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ANALYSIS OF RIVER BANK EROSION BY COMBINED AIRBORNE AND LONG-RANGE TERRESTRIAL LASER SCANNING: PRELIMINARY RESULTS ON THE VISTULA RIVER

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Abstract: In our study, high-resolution digital elevation models (HRDEM) were generated by combining the data from airborne laser scanning (ALS, 2012) and long-range terrestrial laser scanning (TLS, 2015) and used for qualitative and quantitative analysis of recent morphodynamic processes in the Vistula river bed near Nieszawa, Central Poland. The study area was a river stretch nearly 1 km long, in its lowland part, with the 440 m wide channel and 3.5-5.0 m high banks. It is located 27 km downstream from the reservoir in Włocławek, so it is under the influence of the reservoir. The TLS measurements were performed from the opposite bank of the river, from a distance of up to 750 m. By combining the ALS and TLS data, we investigated and evaluated both the horizontal variations in the height of the river bank and changes in its profile, with a high resolution of about 900 points/m^2. Our results show that in this river stretch, both the transverse profile of the river bank and the location of its upper edge have been changed during the three years between the ALS and TLS measurement sessions. The scale of this phenomenon varies from a complete lack of erosion to lowering of the upper edge of the cliff by about 1 m, in some points even up to 2 m. The applied methods allowed us to estimate the area of the observed transformations, in contrast to the conventional methods that enable only analyses in selected transverse sections.

Key words: Vistula; river bank erosion; airborne laser scanning; ALS; long-range terrestrial laser scanning; TLS; high-resolution digital elevation models; HRDEM

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Анализ береговой эрозии комбинированным методом с использованием данных воздушного и наземного лазерного сканирования: предварительные результаты по реке Висла

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Аннотация: В статье показана возможность создания цифровых моделей высот с высоким разрешением (HRDEM) на основе комбинирования данных воздушного лазерного сканирования (ALS, 2012 г.) и наземного лазерного сканирования (TLS, 2015 г.) для качественного и количественного анализа современных процессов, связанных с морфодинамикой русла реки Висла (недалеко от г. Нишава, Центральная Польша). Изучен участок реки длиной почти 1 км в его низинной части, где русло имеет ширину 440 м, а берега – высоту 3.5–5.0 м, расположенный на расстоянии 27 км ниже по течению от водохранилища в г. Влоцлавек, при этом изученный участок находится под влиянием водохранилища. Измерения методом TLS проводились с противоположного берега реки с расстояния до 750 м. Сочетание данных ALS и TLS позволило исследовать и оценить как горизонтальные изменения высоты берега реки, так и изменения его профиля с высоким разрешением – около 900 точек/м^2. Полученные результаты показывают, что на данном участке реки в течение трех лет между измерениями, проведенными методами ALS (2012 г.) и TLS (2015 г.), изменились как поперечный профиль берега, так и местоположение его верхнего края. Масштабы изменений варьируются от полного отсутствия эрозии до опускания верхнего края обрыва примерно на 1 м (в некоторых точках даже до 2 м). Использованные методы позволили оценить площадь наблюдаемых изменений, в отличие от обычных методов, которые позволяют проводить только анализ отдельных поперечных разрезов.

Ключевые слова: Висла; береговая эрозия; воздушное лазерное сканирование; ALS; наземное лазерное сканирование; TLS; цифровые модели высотных разрезов; HRDEM

1. Introduction

Erosion is a common phenomenon linked with a natural system of river bed evolution. Its dynamics depends on many factors, which may be changing slowly (passive, e.g. the geological structure or river bed shape), or changing quickly (linked mainly with the energy of water, depending e.g. on fluctuations in the water level and discharge).

Currently, the banks of many rivers in Europe are to a large extent transformed by human activity. Most of man-made structures aim at stabilizing the river bed or trying to make the river morphodynamic processes more predictable. On the other hand, in many cases, man-made structures on the systems of river channels disturb the systems, make their behaviour unpredictable, and often lead to higher rates of vertical and lateral erosion, especially downstream from river dams [*Babiński et al., 2014*].

Quantitative assessment of erosion and sediment accumulation is important for better understanding and preservation of natural and transformed river systems [*Lawler, 1993; Kędra et al., 2015; Wiejaczaka, Kijowska-Strugała, 2015*]. Such information is also valuable for planning and conservation of reservoirs and other hydrotechnical structures. Traditional methods of lateral erosion assessment usually include measurement networks, sequences based on benchmarks, monitored geodetically by theodolites, tachymeters, and GNSS systems [*Lawler, 1993*; *Lawer et al., 2001; Kaczmarek et al., 2015*]. In parallel, large-scale phenomena and extensive areas are generally studied using both aerial photographs and satellite images. However, the former methods are invasive [*Lawler et al., 2001; Lawler, Leeks, 1992*], requiring intensive fieldwork and resulting in a relatively low spatial resolution. The possibility of high accuracy often contrasts with the subjective selection of laser locations. In case of aerial photographs, the major limitations are resolution and high costs. Besides, masking of river bank morphology by vegetation is another factor limiting the usefulness of an aerial photo.

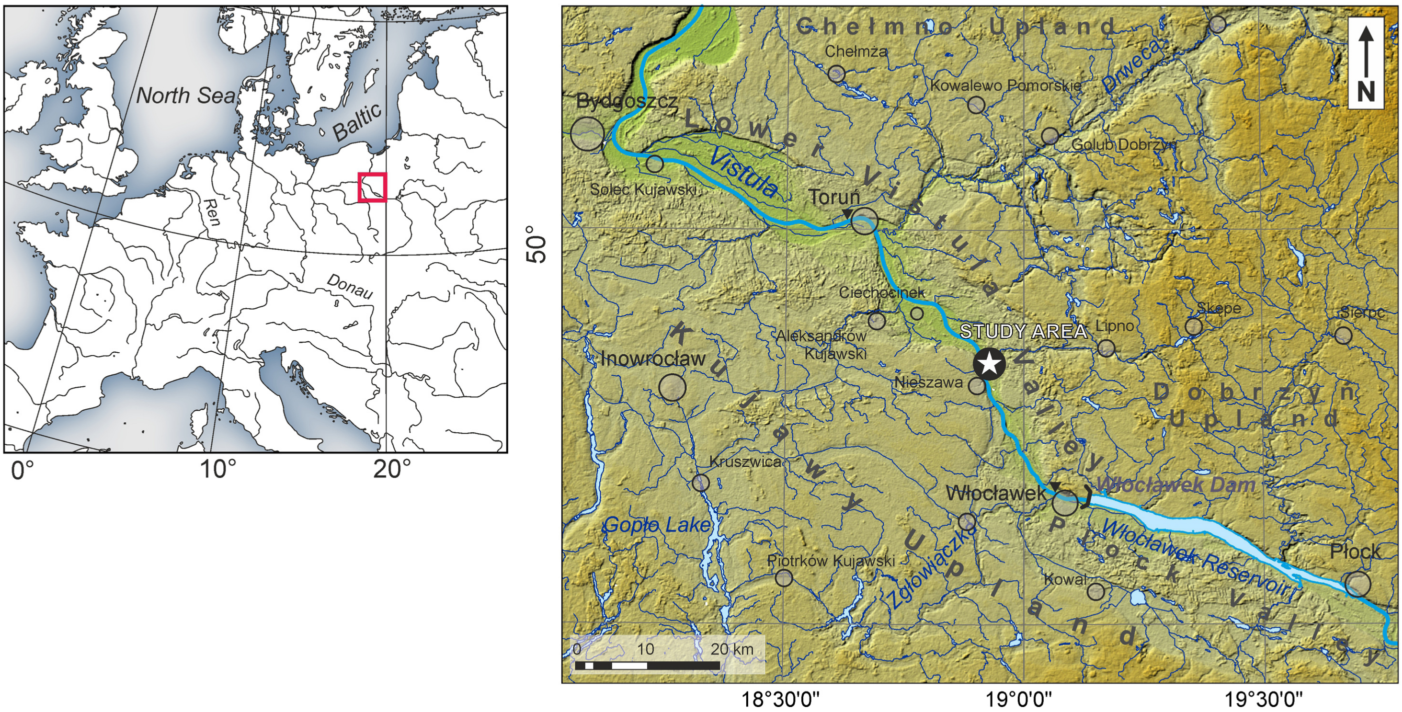

Fig. 1. Location of the study area.

Рис. 1. Расположение района исследований.

During the last decade, the measurement methods based on Light Detection and Ranging (LiDAR) technology were developed and popularized [*Bremer, Sass, 2012; Cebulski, 2014; Day et al., 2013a, 2013b; Jaboyedoff et al., 2009; Julge et al., 2014; Kociuba, 2017; Milan et al., 2007; Telling et al., 2017*], making it possible to generate and analyse high-resolution digital elevation models (HRDEM). The use of airborne laser scanning (ALS) allows researchers to study large areas but it has its limits, especially when surveying vertical or near-vertical structures. In contrast, the application of terrestrial laser scanning (TLS), with the horizontal setup direction of the laser beam, makes it perfect for investigation of river banks, especially for structures inclined by more than 45° [*Resop, Hession, 2010*].

In this study, we attempted to evaluate the combined use of ALS and TLS and the generated HRDEM for the analysis of morphodynamic processes on the river banks. The study is distinguished by the use of a long-range scanner, which enable us to collect point clouds on large rivers while scanning from the opposite banks.

2. Study area

Our study area was a stretch of the right bank of the Vistula River located near the town of Nieszawa (52°50'10" N, 18°54'38" E), i.e. halfway between Toruń and Włocławek, in the Toruń Basin, which is part of the Lower Vistula Valley (Fig. 1). The mean annual precipitation in this region is 522 mm [*Wójcik, Marciniak, 2006*]. The annual mean air temperature is 8.1°C [*Lorenc, 2005*]. The Vistula is one of the largest tributaries of the Baltic Sea and one of the longest rivers in this part of Europe: its total length is 1047 km, the catchment area exceeds 194000 km^2, and the mean annual discharge at its mouth amounts to 1046 m^3·s^{-1}.

In the study area, at 702–703 km of the river, the mean annual discharge is about 950 m^3·s^{-1}. The average water level of the Vistula in Toruń is 302 cm, but during the year it can vary from 227 cm to 409 cm. The main data on the water levels and flows are presented in Table 1. In 1951–2010, the water levels were the lowest mainly in September, August, and October. Overwhelming floods were prevailing in the winter semester. Most of the floods occurred during the spring thaw, in March and April. In fact, the water level of the Vistula river in Toruń is not natural due to the dam that was completed in 1970. The mean slope of the river in this area is 0.3 ‰. The Vistula channel is slightly narrowed in the study area: 420–440 m wide, compared to 550–600 m wide upstream and downstream from Nieszawa. The channel is straight, and the left bank is partly protected by embankments. The mean water level in the study area is 40–41 m a.s.l. The bottom of the river valley is about 1.8 km wide. The left bank is partly eroded in the moraine plateau, which altitude is

Table 1. **Water level and flows of the Vistula river in Toruń (the water gauge located 33 km below Nieszawa)**

Таблица 1. **Уровень воды и течения реки Висла в г. Торунь (водомерная рейка на расстоянии 33 км от г. Нишава)**

Parameter	Toruń
Kilometre of the river	734.7 km
Catchment area	181033 km^2
Lowest Low Water[1]	122 cm
Mean Low Water[1]	227 cm
Mean Average Water[1]	302 cm
Mean High Water[1]	409 cm
Highest High Water[1]	857 cm
Mean Flow[2]	983 $m^3 \cdot s^{-1}$
Mean Flow[3]	979 $m^3 \cdot s^{-1}$
Mean Low Flow[2]	356 $m^3 \cdot s^{-1}$
Mean Low Flow[3]	354 $m^3 \cdot s^{-1}$
Highest Flow[3]	6890 $m^3 \cdot s^{-1}$
Mean High Flow[3]	3650 $m^3 \cdot s^{-1}$
Lowest Flow[3]	205 $m^3 \cdot s^{-1}$

Note. Data sources: 1 – years 1981–2010, IMGW-PIB (Institute of Meteorology and Water Management); 2 – years 1946–2000, RZGW (Regional Council of Water Management); 3 – years 1951–2000, the ISOK project (IT System of the Country's Protection against Extreme Hazards).

Примечание. Источники данных: 1 – 1981–2010 гг., IMGW-PIB (Институт метеорологии и водного хозяйства); 2 – 1946–2000 гг., RZGW (Региональный совет водного хозяйства); 3 – 1951–2000 гг., проект ISOK (ИТ-система защиты страны от экстремально опасных явлений).

up to 70–80 m a.s.l.The right bank has a floodplain about 600 m wide and about 45 m in altitude, which is covered mostly by meadows. The right bank is 3–5 m high on average, with a slope angle of 20–45°.

The Vistula channel has developed in river alluvia, mostly sands and silty deposits. The river bottom in most of the lower Vistula valley has developed on sandy-gravelly deposits, whereas the study area is one of the places where the material has been nearly completely eroded, and some remains of moraine pavement are left on the bottom, containing clays of various types [*Babiński, 1997*].

Evolution of the Vistula channel, construction of the dam, and its influence on morphodynamic processes. The initial "multichannel fluvial system of the lower Vistula, with the main channel of the braided type, is an example of transformation of a unichannel system of a sand-bottomed river with a braided channel into a multichannel system" [*Gierszewski et al., 2015*]. Its transformation currently takes place under the influence of human activity. A strong human impact on the course of the channel processes started in the early 20th century and was associated with the river channelling from Nieszawa to the mouth of Tążyna [*Ingarden, 1921*]. Further works upstream from Nieszawa were carried out in the 1950s. Changes intensified in the late 1960s, when in Włocławek, 27 km upstream from Nieszawa, a reservoir was constructed [*Babiński, 1982, 1992, 1995; Babiński et al., 2014; Babiński, Habel, 2017*]. Both upstream and downstream from the reservoir, created by impoundment of the river, channel forms and between-channel forms have decreased in number [*Gierszewski et al., 2015*].

Construction of the dam and its operation clearly influenced the process of vertical erosion downstream from the reservoir. Transformation of the channel was observed in the river stretch over 25 km long. In its initial part (6 km), the bottom lowered by more than 3 m. In the Ciechocinek region, 35 km below the dam, it raised by about 1 m [*Babiński 1993*]. Also bank erosion was intensified due to (1) 'impulsive' water discharge from the dam; (2) variable flow rates and water volumes; (3) frequent and significant variations in the water level; (4) water freed load sediments (100 %) and partly from suspension (less than 50 %). The intensity of these processes decreased with increasing distance from the dam in Włocławek [*Banach, 1998*]. The results of the cited study showed that in the river stretch of 45 km downstream from the dam, 24.5 % of the river banks were eroded, while nearly 36 % were neutral. According to the latest study by *M. Habel* [*2013*], the process of extension of the impact zone of the dam is continued.

The reservoir in Włocławek is the first and so far the only one of the planned cascade in the lower Vistula valley. Other reservoirs were supposed to be constructed further downstream. In recent years, the most frequently discussed location of a second dam is Nieszawa.

3. Materials and methods

In this study, we used data from laser scanning, both airborne (ALS) and terrestrial (TLS). The TLS was performed in November 2015, using a Riegl VZ-4000 laser scanner located on the left bank of the river (Fig. 2). It is a pulse scanner constructed in 2011, which can collect point clouds from a distance of up to 4000 m [*RIEGL 3D, 2013*]. The *RIEGL*'s unique V-Line technology is based on echo digitization and online waveform processing, enabling such extreme long-range measurements. The angle measurement resolution is better than 0.0005°, with an angular step of 0.002°. The accuracy of the scanner is 15 mm, and its precision is 10 mm. The *RIEGL* VZ-4000 incorporates waveform processing, capable of detecting and processing multiple echoes from the same direction, which means that complex structures, fences, wires, and vegetation can be handled.

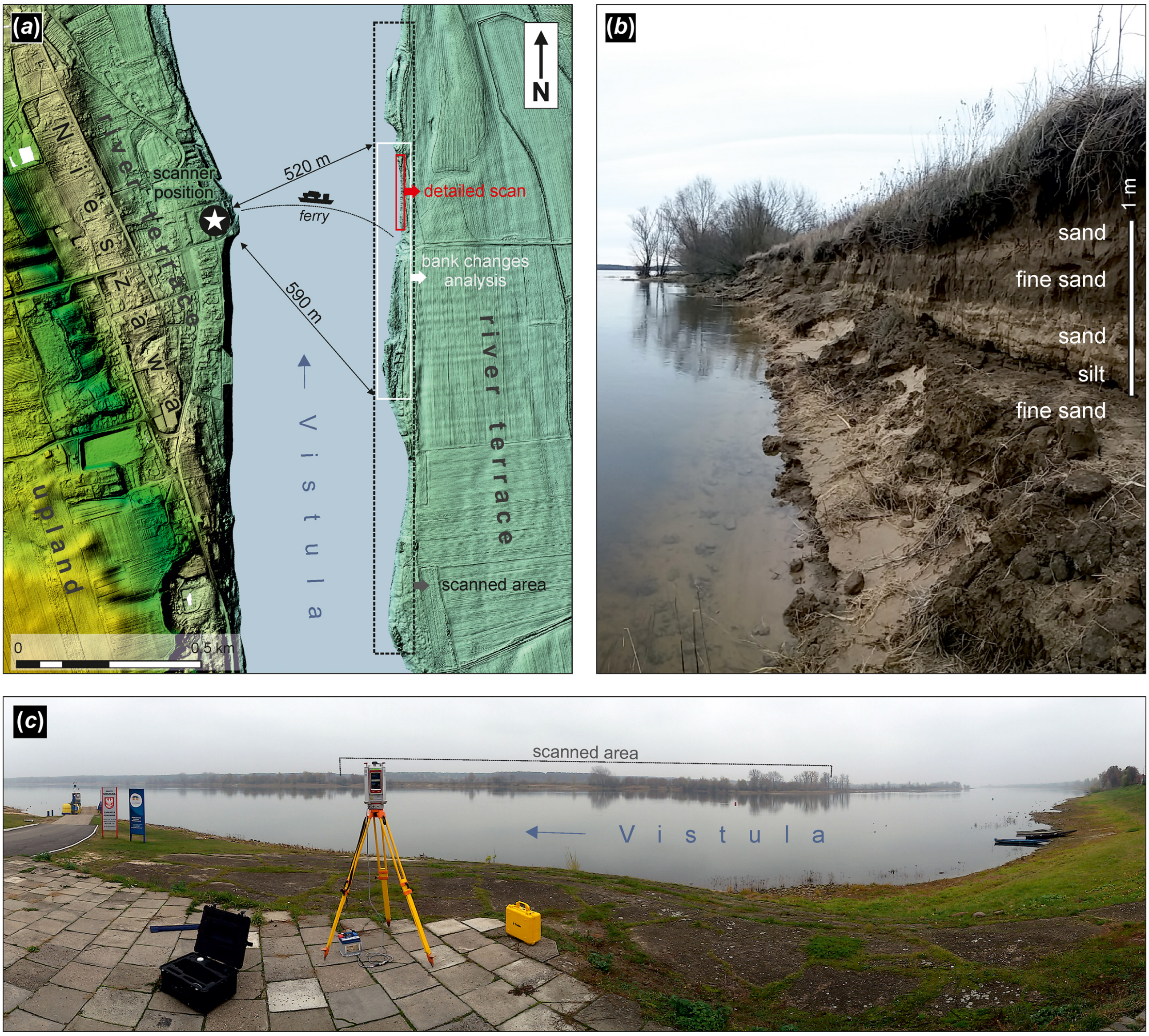

Fig. 2. Map of the study area. (*a*) – locations of the scanner position and the scanned area; (*b*) – river bank of section 3 in 2017; (*c*) – Nieszawa, Riegl VZ-4000 scanner during scanning (180° photo).

Рис. 2. Карта района исследований. (*a*) – местоположение сканера и области сканирования; (*b*) – берег реки (участок 3) в 2017 г.; (*c*) – г. Нишава, сканер Riegl VZ-4000 во время сканирования (фотография 180°).

During our study in Nieszawa, the minimum distance between the scanner and the investigated opposite bank of the river was 430 m, while the maximum was 750 m (Table 2). The measurements were made with a frequency of 30–150 kHz and resolutions theta 0.011-0.003 and phi 0.2–0.003°. Thanks to this, in our study area, the points projected onto the bank were spaced 0.03 m apart or more. The collected point cloud was filtered by RISCAN PRO software to separate only reflections from the ground. The procedure involved elimination of indirect echoes of signal reflection (leaving only single and last reflections), removal of reflections from places located outside our study area, checking the amplitude and intensity of wave reflection from individual categories of objects, such as the ground or vegetation, and their separation (Fig. 3). The final step was manual verification of the point cloud, until only reflections from the ground were left. For the geospatial location of the laser, we applied a GNSS receiver (TRIMBLE R4, coupled with the scanner), using Real Time Kinematic (RTK) corrections from the ASG-EUPOS system.

Our reference data were ALS point clouds from the National Geodetic and Cartographic Resources, generated as part of the IT System of the Country's Protection against Extreme Hazards. The ISOK project aims to create a uniform IT system, which protects citizens, increasing their security and limiting the financial

Table 2. **Parameter of point clouds from TLS**

Таблица 2. **Параметр точечных облаков по данным TLS**

Parameter	General scan	Detailed scan
River bank length	790 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

losses caused by natural, technological, and synergic hazards, especially by floods. The collected data in LAS 1.2 format are characterized by point classification correctness of at least 95 %, the mean point density of at least 4 or 6 points/m^2, and the acceptable mean error of up to 0.2 m. The ALS measurements were carried out in October 2012, and the data were used also to visualize the study area as digital elevation models. The comparative analysis of the river bank morphology between 2012 and 2015 was conducted directly on the point clouds and the elevation models, using LP360, RiSACN PRO, and ArcGIS software.

4. Results and discussion

During the scanning, we collected a point cloud from the Vistula river bank nearly 3.7 km long. For the detailed analysis, we chose the central part, 790 m long, located directly opposite to the laser location. The bank is developed in river alluvial sediments, mostly fine sands and silts (see Fig. 2, *b*).

The point cloud for this stretch of the river included 2.3 million points before filtration reflections directly from the ground. Additionally, we performed a very detailed, high-resolution scan of a 120 m stretch characterized by the major morphodynamics.

The differential analysis of the river bank morphology shows that the changes in the river bank shape are uneven along its length, and various types of changes can be distinguished. Based on the observed transformations, six geomorphologically uniform sections were distinguished in the studied stretch of the Vistula river, each being characterized by similar morphodynamics.

The ALS and TLS measurements were performed at different water levels (in 2012, water surface elevation

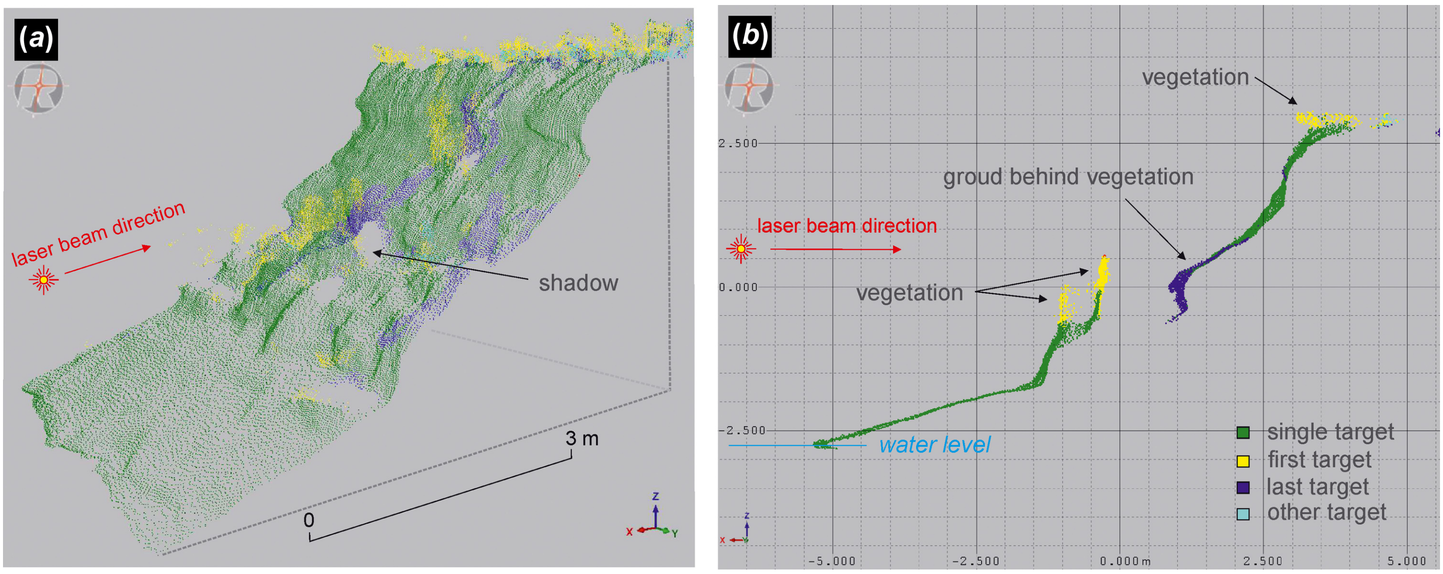

Fig. 3. Point cloud in separation by echo signal (single, first, other and last targets) from terrestrial laser scanning (TLS). (*a*) – point cloud, part of the river bank; (*b*) – cross-section of a point cloud with visible signals from vegetation and lack of data in “shadows”.

Рис. 3. Точечное облако в разбиении по эхосигналу (одиночные, первые, прочие, окончательные цели) от наземного сканирования (TLS). (*a*) – облако точек, часть берега реки; (*b*) – поперечный разрез облака точек с видимыми сигналами от растительности и отсутствие данных в «тенях».

was 41.25 m a.s.l., compared to 39.14 m a.s.l. in 2015). The mean water level on the topographic maps of the study area is estimated at 40.4 m a.s.l. Considering that TLS reflects river bank morphology better, we decided to assess the bank height on the basis of TLS.

Section 1, about 100 m long, includes a strengthened fragment of a parallel dam, that functions as an anti-erosion structure. According to the ALS data, the section is to a large extent covered with water, but the comparison of data from 2012 and 2015 for the visible parts of the bank does not show any changes in morphology.

Section 2, about 15 m long, is located in the western part, very close to the parallel dam. The bank is up to 4.5 m high, covered with shrubs and trees, so it was difficult to observe its shape. However, we noticed that a small landslide appeared between 2012 and 2015, which only slightly changed the shape of the river bank but resulted in remarkable bending of trees growing there. In the immediate vicinity of the upper edge of the cliff, the root systems of trees were disturbed. The structure of the ground in this section was also disturbed, so it can be expected that in the years to come this section of the river bank will be more susceptible to subsidence.

Section 3, nearly 120 m long, is covered only by low vegetation dominated by grasses. According to the ALS data, the slope of the river bank is nearly even, with a slope angle of 35–45°, 4–5 m high. In the western part, the slope after the 3 years has a similar shape and inclination but is moved about 0.7–1.0 m back. The greatest changes took place in its central part, 70 m long. The river bank is 4 m high there. The bank in the vertical profile can be divided into two parts. The upper, steep part has a slope angle of 70° to nearly 90° and is about 1.5 m high, while the slope angle of the lower part is about 40°. In this fragment, nearly 2.8–4.0 m^3 of material were eroded per 1 m of the river bank length (Fig. 4).

Section 4, about 115 m long, is partly covered by shrubs and trees, up to 4.5 m high. In 2012, the bank had a nearly uniform slope angle of 35–40° but the data from 2015 shows significant erosion. The upper edge of the slope was not moved, but the bank profile was changed. An incision was formed in its upper part, so that the slope angle increased to 60–80°, at the height of 1.5–2.0 m. As a result, a well-defined shelf was formed, and no considerable changes were observed below it.

Section 5, about 40 m long, partly strengthened as a ferry berth. In this section, no changes were observed. The bank is sloping gently, covered with grassy vegetation.

Section 6,about 400 m long, with banks up to about 3.5 m high, nearly completely covered with grassy vegetation, shrubs, and trees; the slope angle ranges from 35° to 45°. Between 2012 and 2015, both the upper and lower edges did not change; the shape of the banks is mostly convex, without remarkable depressions. Only the river bank profile changed in some parts of this section. In the middle part, the bank moved up to 1 m back. Like in section 4, a well-defined shelf was formed. The eroded material was completely removed by the river, as it did not accumulate (or was not preserved). This phenomenon was identified in small parts of the bank, up to several metres long. Generally, the changes are much smaller in this section than in the western part of the scanned bank.

East of section 6, the bank is lower, less inclined, covered with shrubs and trees. However, considering the decreasing angle between the shoreline and the laser beams, as well as vegetation absorbing most of reflections, the observation of changes was very difficult. The general image can only show a lack of significant, spectacular movements of the shoreline.

The above results of scanning, processing and analysis of the ALS and TLS data showed that in the studied stretch of the river, during the 3 years between the measurements, the changes occurred in both the bank shape in the vertical profile and the location of the upper cliff edge. The scale of this phenomenon varies, as in many places the process of erosion was not observed. In other places, the bank moved up to 2 m back, but it can be assumed that wherever erosion took place, the banks moved by about 1 m.

The factors that particularly favour bank erosion are frequent and remarkable variations in the water level, as it enhances the dynamic pressure of groundwater, causes suffusion on the banks, decreases the cohesion between rock particles due to their continuous soaking, expansion, and repeated drying [*Banach, 1998*]. In the hydrological years 2012–2015, the water level of the Vistula river in Toruń was low and showed a negative trend (Fig. 5). The lowest annual average water level (214 cm) was recorded in 2015: on 2-6 September an absolute historical minimum water level in Toruń was recorded (94 cm). At that time no hydrological factors significantly affected erosion.

However, we are aware that the analysed stretch of the Vistula, subjected to ALS and long-range TLS, is too short to be representative and allow an assessment of the scale of erosion for longer sections of the river. Nevertheless, the recorded values indicate that the process of erosion takes place unevenly.

The combined use of the ALS and long-range TLS data enabled us to trace changes in river bank morphology in sufficient detail (Fig. 6). The ALS data do not reach such a high resolution as the long-range TLS, but made it possible to determine the river bank shape and – most importantly – to identify its upper edge. These database is crucial for estimating the rates of erosion. The density of the applied ALS point cloud, ensuring at least 4–6 reflections from the ground per 1 m^2, allows

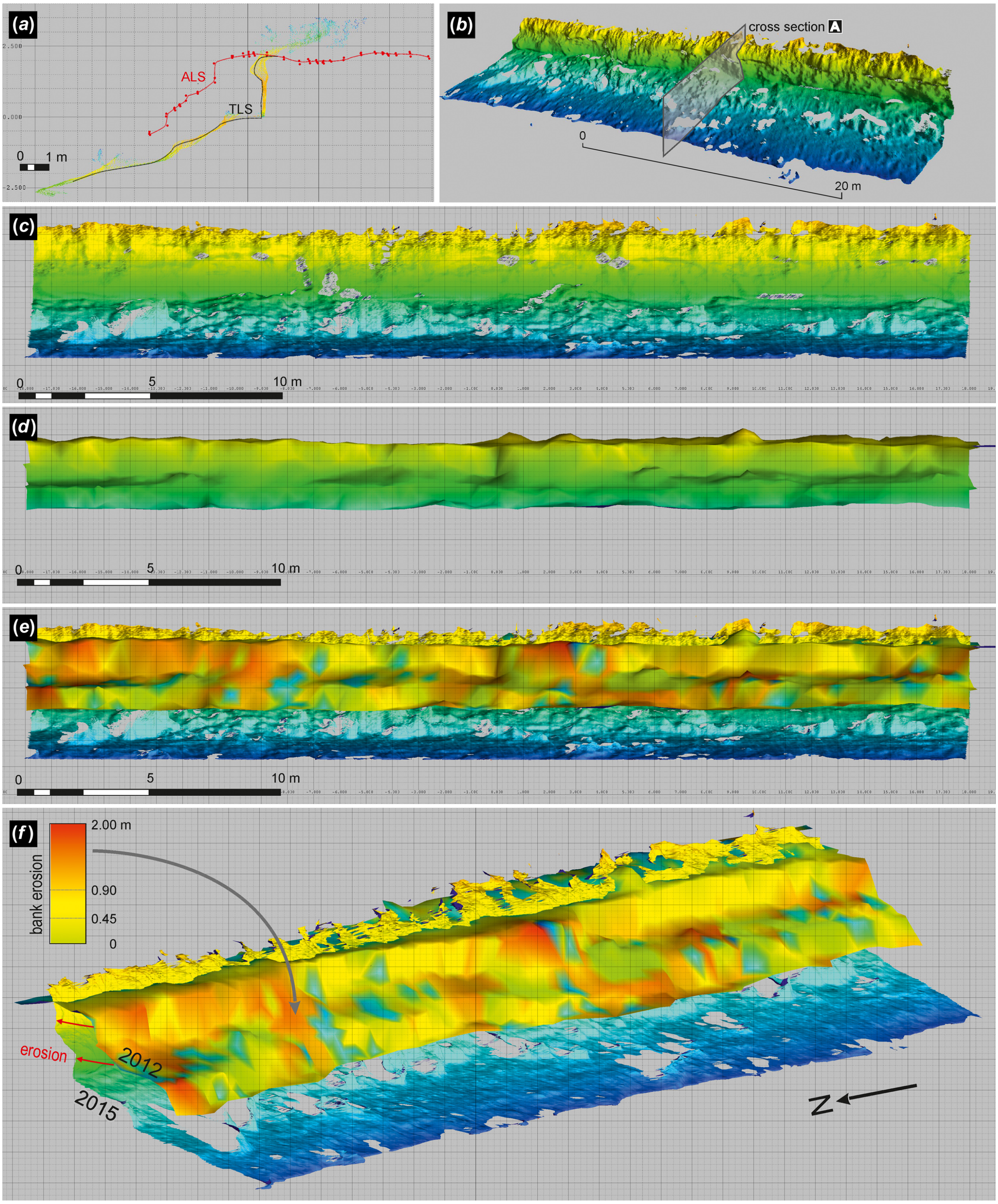

Fig. 4. Analysis of bank erosion of the part of section 3 in combined airborne and long-range terrestrial laser scanning (ALS and TLS). (*a*) – cross-section of ALS and TLS point clouds, 1 m thick (red dots are beams based on ALS); (*b*) – high-resolution digital elevation model (HRDEM) based on TLS; (*c*) – HRDEM of the river bank based on TLS – front view; (*d*) – HRDEM of the river bank based on ALS – front view; (*e*) and (*f*) – differential analysis of HRDEMs based on ALS and TLS (erosion in red).

Рис. 4. Анализ береговой эрозии части участка 3 по результатам комбинированного воздушного и наземного лазерного сканирования (ALS и TLS). (*a*) – поперечный разрез точечных облаков ALS и TLS толщиной 1 м (красные точки – лучи на основе ALS); (*b*) – цифровая модель рельефа в высоком разрешении (HRDEM) на основе TLS; (*c*) – модель HRDEM берега реки на основе данных TLS – вид спереди; (*d*) – модель HRDEM берега реки на основе данных ALS – вид спереди; (*e*) и (*f*) – дифференциальный анализ моделей HRDEM, созданных на основе данных ALS и TLS (эрозия показана красным цветом).

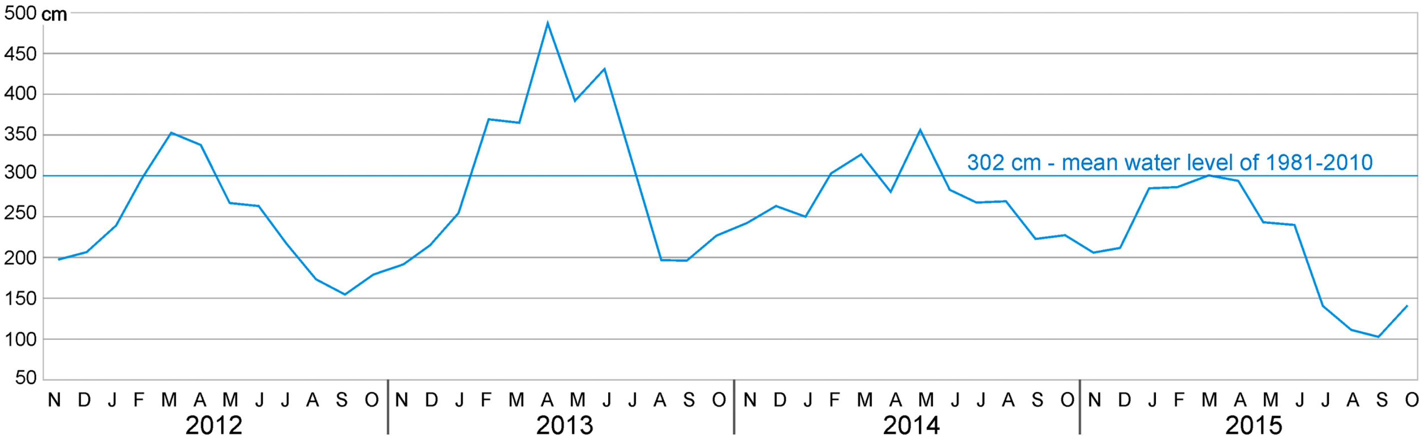

Fig. 5. Water level in Toruń (the water gauge located 33 km below Nieszawa) in hydrological years 2012–2015.

Рис. 5. Уровень воды в реке в районе г. Торунь (водомерная рейка на расстоянии 33 км от г. Нишава) в гидрологические годы 2012–2015 гг.

an assessment of the location of the upper edge of the river bank with the horizontal accuracy of at least 20–30 cm.

On the other hand, TLS makes it possible not only to collect quantitative data on erosion but also to determine the type of erosion. The high resolution of point clouds and the generated HRDEM clearly show the river bank shape, allowing an assessment, interpretation of directions of movements, appearance of characteristic incisions, identification of landslides or even small erosional dissections, when the scanned object is several kilometres away from the scanner.

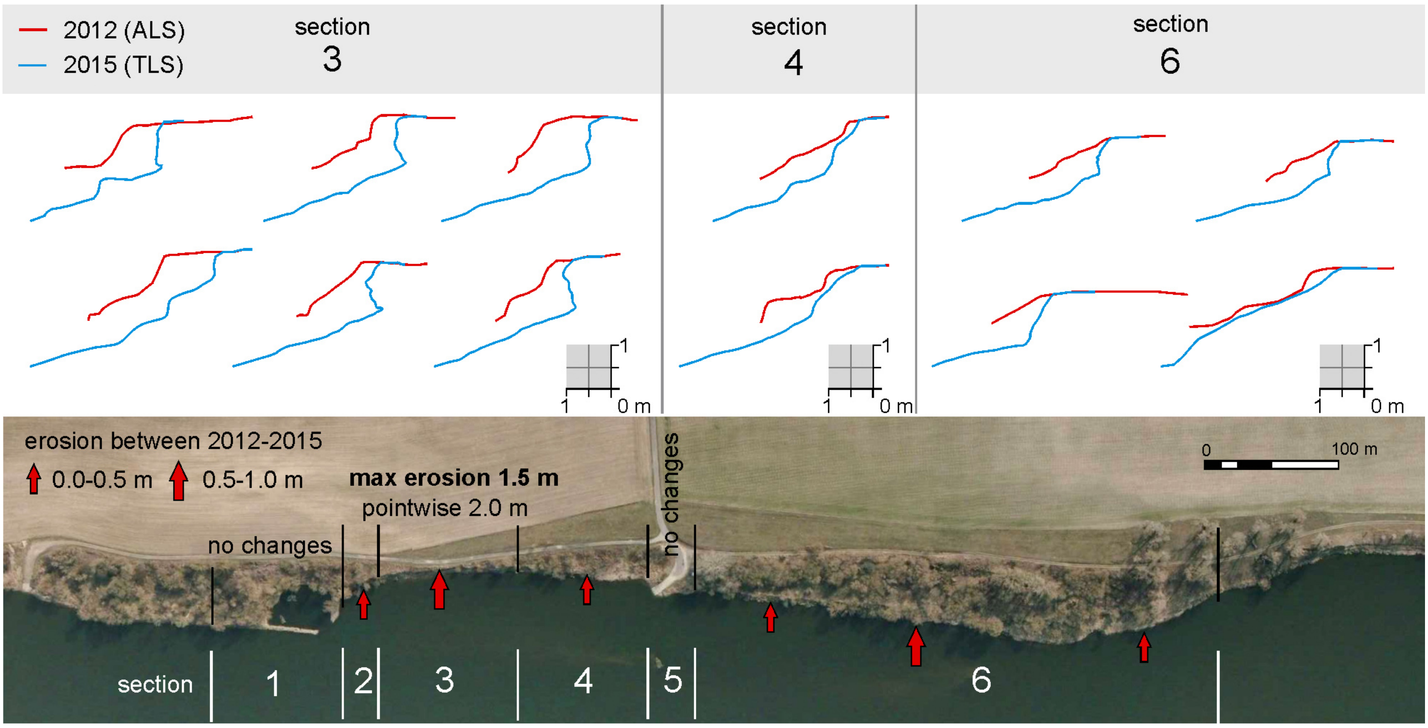

Fig. 6. Changes of the river bank between 2012 and 2015. Cross profiles of high-resolution digital elevation models (HRDEMs) based on airborne and long-range terrestrial laser scanning (ALS and TLS).

Рис. 6. Изменения речного берега в период с 2012 по 2015 г. Перекрестные профили цифровых моделей рельефа в высоком разрешении (HRDEM) на основе данных воздушного и наземного лазерного сканирования (ALS и TLS).

Our experience in scanning the banks of reservoirs with the long-range *RIEGL* VZ-4000 scanner indicates that in successive measurements from a distance of 2000–4000 m, it is possible to detect very small changes, of several cm [*Avian, 2012; Fisher et al., 2016; Tyszkowski, 2015; Wiśniewska et al., 2015*].

The presented combination of ALS and TLS seems to be a very effective solution in terms of cost and time effectiveness in monitoring of banks of a large river. ALS can be performed quickly, simultaneously for long stretches of a river, and when necessary, additional point clouds can be collected with the use of long-range TLS for a detailed study. Point clouds, as well as elevation models based on ALS will then constitute a reference allowing detection of changes of the order of 10 cm in river bank morphology. TLS is better for vertical surfaces, while ALS is better for horizontal ones, so when studying river bank morphology with both types of surfaces, these methods supplement each other.

The combined procedure of river bank monitoring and morphology assessment is of particular importance for interpretation and assessment of environmental impacts caused by constructions (e.g. dams on rivers) in the regions wherein morphodynamic processes can take place quickly and are often unpredictable. It is also important to know when the intensity of such processes increases, declines or ceases.

Conventional methods are still irreplaceable in many cases and will remain in use. However, with further progress in ALS and TLS, these modern techniques become less and less subjective and provide for an easier and more efficient access to the studied objects. Point clouds and elevation models allow in-depth analysis of data and facilitate the data exchange in public formats, such as *.e57 or *.las, as well as easy data transformations to GIS or CAD systems.

5. Conclusion

The study area near Nieszawa, selected for an analysis of the rate of bank erosion of the Vistula river, was characterized by moderate morphodynamic processes in 2012-2015. By comparing the ALS and TLS point clouds, we identified both the stable parts of the river bank and the regions of increased erosion. The differential ALS and TLS models enabled us to detect horizontal changes in the location of the upper edge of the river to the nearest 20-30 cm or even less. In some sections, changes in the shoreline indicate lateral erosion, reaching up to 1.5–2.0 m over the last 3 years. The HRDEM based on TLS allowed a detailed study of the river bank profile, where in some places, in spite of the relative stability of the upper edge, a change in its profile was observed.

With account of using a long-range terrestrial scanner and a relatively high rate of the data collection, the combination of ALS and TLS is an effective tool that can be used on rivers up to 3–4 km wide. River bank erosion at sites located downstream from dams is common, but such a detailed monitoring of those processes is a new, valuable source of information about river bank erosion rates. The results motivate us to undertake more measurements in the river sections located further downstream from the dam, to identify various effects of its operation. In addition, our further studies will focus on assessment of the influence of the bank lithology on the erosion processes.

The integrated use of various systems of laser scanning is a new way to collect data on recent geological processes. The methods described here can be effectively used for monitoring, comparative analyses, etc., as well as for selecting appropriate environmental activities related to river engineering.

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7. References

Avian M., 2012. Performance and limits of different long-range TLS-sensors for monitoring high mountain geomorphic processes at different spatial scales. *Geophysical Research Abstracts* 14, EGU2012-10081. Available from: http://meetingorganizer.copernicus.org/EGU2012/EGU2012-10081.pdf.

Babiński Z., 1982. The influence of the water dam in Włocławek of fluvial processes of the Vistula River. *Dokumentacja Geograficzna* 1–2, 1–92 (in Polish).

Babiński Z., 1992. The present-day fluvial processes of the Lower Vistula River. *Prace Geograficzne, IGiPZ PAN*, 157 (in Polish).

Babiński Z., 1993. Ciechocinek dam and its Nieszawa Reservoir – forecast of geographical environment changes chemical denudation within the drainage basin of the Ruda River. *Zeszyty IGiPZ PAN* 12, 5–27 (in Polish).

Babiński Z., 1995. Procesy erozyjno-akumulacyjne poniżej stopnia wodnego "Włocławek". In: Hydrologiczne i geomorfologiczne problemy zbiornika Włocławek, Przewodnik Wycieczki, Nr. 1, 44 Zjazd PTG, Toruń, p. 16–20 (in Polish).

Babiński Z., 1997. Erosion-accumulation processes below the Włocławek Reservoir, their consequences and impact on the morphodynamics of the planned Nieszawa Reservoir, IGiPZ PAN, Toruń (in Polish).

Babiński Z., Habel M., 2017. Impact of a single dam on sediment transport continuity in large lowland rivers. In: River sedimentation – proceedings of the 13th International Symposium on river sedimentation. ISRS 2016, p. 975–982.

Babiński Z., Habel M., Chalov S., 2014. Prediction of the Vistula channel development between Wloclawek and Torun: evaluation with regard to the new geological survey. *Quaestiones Geographicae* 33 (3), 7–15. https://doi.org/10.2478/quageo-2014-0025.

Banach M., 1998. Dynamics of the Lower Vistula banks. *Dokumentacja Geograficzna IGiPZ PAN* 9 (in Polish).

Bremer M., Sass O., 2012. Combining airborne and terrestrial laser scanning for quantifying erosion and deposition by a debris flow event. *Geomorphology* 138 (1), 49–60. https://doi.org/10.1016/j.geomorph.2011.08.024.

Cebulski J., 2014, The use of Terrestrial Laser Scanner (TLS) to assess the activity of landslides, for example of Bodaki landslide (BeskidNiski Mts.) *Landform Analysis* 26, 105–113. https://doi.org/10.12657%2Flandfana.026.010.

Day S.S., Gran K.B., Belmont P., Wawrzyniec T., 2013a. Measuring bluff erosion part 1: terrestrial laser scanning methods for change detection. *Earth Surface Processes and Landforms* 38 (10), 1055–1067. https://doi.org/10.1002/esp.3353.

Day S.S., Gran K.B., Belmont P., Wawrzyniec T., 2013b. Measuring bluff erosion part 2: pairing aerial photographs and terrestrial laser scanning to create a watershed scale sediment budget. *Earth Surface Processes and Landforms* 38 (10), 1068–1082. https://doi.org/10.1002/esp.3359.

Fischer M., Huss M., Kummert M., Hoelzle M., 2016. Application and validation of long-range terrestrial laser scanning to monitor the mass balance of very small glaciers in the Swiss Alps. *The Cryosphere* 10 (3), 1279–1295. https://doi.org/10.5194/tc-10-1279-2016.

Gierszewski P., Szmańda J., Luc M., 2015. Changes of Vistula River channels pattern caused by Włocławek Dam functioning based on the analysis of aerial photographs. *Przegląd Geograficzny* 87 (3), 517–533 (in Polish).

Habel M., 2013. Dynamics of the Vistula River Channel Deformations Downstream of the Włocławek Reservoir. Wydawnictwo Uniwersytetu Kazimierza Wielkiego, Bydgoszcz, 138 p.

Ingarden R., 1921. Rivers and Waterways in Former Three Partitions and Their Economic Significance for Poland. Kraków (in Polish).

Jaboyedoff M., Demers D., Locat J., Locat A., Locat P., Oppikofer T., Robitaille D., Turmel D., 2009. Use of terrestrial laser scanning for the characterization of retrogressive landslides in sensitive clay and rotational landslides in river banks. *Canadian Geotechnical Journal* 46 (12), 1379–1390. https://doi.org/10.1139/T09-073.

Julge K., Eelsalu M., Grünthal E., Talvik S., Ellmann A., Soomere T., Tonisson H., 2014. Combining airborne and terrestrial laser scanning to monitor coastal processes. In: Measuring and modeling of multi-scale interactions in the marine environment – IEEE/OES Baltic International Symposium 2014, BALTIC 2014, Art. no. 6887874.

Kaczmarek H., Tyszkowski S., Banach M., 2015. Landslide development at the shores of a Dam reservoir (Włocławek, Poland), based on 40 years of research. *Environmental Earth Sciences* 74 (5), 4247–4259. https://doi.org/10.1007/s12665-015-4479-3.

Kędra M., Wiejaczka Ł., Wesoły K., 2015. The role of reservoirs in shaping the dominant cyclicity and energy of mountain river flows. *River Research and Applications* 32 (4), 561–571. https://doi.org/10.1002/rra.2880.

Kociuba W., 2017. Analysis of geomorphic changes and quantification of sediment budgets of a small Arctic valley with the application of repeat TLS surveys. *Zeitschrift für Geomorphologie*, *Supplementary Issues*, 61 (2), 105–120. https://doi.org/10.1127/zfg_suppl/2017/0330.

Lawler D.M., 1993. The measurement of river bank erosion and lateral channel change: a review. *Earth Surface Processes and Landforms* 18 (9), 777–821. https://doi.org/10.1002/esp.3290180905.

Lawler D.M., Leeks G.J.L., 1992. River bank erosion events on the Upper Severn detected by the Photo-Electronic Erosion Pin (PEEP) system. In: J. Bogen, D.E. Walling, T.J. Day (Eds.), Erosion and sediment transport monitoring programmes in river basins: Proceedings of the Oslo Symposium. International Association for Hydrological Sciences Publication, vol. 210, p. 95–105.

Lawler D.M., West J.R., Couperthwaite J.S., Mitchell S.B., 2001. Application of a novelautomatic erosion and deposition monitoring system at a channel bank site on the tidal River Trent, UK. *Estuarine, Coastal and Shelf Science* 53 (2), 237–247. https://doi.org/10.1006/ecss.2001.0779.

Lorenc H. (Ed.), 2005. Atlas of Poland climate. IMGW, Warszawa (in Polish).

Milan D.J., Heritage G.L., Hetherington D., 2007. Application of a 3D laser scanner in the assessment of erosion and deposition volumes and channel change in a proglacial river. *Earth Surface Processes and Landforms* 32 (11), 1657–1674. https://doi.org/10.1002/esp.1592.

Resop J.P, Hession W.C., 2010. Terrestrial laser scanning for monitoring streambank retreat: comparison with traditional surveying techniques. *Journal of Hydraulic Engineering* 136 (10), 794–798. https://doi.org/10.1061/(ASCE)HY.1943-7900.0000233.

RIEGL 3D Terrestrial Laser Scanner, Riegl VZ-4000/VZ-6000, General Description and Data Interfaces, 2013.

Telling J., Lyda A., Hartzell P., Glennie C., 2017. Review of Earth science research using terrestrial laser scanning, *Earth-Science Reviews* 169, 35–68. https://doi.org/10.1016/j.earscirev.2017.04.007.

Tyszkowski S., 2015. Mass movements of lowland areas in long range TLS and ALS monitoring. *Geophysical Research Abstracts* 17, EGU2015-12805. Available from: https://meetingorganizer.copernicus.org/EGU2015/EGU2015-12805.pdf.

Wiejaczka Ł., Kijowska-Strugała M., 2015. Dynamics of the channel beds level in mountain rivers in the light of the minimum water stages analysis. *Carpathian Journal of Earth and Environmental Sciences* 10 (4), 105–112.

Wiśniewska D., Kramkowski M., Tyszkowski S., 2015. Application of a long-range terrestrial laser scanner in research on lowland geodynamic processes. *Geophysical Research Abstracts* 17, EGU2015-616-1. Available from: https://meetingorganizer.copernicus.org/EGU2015/EGU2015-616-1.pdf.

Wójcik G., Marciniak K., 2006. Climate. In: L. Andrzejewski, P. Weckwerth, S. Burak (Eds.), Torun and its surroundings. Natural monograph, Nicolaus Copernicus University, Toruń, p. 99–128 (in Polish).

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