GEOMORPHOMETRY 2020 PERUGIA, ITALY JUNE 22 - 26 2020

Volumetric assessment of river bank erosion using terrestrial laser scanning and high-resolution digital terrain modelling

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Abstract— **The dynamic geomorphological phenomena such as riverbank erosion require accurate and frequent mapping. In this study, we present a methodology for the assessment of volumetric changes in the river banks represented by high-resolution digital terrain models derived from 12 periodic terrestrial laser scanning surveys over the 3-year period. The methodology was applied to assess a sediment delivery from a cut-bluff induced by lateral erosion of the high-energy braided-wandering river Belá in West Carpathians. The slope-channel processes were identified as a significant sediment delivery contributor to the channel. Sliding activation was supported by channel incision and lateral erosion of the riverbanks. The amount of sediment supply from the cut-bluff to the channel was associated with the river discharge system.**

I. Introduction

The sediment from stream banks accounts for as much as 85% of watershed sediment yields [1]. It is a result of processes between the river channel and adjacent slopes, terraces, alluvial plains, and landforms often called a streambank erosion [2]. The bank erosion and bluff failure are commonly acting together resulting in a bank retreat dominantly located at the outside meander bend of a river [3,4].

Over the last decade, the laser scanning (LiDAR) technology has been applied in the research of bank erosion and failures by many authors. Grove et al. [5] and Nardi et al. [6] demonstrate the application of multi-temporal LiDAR mapping and high-resolution aerial imagery to determine processes and volumes of riverbank erosion at a catchment scale. The rates and spatial patterns of annual riverbank cliff erosion using sequential LiDAR and historical photography analyses present a unique tool for sediment erosion research [7-9]. Despite the development of quantitative assessment by application of high accuracy topography measurement, the complexity of the processes limits a better conceptualization of the phenomenon. Moreover, sufficiently accurate sediment transfer models predicting spatially-distributed elevation changes are still missing. A better understanding of the phenomenon requires high-resolution, multi-temporal spatially-distributed data documenting the processes [9].

The main aim of this paper is to present a methodology for calculation of volumetric and detailed morphological changes in the bank of the Belá River by multi-temporal, seasonal, and post-flood terrestrial laser scanning (TLS) and high-resolution digital terrain models (DTMs). This analysis helps to calculate spatial and temporal changes in the mechanism of mass movement from upper to lower bluff positions with a detailed assessment of morphological changes and sediment budget calculations.

II. Methods

A. Study area

The area of interest comprises a system of a channel and cut-bluff of the Belá river near the village of Vavrišovo in West Carpathians, Slovakia (Fig. 1). The area was selected for long-term monitoring of the sediment budget and mass movement from valley slope into the river channel. Belá represents a natural laboratory of high energy gravel-bed river with braided-wandering river pattern formed by the confluence of Tichý potok and Kôprovský potok (creeks) draining the glacial troughs of Tichá dolina and Kôprová dolina in the western part of High Tatras (Vysoké Tatry). Belá is the main right-side tributary of the upper Váh River which is a major tributary of the Danube from West Carpathians. The drainage basin of Belá (244 km^2, minimal altitude 630 m a. s. l., maximal 2 494 m a. s. l.) is characterized by an asymmetric drainage network. Most of its course is predominated by longitudinal as well as transverse tectonic faults. The valley bottom is filled with typical non-cohesive glaciofluvial river sediments. The average annual discharge (1964-2006) is 3.5

Jan Sasak, Michal Gallay, Jaroslav Hofierka, Jan Kanuk, Milos Rusnak and Anna Kidova (2020)

Geomorphometry based geodiversity for Lesser Antilles:

in Massimiliano Alvioli, Ivan Marchesini, Laura Melelli & Peter Guth, eds., Proceedings of the Geomorphometry 2020 Conference, doi:10.30437/GEOMORPHOMETRY2020_50.

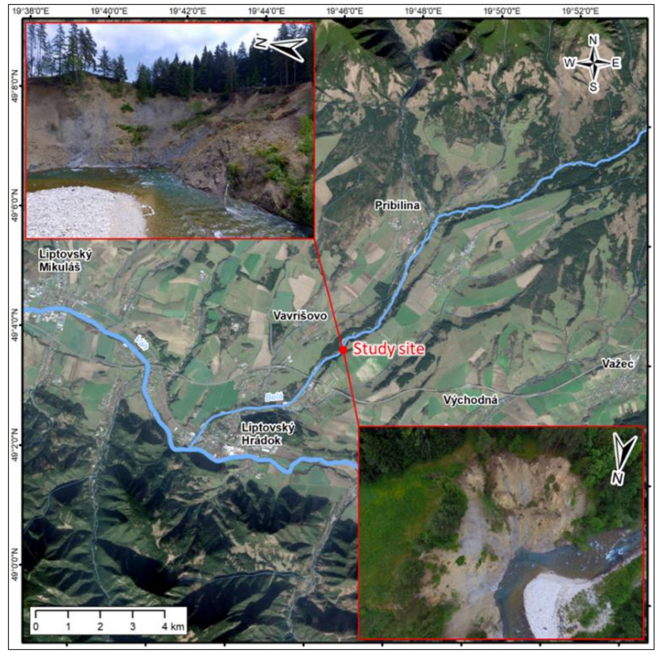
m^3.s^{-1} at the gauging station Podbanské and 6.8 m^3.s^{-1} at the confluence of Belá with Váh in Liptovský Hrádok [10]. The study area is located about 5.5 km northeast from the confluence of the Belá and Váh rivers. Hydrologic maximum of Belá occurs during spring floods generated by snowmelt in April/May and during summer floods from intensive rainfalls occurring often in the Tatry region in July/August [11].

The river undercuts a 30 m height terrace of the Mindel age (Fig. 1A). Terrace slope is covered by glacifluvial deposits from the Tatry Mountains and built by lithofacies of the Inner-Carpathian Paleogene formed by altering claystone and sandstone lithofacies. Coupling processes between the river and terrace slope are controlled by the river dynamics. Belá formed a wandering channel system in this section with an intensive valley floor reworking leading to channel migration associated with the arm abandonment.

B. Terrestrial laser scanning (TLS)

The area of the cut bluff has a complex microtopography locally obscured by growing trees and grass. For this reason, TLS was preferred to close-range photogrammetry from a drone. The Riegl VZ-1000 scanner was used for data collection with the maximum range set to 450 m and 300 MHz pulse rate frequency. Moreover, TLS did not require placing ground control points (GCP) prior to the survey as is the case of photogrammetry [9]. In our case, ground control (georeferencing) was performed based on 4 to 5 GCPs (black-white checkerboards) placed around each scanning position and recorded by a dual-frequency GNSS receiver in real-time kinematic mode. For this task, differential corrections of the Slovak Positioning Service (SKPOS) broadcasted within a mobile broadband network were used. There were about 20-30 GCPs measured during each TLS mission.

Systematic monitoring of the cut-bluff started in March 2016 and continued to November 2018 with a 3 months interval. There were 10 scan positions located within the study area (Fig. 1B). Local topographic conditions had changed frequently, therefore, scan positions were adjusted accordingly to capture the required land surface topography.



(A)

(B)

Figure 1. (A) Location of the study site in the West Carpathians, Slovakia, with detailed photographs of the cut-bluff from a vertical perspective. (B) Orthophoto image with positions of laser scanner (red dots).

C. Data processing

The TLS data obtained during a single campaign were processed in several steps. In the first step, the scanning positions were mutually registered in the project coordinate system. This step involved a manual change of position and orientation of every single scan (Coarse registration) and an automatic alignment using the MSA (MultiStation Adjustment) tool implemented in the

RiSCAN Pro software. The tool is based on the Iterative Closest Point (ICP) algorithm [12] minimizing the deviations between identical planes derived from each scan position. To keep the calculation of volumetric changes at a reasonable level of accuracy, the scans of each campaign were mutually oriented achieving the average standard error below a centimeter. Georeferencing a point cloud for each campaign was done with the GCPs in the S-JTSK national coordinate system (EPSG code: 5514) and the Baltic Sea vertical reference system after adjustment. The achieved standard errors were between 3 to 5 centimeters per unified point cloud in each campaign. Such an error resulted in a volumetric error that ranged between 100-300 m^3 across the 6000 m^2 of the area of interest.

To derive a DTM, ground points were extracted using the automatic Vegetation filter tool of the RiSCAN Pro software. The points classified as vegetation were visually inspected to verify the classification. The problematic places such as slope cliff, overhangs, main scarp could be classified as vegetation as well. These parts were then manually unclassified. The points classified as vegetation, noise, and other objects except terrain were removed from the point cloud. Overall, more than 70% of all points were removed by filtration, and only points representing the land surface were used in further data processing and analysis. The DTMs for each campaign were derived in GRASS GIS using the parallelized version of the regularized spline with tension and smoothing implemented in the v.surf.rst module [13]. The parameters of the interpolation function were identical for each model with smoothing 0.4, the minimum point distance (dmin) set to 0.09 m, and spatial resolution of the final DTM 0.1 m.

III. RESULTS

The Belá River is a dynamic and laterally unstable river system [14] and activation of slope failure is controlled by channel evolution and position of the channel on the valley floor. Channel movement and lateral erosion to the distinct contact of the cut-bluff slope triggers the mass transport into the channel. Frequent flooding affects the intensity of toe erosion and accelerates material removal and entrainment by water flow leading to changes in slope failure geometry and activation of block failures in the upper cut-bluff positions. The amount of relocated sediment during the monitoring period in relation to the river discharge is depicted in Fig. 2. It can be seen that erosion dominates the process of relocation and the marked changes occurred after strong hydrologic events. Further analysis is needed to interpret the volumetric changes more convincingly, e.g. using rainfall data.

The spatial pattern of the changes in the sediment volume is depicted in Fig. 3. The pattern of material gains and losses summarizes quantity and spatial variation of slope processes and mass movement. Spatial-temporal changes in mass replacement are evident. In the first monitoring periods from March 2016 to March 2017 slightly prevailing erosional processes over deposition with material deposition in the lower position and vertical movement in the upper position of bluff. In this cut-bluff stage, mass transport is a little higher over detectable limit calculated based on the cumulative effect of measurement and post-processing errors. Intensive toe erosion from March 2017 to June 2017 was documented and 3529 m^3 of cut-bluff material was eroded into the river channel. Intensive toe erosion is connected with river undercutting and high magnitude flood events occurred between monitoring campaigns. Increasing energy of water flow resulted to less cohesive claystone block destruction and collapsing lower slope parts into the channel. Morphometric changes in toe slope parts initiated sediment cascade from the upper slope position. These morphological changes was followed by period of mass deposition in former foot surface and accelerated erosion in downstream direction after channel bend extension. In the next period (September 2017 - November 2017), upper scarp material loss prevails resulting in erosion of 2394 m^3 of sediment. In both cases, winter periods are presented by a very small material displacement indicating a low interaction with frost weathering and thermal stress. In the first half of the year 2018, changes in the upper collapsed zone were recorded and mass movement acceleration from the main scarp occurred in the form of sliding blocks.

There were 3,130 m^3 of material eroded and 789 m^3 accumulated between April and June 2018. Then a massive scarp retreat occurred caused mainly by fluvial undercutting of the cut-bluff toe during snowmelt season in the Tatry Mountains. Erosion and removal of the material dominated further on (3,189 m^3 eroded, 549 m^3 accumulated) which can be primarily attributed to an extraordinary flash-flood event that occurred in late-July 2018. Subsequent forceful human interventions in the river channel and gravel extraction for river regulation preserved slope undercutting which resulted in the reduction of the mass movement on the cut-bluff slope. After the artificial measures, the erosion relocated only 639 m^3 in the upper zone of the cut-bluff and 641 m^3 were accumulated in its foot zone.

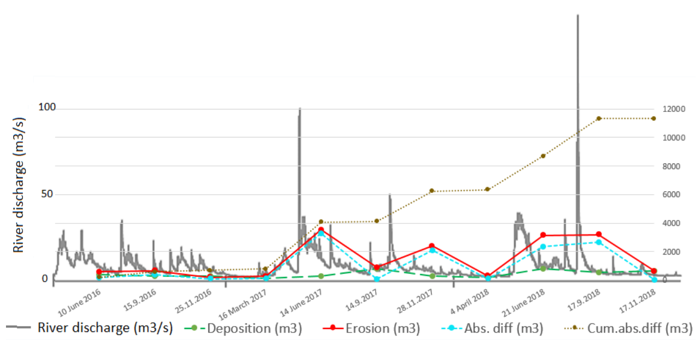


Figure 2. River discharge (left vertical axis) and the calculated volume of relocated sediment mass based on TLS monitoring (right vertical axis) in cubic meters.

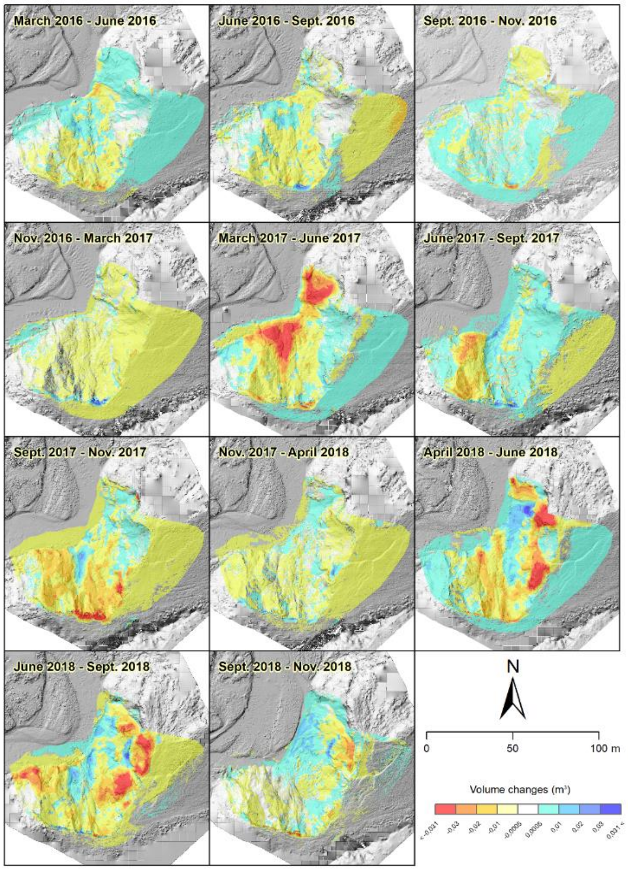


Figure 3. The difference between successive DTMs (DoD) presenting volumetric changes of cut-bluff slope material.

IV. CONCLUSIONS

Mass movement mechanism operation and processes of material movement from cut-bluff into the channel were measured by TLS techniques during three years and 12 monitoring campaigns. We have presented a methodology for the evaluation of volumetric changes in the river banks represented by high-resolution DTMs derived from periodic TLS surveys. The study also demonstrated the potential of this approach for a high accuracy assessment of sediment delivery to the river channel. Changes in the Belá River channel planform activated several failures in the 30m high river Pleistocene terrace and reactivated the studied cut-bluff slope in 2013. The results of this analysis along with the associated hydrological data provide insight into the physical mechanism of cut-bluff sliding. Future research will focus on the analysis of the connectivity between the river channel and the cut-bluff.

ACKNOWLEDGMENT

The research was financially supported by the Science Grant Agency (VEGA) of the Ministry of Education of the Slovak Republic and the Slovak Academy of Sciences (Grant Nr. 02/0098/18 and by the Slovak Research and Development Agency (APVV, Grant nr. 15-0054).

REFERENCES

[1] Simon, A., Curini, A., Darby, S.E., Langendoen, E.J., 2000. Bank and near-bank processes in an incised channel. Geomorphology 35, 193–217.

[2] Luppi, L., Rinaldi, M., Teruggi, L.B., Darby, S.E., Nardi, L., 2009. Monitoring and numerical modelling of riverbank erosion processes : a case study along the Cecina River (central Italy) 546, 530–546.

[3] O'Neal, M. a., Pizzuto, J.E., 2011. The rates and spatial patterns of annual riverbank erosion revealed through terrestrial laser-scanner surveys of the South River, Virginia. Earth Surf. Process. Landforms 36, 695–701.

[4] Yenes, M., Monterrubio, S., Nespereira, J., Santos, G., Fernández-Macarro, B., 2015. Large landslides induced by fluvial incision in the Cenozoic Duero Basin (Spain). Geomorphology 246, 263–276.

[5] Grove, J.R., Croke, J., Thompson, C., 2013. Quantifying different riverbank erosion processes during an extreme flood event. Earth Surface Processes and Landforms 38, 1393-1406.

[6] Nardi, L., Campo, L., Rinaldi, M., 2013. Quantification of riverbank erosion and application in risk analysis. Nat. Hazards 69, 869–887.

[7] De Rose, R.C., Basher, L.R., 2011. Measurement of river bank and cliff erosion from sequential LIDAR and historical aerial photography. Geomorphology 126, 132–147.

[8] Thompson, C., Croke, J., Grove, J., Khanal, G., 2013. Spatio-temporal changes in river bank mass failures in the Lockyer Valley, Queensland, Australia. Geomorphology 191, 129–141.

[9] Spiekermann, R., Betts, H., Dymond, J., Basher, L., 2017. Volumetric measurement of river bank erosion from sequential historical aerial photography. Geomorphology 296, 193-208.

[10] Majerčáková, O., Škoda, P., Danáčová, Z., 2007. Vývoj vybraných hydrologických a zrážkových charakteristík za obdobia 1961–2000 a 2001–2006 v oblasti Vysokých Tatier. Meteorologický Časopis 10, 205–210.

[11] Halmová, D., Pekárová, P., 2011. Statistical evaluation of the extreme flood and drought changes in the Belá River basin. In: Gomboš,M., Pavelková, D., Tall, A. (Eds.), Influence of Anthropogenic Activities on Water Regime of Lowland Territory. Physics of Soil Water, Institute of Hydrology SAS, Bratislava, pp. 125–133.

[12] He, Y., Liang, B., Yang, J., Li, S., He, J., 2017. An iterative closest point algorithm for registration of 3D laser scanner point clouds with geometric features. Sensors 17, 1-16.

[13] Hofierka, J., Lacko, M., Zubal, S., 2017. Parallelization of interpolation, solar radiation and water flow simulation modules in GRASS GIS using OpenMP. Computers & Geosciences. 107, 20–27.

[14] Kidová, A., Lehotský, M., Rusnák, M., 2016. Geomorphic diversity in the braided-wandering Belá River, Slovak Carpathians, as a response to flood variability and environmental changes. Geomorphology 272, 137–149.