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TESTING OF DIFFERENTIAL ELEVATION MODELS BASED ON COMBINED AIRBORNE AND LONG-RANGE TERRESTRIAL LASER SCANNING FOR ASSESSMENT OF RIVER BANK EROSION

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Since 2013, at the Institute of Geography and Spatial Organization, Polish Academy of Sciences (IGSO PAS), we have implemented a research project on the use of terrestrial laser scanning (TLS) in geographic studies. It is divided into several directions, e.g. landslide monitoring in the mountains, uplands, and lowlands; assessment of slope transformations in high mountains; shaping of shore zones of reservoirs; river erosion; morphometric monitoring of peatlands; and biomass analysis.

In the project we have used a Riegl VZ-4000 laser scanner¹ owned by IGSO PAS.

It is a pulse scanner, with angle measurement resolution better than 0.0005° and angular step of 0.002°. The accuracy of the scanner is 15 mm, and precision 10 mm. The Riegl VZ-4000 incorporates waveform processing, capable of detecting and processing multiple echoes from the same direction, so that complex structures, fences, wires, and vegetation can be handled. The scanner can collect point clouds from a distance of up to 4000 m, so it is one of a group of scanners capable of extreme long-range measurements. This set

¹ Riegl 3D terrestrial scanning system was purchased under project No. 6360/IA/32/2013 financed

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of specific properties of the scanner enabled us to analyse the potential of long-range terrestrial laser scanning in the evaluation of changes in river bank morphology.

This report presents results of the first test scans aimed to investigate the possibility of using simultaneously data from TLS and airborne laser scanning (ALS) as sources of information about morphodynamic processes on the banks of large lowland rivers.

River bank erosion depends on many factors, e.g. the geological structure, shape of the river bed or the energy of impact. The process can be slow or change dynamically with fluctuations in water level or flow rate. The most frequently used methods of lateral erosion were measurement networks and sequences based on benchmarks, monitored geodetically by means of theodolites, tachymeters or GNSS

systems. Simultaneously, for more extensive areas, aerial photographs and satellite images were used.

During the last decade, the measurement methods based on Light Detection and Ranging (LiDAR) technology were developed and popularized, making it possible to generate and analyse high-resolution digital elevation models (HRDEM). In environmental studies, most commonly ALS data are used, as this method allows collection of data from large areas, whereas TLS is usually limited to distances of about 30-200 m and used in engineering works. Only rarely long-range TLS is used, enabling collection of data from inaccessible areas, e.g. from an opposite bank of a river or reservoir.

This project aimed to use a combination of both laser scanning methods (ALS and long-range TLS) and the generated HRDEM based on them for analysis of morphodynamic processes on river banks.

Our study area was a stretch of the right bank of the Vistula River located near the town of Nieszawa ($52^{\circ}50'10''\text{N}$, $18^{\circ}54'38''\text{E}$), halfway between the towns of Toruń and Włocławek in Lower Vistula Valley (Fig. 1). In the study area, at 702-703 km of the river, the Vistula has a straight channel, slightly constricted, about 420-440 m wide, with a mean annual discharge of about $950 \text{ m}^3 \cdot \text{s}^{-1}$ and mean slope of the river of 0.3‰. The mean water level of the Vistula in the study area is 40-41 m a.s.l. The investigated right bank of the river has developed in river alluvia, mostly sands and silty deposits. It is on average 3-5 m high, with a slope angle of $20\text{-}45^{\circ}$, and is directly linked with an extensive floodplain, about 600 m wide and about 45 m in altitude, covered mostly with meadows.

The river channel evolution of the Vistula in its lower section is currently also affected by human disturbance (Gierszewski et al. 2015) caused by the dam in Włocławek, located 27 km upstream from Nieszawa. Construction of the dam, and its operation, clearly influenced the process of vertical erosion downstream from the reservoir. Moreover, bank erosion was intensified because

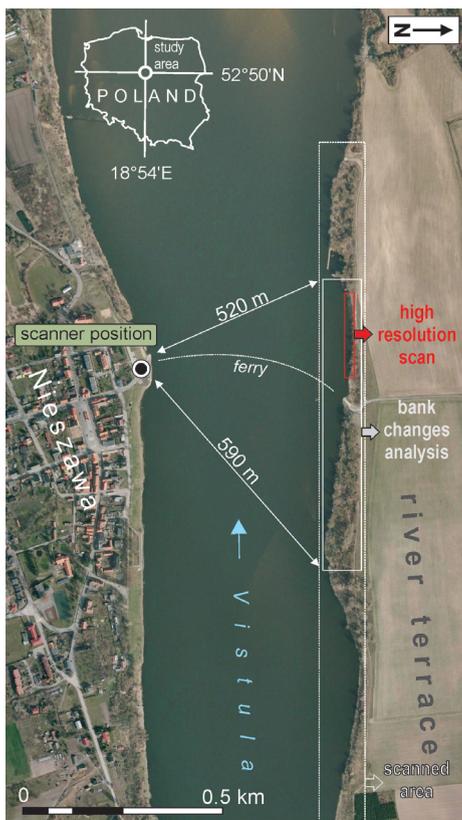


Figure 1. Location of the study area

Table 1. Parameters of point clouds from TLS

| Parameter | General scan | Detailed scan |
|--------------------------------------------------|---------------|---------------|
| River bank length | 770 m | 120 m |
| Scanning frequency | 30 kHz | 150 kHz |
| Theta resolution | 0.011° | 0.003° |
| Phi resolution | 0.200° | 0.003° |
| Mean distance from scanned object | 530 m | 485 m |
| Size of river bank point cloud before filtration | 2,334 million | 1,585 million |

of 'impulsive' water discharge from the dam, variable flow rate and water volume, frequent and substantial variation in water level, as well as water freed from river sediments and suspension to a large extent (Banach 1998; Babiński & Habel 2017).

In this report, we used data from laser scanning, both ALS and TLS. TLS was performed in November 2015 using a Riegl VZ-4000 laser scanner. The measurements of the opposite bank of the river were taken from distances varying between 430 m and 750 m. We used frequencies of 30 kHz and 150 kHz, theta resolution of 0.011-0.003, and phi resolution of 0.200-0.003°. Such settings enabled us to record point clouds of the river bank with points spaced 0.03 m apart or more (Tab. 1).

The collected point cloud was filtered by RiSCAN PRO software to separate only reflections from the ground. We eliminated indirect echoes of the signal, leaving only single and last reflections. To detect vegetation, we used the amplitude and intensity of signal reflection. The final step was manual verification of the point cloud. For geospatial location of the laser, we used a GNSS receiver (TRIMBLE R4, coupled with the scanner), using Real Time Kinematic corrections. Our reference data were ALS point clouds originating from the National Geodetic and Cartographic Resources. The collected data in LAS 1.2 format have a mean point density of at least 4 or 6 points/m², and acceptable mean error of up to 0.2 m. The ALS measurements were made in October 2012. Changes in river bank morphology between 2012 and 2015 were analysed directly on the point clouds and

elevation models, using LP360, RiSCAN PRO, and ArcGIS software.

We scanned a river bank nearly 3.7 km long, but for a detailed analysis we selected the middle part, 790 m long, located directly opposite to the laser location. The point cloud for this section was composed of 2.3 million points. Additionally, we performed a detailed, high-resolution scan of a 120m stretch characterized by the greatest morphodynamics (Fig. 2).

As a result of the differential analysis of ALS and TLS data, we distinguished 6 sections that differed in bank morphology and morphodynamics.

- **Section 1**, about 100 m long, is part of a parallel dam. A differential analysis of elevation models between 2012 and 2015 did not detect any changes in bank morphology.
- **Section 2**, about 15 m long, is 4.5 m high, and a small landslide appeared there between 2012 and 2015. It is visible because of small changes in river bank morphology and remarkable bending of trees growing there.
- **Section 3**, nearly 120 m long, is 4-5 m high, with a slope angle of 35-45°, covered with low grassy vegetation. It is the most transformed section of the river bank, with the greatest changes in the middle part, 70 m long, where nearly 2.8-4.0 m³ of material were eroded per 1 m of river bank length (Fig. 3).
- **Section 4**, about 115 m long, is up to 4.5 m high, with a uniform slope angle of 35-40°. It is clearly subject to erosion, reflected in an incision at the height of 1.5-2.0 m and

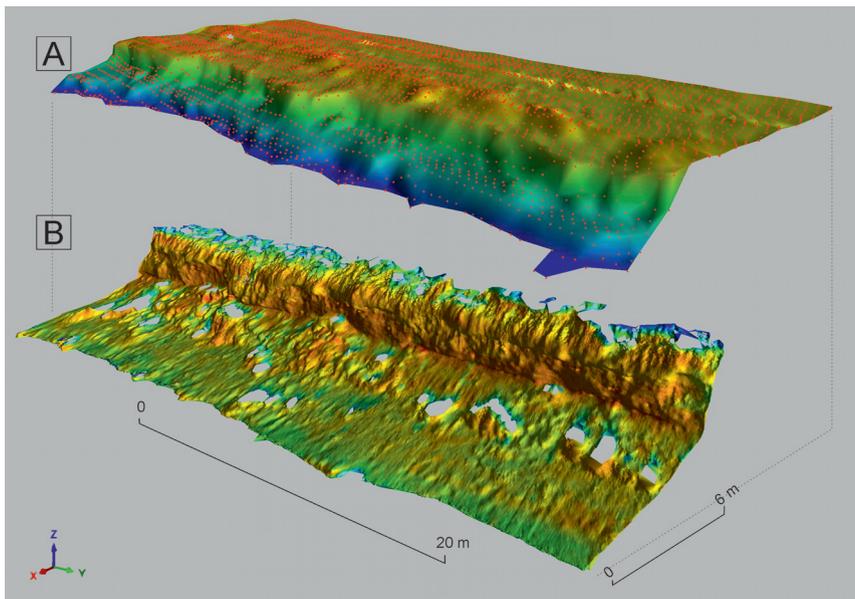


Figure 2. HRDEM of river bank of section 3 based on: A – airborne laser scanning in 2012 (red dots are beams based of ALS); B – long-range terrestrial laser scanning in 2015

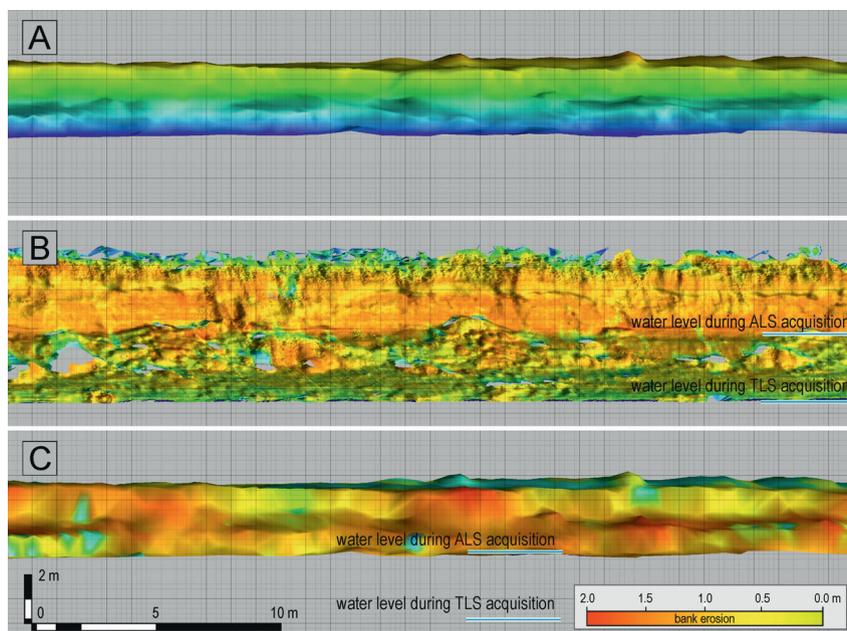


Figure 3. Analysis of bank erosion of part of section 3 in combined airborne and long-range terrestrial laser scanning. Front view of: A – HRDEM based on ALS, colorizes by elevation, B – HRDEM based on TLS, colorizes by reflectance, C – differential analysis of HRDEMs based on ALS and TLS, colorized by river bank erosion (high values in red colour)

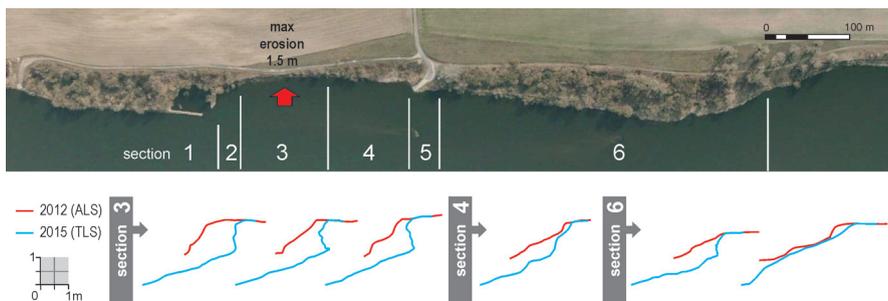


Figure 4. Changes of the river bank between 2012 and 2015. Examples of cross profiles of HRDEMs based on airborne and long-range terrestrial laser scanning

a slope angle of $60\text{--}80^\circ$ in the upper part of the bank profile.

- **Section 5**, about 40 m long, is a partly strengthened fragment of the bank, with no visible transformations.
- **Section 6**, about 400 m long, with banks up to about 3.5 m high, bank profile convex, nearly completely covered with grassy vegetation, shrubs, and trees; slope angle $35\text{--}45^\circ$. In the study period, the fragment was relatively stable, with only a few places where the bank moved up to 1 m back, in the middle part of the transverse profile, linked with formation of a shelf.

The used ALS data ensure at least 46 reflections from the ground per 1 m^2 , allowing in practice an assessment of location of the upper edge of the river bank with horizontal accuracy of at least 20–30 cm. The combination of these data with high-resolution TLS data from 2015 enabled us to analyse quantitatively the process of erosion taking place in the study area in the study period. The HRDEM based on TLS data show in detail the river bank morphology, allow identification of landslides and small erosional dissections or a detailed examination of the bank profile, where in spite of the relative stability of the upper edge, a change in its profile was observed (Fig. 4). The generated HRDEM are simultaneously a basis for successive measurements of the river bank.

Because of the long range of the terrestrial scanner and a relatively high rate of data collection, the applied method can be successfully

used for research on rivers up to 3–4 km wide, with possible to detect very small changes, of several centimetres. The results motivate us to undertake more measurements in sections located further downstream from the dam, hoping to identify various effects of its operation.

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