 1960, 1961, 1965, 1966, 1968, 1969, 1970, 1977, and 1980. Generally, these events are related with high-magnitude flow energy and large sediment transport where boulders with more than 1 m diameter can occur, with the breakout of surges from the main channels (1, 2, 4) at the apex of the cone. Based the historical records, at least the events of 1960, 1961, 1965, 1966, 1968, 1969, 1970, and 1980 were caused by the outburst of proglacial Lake Aksay. The same pattern has also been observed for the previously unrecorded events in 1922, 1928, 1936, 1950, and 1955. This pattern is therefore considered congruent with the imprint of past GLOFs events. Under this pattern, existing infrastructure can be affected during future events.

Pattern B.

Debris flows affecting the southern part of the cone: Reconstructed events: 1877, 1916, 1918, 1924, 1934, 1941, 1943, 1973, 1975, 1993, 1999, and 2015. Existing records suggest that these events may be triggered by rainfall (1999) or intensive snow and ice melting in the absence of rainfall (2015). In this pattern, debris flows are affecting exclusively channels 12 and 13 located in the southern part of the cone. In comparison with pattern A, pattern B is characterized by a transport of smaller amounts of sediments insufficient to produce outbreaks at the cone apex. Consequently, channels located in the northern of the cone are not affected. Also, the capacity of sediment to produce temporal dams at Ala-Archa River is minimal. Most sediment is deposited in the un-vegetated area on the cone. Infrastructures are not affected under this pattern.

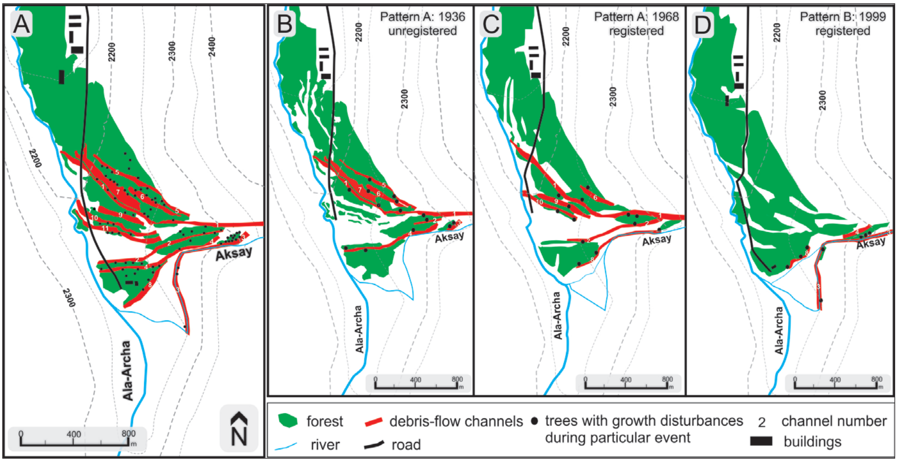

Figure 5: Spatial patterns of past debris-flow events: (A) Sketch of the Aksay cone with the localization of the identified channels, forest cover and sampled trees. (B) Debris flows affecting a north and south parts of cone an event in 1936 (pattern A). (C) Debris flows in 1968 affected almost cone, using channels in north, central and south parts of cone. In some cases flows reached a main Ala-Archa river following channels 10, 9, 1 (pattern A). It was registered event after outbursting glacier water pocket (D) In pattern B trees with growth disturbances by the 1999 event found in channel 8 in a central part and channels 4 and 3 in a current Aksay river channel (pattern B).

CONCLUSIONS

The coupled tree-ring analysis and classical geomorphic inspection has allowed to provide the longest annually-resolved debris flow history of Northern Tien Shan. Our results suggest that at least 26 events took place between AD 1877 and 2015, allowing tracking process dynamics in 11 mapped channels which are inactive under normal conditions. Results here provided are in agreement with historical records from 1960 to 1970, and therefore point out the reliability of this reconstruction. Our results are the basis to understand the glacier-climate-debris flow linkages in the region, as well as for the design of more reliable hazard maps and subsequent integrated risk management. Therefore, it is expected that both defined pattern will be useful to calibrate numerical model outcomes based on accurate topography to define future GLOFs/debris flow event scenarios. Moreover, the average occurrence of events here reported may be useful to define the probability of occurrence, and consequently the hazard level at the cone. Taken into account that the national natural park Ala-Archa is a popular tourist place, especially in summer season, our event pattern may be used to re-define hazard areas. This is specially the case in the central part of a cone (channels 4 and 8), where many tourist facilities have been constructed in hazard areas during last years.

ACKNOWLEDGEMENTS

This study was funded by the Swiss National Science Foundation (SNF, Schweizerischer Nationalfonds zur Forderung der Wissenschaftlichen Forschung) in the framework of the DEFENCC (n° 152301; Future DEbris Flows and lake outburst floods in Tian Shan: possible impacts of projected Climate Change) project.

REFERENCES

- Erochin, S.A., Mamatkanov, D.M., Tuzova, T.V., 2009 a. Monitoring of Kyrgyz lakes at risk of outburst floods. Int. Conf. Floods. Tbilisi, Georgia, pp.130-147.
- Erochin, S.A., Cerny M., 2009 b. Monitoring of outbursting lakes of Kyrgyzstan. Final Proc. Int. Conf. Mauntain-hazards, Bishkek, Kyrgyzstan, pp. 30–34.
- Kogelnig-Mayer, B., Stoffel, M., Bollschweller, M., Hubl, J., Rudolf-Miklau, F., 2011. Possibilities and imitations of dendrogeomorphic time-series reconstructions on sites influenced by debris flows and frequent snow avalanche activity, Arct. Antarc. Alp. Res. 43 (3), 649–658.
- Schneuwly-Bollschweiler, M., Corona, C., Stoffel, M., 2013. How to improve dating quality and reduce noise in tree-ring based debris-flow reconstructions. Quat. Geochronol. 18, 110–118.
- Stoffel, M., 2008. Dating past geomorphic processes with tangential rows of traumatic resin ducts. Dendrochronologia 26 (1), 53-60.
- Stoffel, M., Huggel, C., 2012. Effects of climate change on mass movements in mountain environments. Progress in Physical Geography 36, 421–439.
- Stoffel, M., Corona, C., 2014. Dendroecological dating of geomorphic disturbance in tress. Tree Ring Res. 70, 3-20.