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3D laser scanning as a new tool of assessment of erosion rates in forested loess gullies (case study: Kolonia Celejów, Lublin Upland)

Skaning laserowy 3D jako nowe narzędzie oceny dynamiki rozwoju zalesionych wąwozów lessowych na przykładzie Kolonii Celejów (Wyżyna Lubelska)

Keywords: Terrestrial Laser Scanning, TLS data, DTM, DSM, loess gully development
Słowa kluczowe: naziemny skaning laserowy, dane TLS, DTM, DSM, rozwój wąwozu lessowego

INTRODUCTION

The gully network existing in a number of loess areas under agricultural use in the Lublin Upland has been subject to secondary vegetation succession. The dense plant cover makes the application of remote sensing methods difficult. As a result, topographic maps frequently present the general outlines of the gullies, and in the case of a considerable dissection of the badlands type – only the boundaries between the occurring forest assemblages and cultivated fields. Aerial photographs do not permit tracing the modern development of the lateral branches of the gully, or the qualitative assessment of material transported in the gully system. The application of satellite geodesy tools is also problematic due to weak penetration of tree crowns by the signal. The application of traditional geodesic tools, including laser total stations, is time-consuming and strenuous, particularly in the case of measurement of microforms. Moreover, measurements by means of total stations require relevant preparation of the polygon, and frequently the removal of bushes and high perennials. Such measurement problems can be solved by the application of the modern Terrestrial Laser Scanning (TLS) technology.

The primary objective of the paper is to develop a strategy of measurement of active gully landforms, and the application of the TLS technology for geomorphological mapping in forested and branched gully systems. Moreover, detailed measurements of the geometry of the secondary landforms permit the monitoring of tendencies and the determination of the rate of development of gullies.

STUDY OBJECT AND STUDY AREA

The study area is located in the north-western part of the Lublin Upland, covered with a thick loess layer (from 5 m to 30 m), developed predominantly during the last Vistulian alimentation cycle (Maruszczak 1963). The high susceptibility of the loesses to erosion, and low location of the erosion base of the Vistula River gorge valley through the Polish Uplands belt at a denivelation with the loess plateau of up to 100 m, provide conditions for the development of gully systems (Maruszczak 1958, 1972, Rodzik et al. 2002). As a result of intensive agricultural use of the loess area in the prehistoric, historic, and modern period, a network of gullies with a mean density of 2.5 $km \cdot km^{-2}$, and locally even up to 10 $km \cdot km^{-2}$ developed in the western part of the Nałęczów Plateau (Maruszczak 1973; Schmitt et al. 2006; Gawrysiak, Harasimiuk 2012). In the period of particularly high agricultural pressure in the 2nd half of the 19th and the 1st half of the 20th century, resulting from the overpopulation of rural areas, wars, and economic crisis, the gullies were used in multiple ways. Wood and forest bed were commonly collected. The gullies were used as pastures for cattle, and some of their slopes and bottoms as agricultural fields. The depopulation of the rural areas in this part of Poland, observed since the 1970's, and industrialisation contributed to the abandoning of the exploitation and reforestation of the gullies. The process of setting fields aside has been progressing, in particular in the case of fields located at the edges of gullies. The bottoms and slopes of the gullies are currently occupied by oak-hornbeam forests (*Tilio-Carpinetum*) at various degradation and regeneration stages. The majority of the gullies are currently inactive, although numerous lateral branches and bottom dissections appear during intensive rainfalls and snowmelts (Rodzik et al. 2009).

The analysed gully system in Kolonia Celejów is located in the western part of the Nałęczów Plateau. It dissects the catchment under agricultural use with an area of 1.24 km^2 (Fig. 1). The total length of the gullies in the catchment amounts to 7.7 km. Their density reaches 6.1 $km \cdot km^{-2}$ (Rodzik et al. 2009). The slopes and edges of the gully are stabilised by oak-hornbeam assemblages. In certain places, however, at the boundaries of fields and forests, particularly at fields cultivated along the slopes, numerous erosion forms develop (Rodzik, Zgłobicki 2000). The accumulative bottom of the gully, with a width of 5–10 m, is dissected at the confluence of the main landforms, resulting in the development of headcutting terraces on its bottom (Rodzik 2010), composed of layered silts, accumulated from the 16th to the mid-20th century (Zgłobicki, Rodzik 2007). The process of dissection of the gully bottom by the secondary gully constituting the object of this study commenced in 1997, and proceeded over the next several years abundant in heavy rainfalls and snowmelts (Rodzik, Zgłobicki 2000). In the dry years of 2002–2008, the gully stabilised, among others as a result of the disappearance of the outflow from a small spring in the upper part of the main gully (Rodzik et al. 2009). From 2009, its gradual development occurred again, partly due to the reappearance of the outflow from the spring. In spring 2013, the volume of the analysed form reached almost 1,000 m^3, and its basic parameters were as follows: length: 160 m, width: 2.5 m–4.5 m, and depth: 1.5 m–3 m.

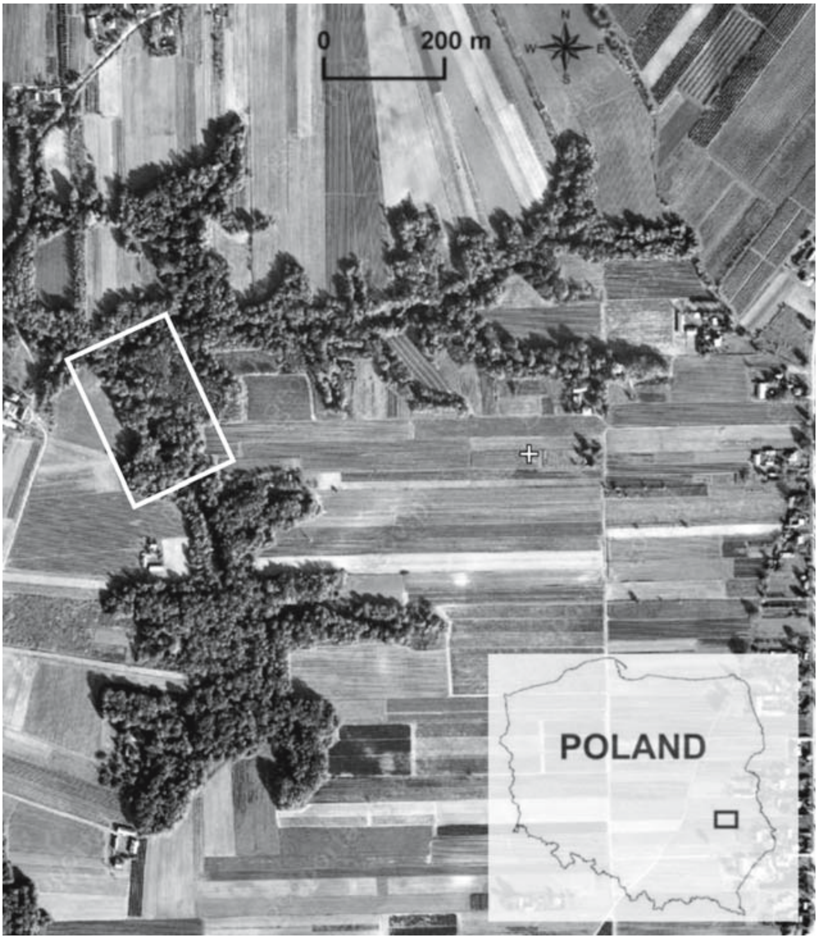

Fig. 1. Location of the study area on the orthophotomap: 1– study area

METHODS

The rate of development of the secondary gully was determined by means of 3D Terrestrial Laser Scanning. The field research in the conditions of the forested loess gully was conducted during two measurement campaigns: in October 2012 and April 2013 by means of a Leica HDS 7000 scanner. Although the measurements were conducted at the end and beginning of the vegetation period, small bushes were removed for the purpose of improvement of the quality of the scanned image (Fig. 1).

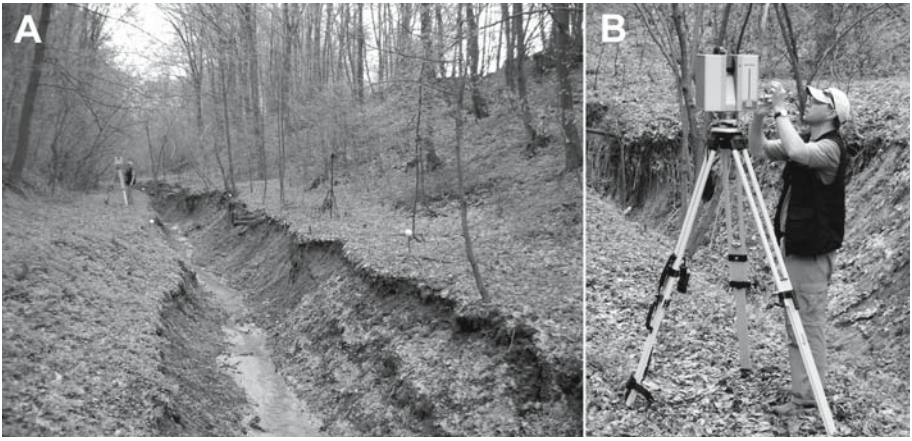

Fig. 2. A. Measurement of the dissection of the main gully bottom (secondary gully landform) with the application of target points (spring 2013). B. Measurement on a forested gully bottom by means of a 3D Leica HDS 7000 after the removal of bushes

The functioning of the scanner applied for the measurements involves stationary laser measurement of the 3D location of a point at a rate of up to 1,016,727 $pt \cdot s^{-1}$ by means of an invisible phase-shift laser with a wavelength of 1.5 µm. The maximum measurable distance according to the producer amounts to 187 m. The range of scanning by means of a Leica HDS 7000 (up to 360° horizontally and up to 270° vertically) permits measurements in difficult terrain conditions. The measurement data obtained in the form of a point cloud constitute a model space with the accuracy of the 3D point location of up to 6 mm. The applied Leica Cyclone 8.0 software transforms the point cloud and generates a Digital Terrain Model (DTM), providing a basis for multi-aspect data analysis. The high accuracy of the model permits the analysis of parameters at various spatial scales in relation to both the entire analysed object and selected landforms, as well as generating any defined cross- and longitudinal sections within such landforms.

In the case of the application of a medium-range scanner for measurements of large objects, the quality of the obtained model largely depends on the applied measurement strategy and the accuracy of integration of particular model spaces composed of point clouds. The predefined measurement resolution is of considerable importance for the interpretative possibilities of the obtained model. It determines the number and quality of single measurements. In this case, high resolution was applied, permitting obtaining an average of 125,000,000 point measurements at each of the measurement sites. Due to the lack of the possibility to position the scanner by means of GPS (due to the lack of signal as a result of the location in the gully and high density of tree crowns), the model was integrated by means of the method involving so-called target points (TP) (Kociuba et al. 2013). It permits the integration of adjacent model spaces by referring to permanent target points distributed between the measurement sites (Fig. 3).

Fig. 3. Laser scanning scene (point cloud) with vegetation (before its removal from DTM)

The device's interface has a coded pattern of normalised black and white targets, identified during scanning. The targets are decoded during the import of data to the Cyclone 8.0 software in the form of vertexes, i.e. non-dimensional reference points in 3D space, corresponding to the middle of each target (Fig. 3). The indication of a minimum of two target points common for consecutive sites and located at a distance of 20 m–40 m from the scanning site (maximum distance permitting automatic identification of a target) enables accurate integration of particular point clouds and obtaining a high accuracy DTM. For a higher precision of the model, in the case of both of the measurement campaigns, 11 target points were applied, constituting a permanently established network of target point polygons, distributed with the assumption of a minimum visibility of 3–4 of them from each consecutive measurement site. Moreover, auxiliary target points were established at distinctive sites, namely measurement spheres with a diameter of 12 cm.

The applied method involving TP (target points) as common reference points permitted the integration of individual point clouds into the target model by means of the Leica Cyclone 8.0 software. The final effect of the measurements was the development of an integrated model obtained by means of integrating 14 model spaces. As a result of their integration, a DTM was obtained with the total error not exceeding ±1 cm. The integration was performed with the application of the algorythm of automatic identification of the geometry of the target point system. The integrated DTM was transformed to a Digital Surface Model (DSM) by means of the "manual" removal of trees, bushes, and branches and stems of plants from the DTM using the "fence" function offered by Cyclone 8.0. The resulting DSM constituted the basis of the performed spatial analyses.

RESULTS

Strong erosion in the bottom of the main gully in Kolonia Celejów, resulting from heavy rainfalls in summer 2012, largely increased the dimensions of the secondary gully. In addition to its elongation, deepening, and widening, also new headgully forms were observed (Table 1). A number of microforms resulting from slumps appeared on the slopes and in the bottom of the dissection, difficult to measure by means of traditional methods. Due to this, the laser scanning method of measurement was applied (Fig. 4).

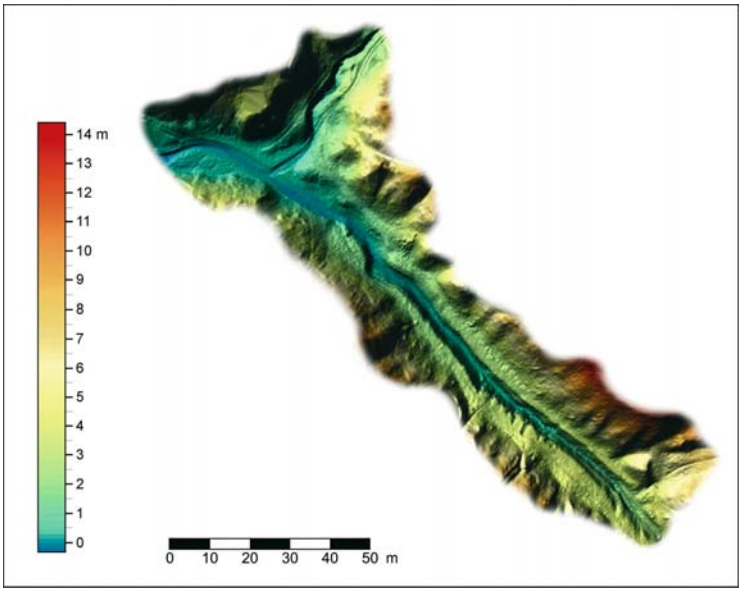

Fig. 4. DSM of the study object with hypsometry. Permanent gully bottom dissections by erosion landforms (autumn 2012)

Repetitions of the study every autumn after summer rainfalls was assumed due to the observed low effectiveness of snowmelt wash in dissecting gully bottoms. Due to the multi-phase character of snowmelt in the winter-spring seasons 2012/2013, however, the relatively large periodical outflow from the spring was frequently substantially increased by snowmelt wash. This caused the dissection of the gully bottom, and a considerable increase in its size in the period from February to April 2013. Due to this, the measurement was repeated in spring 2013. The results of both of the measurements are presented in Table 1.

Table 1. Development of the secondary gully landform as a result of snowmelt in 2013

	Geometric parameters				
Measurement term	Length [m]	Width [m]	Depth [m]	Volume [m^3]	Headgully form [m^3]
Autumn 2012	160	2.5-4.5	1.5-3.0	765.4	163.18
Spring 2013	182	2.6-5.5	1.6-4.0	939.1	212.68

As a result of snowmelt wash in 2013, the length of the secondary gully increased by 22 m, and the maximum depth and width by 1 m. The bottom was deepened by 0.3 m on the average, and the width of the dissection increased by 0.5 m. The volume of the measured gully increased by more than 20%. The spatial development of the dissection was primarily manifested in a substantial retreat of the upper erosional scarp as a result of intensified headcutting (Fig. 5).

The shift of the main erosional scarp in the upper section of the analysed dissection, and changes in its morphology resulting from headcutting, are presented in Figure 5. The DTM obtained as a result of scanning permits distinguishing a total of 5 avens with a diameter and depth of approximately 1 m, interconnected by narrowings. The changes can be accounted for by multi-phase pronival wash. The high effectiveness of the headcutting processes particularly results from long-lasting melt water wash and the dissection of the susceptible to erosion colluvia in the bottom of the main gully.

Cross-sections below both of the erosional scarps (Fig. 6), performed based on the DTM, confirm such an interpretation. At the moment of obtaining the balance curve (profile a–b), deep erosion is limited, and lateral erosion is activated. The avens are widened, and their profile changes into a box section. As a result of headcutting during snowmelt in 2013, the cross-profile of the dissection in the place of the lower erosional scarp increased by 1.7 m^2. In the place of the upper erosional scarp, an increase by almost 3 m^2 was recorded.

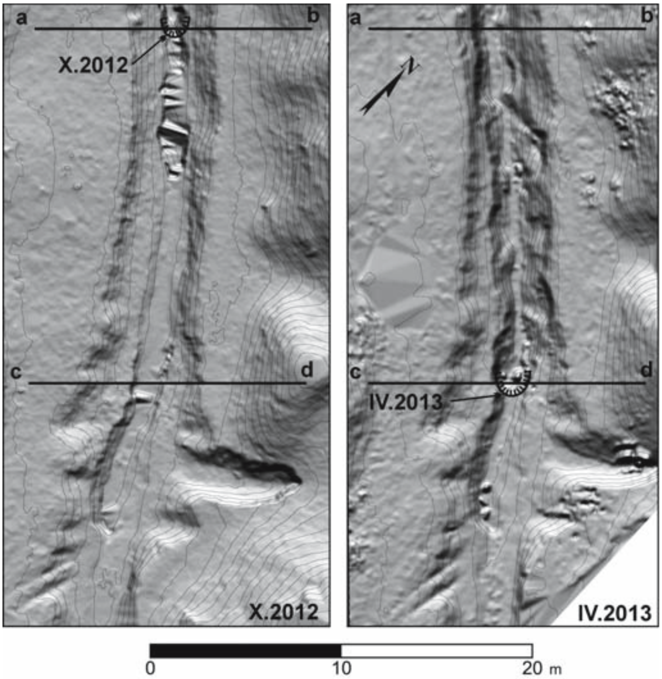

Fig. 5. Erosion scarp retreat as a result of headcutting: profile a–b shows the state in October 2012, and profile c–d shows the state in April 2013

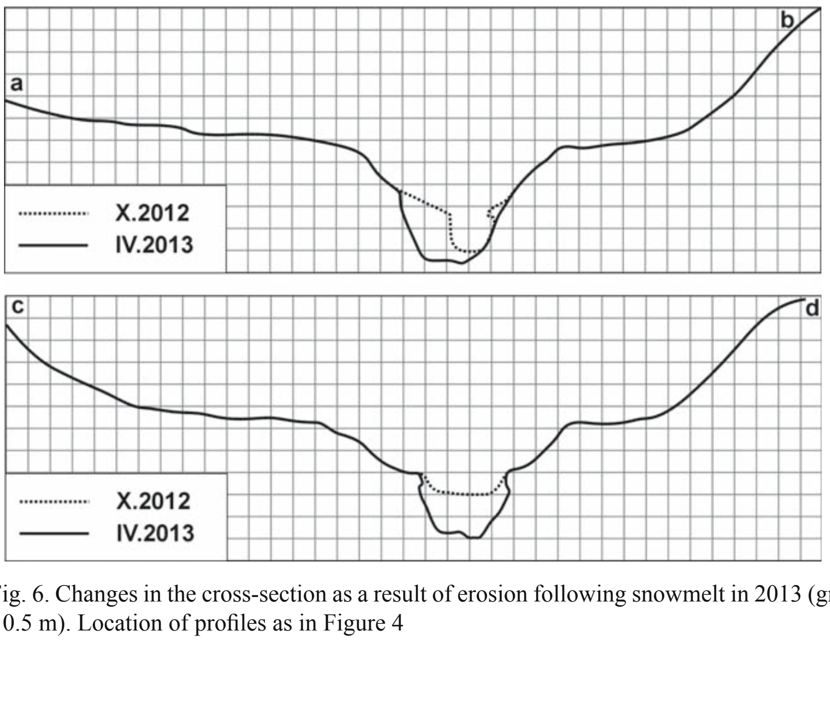

Fig. 6. Changes in the cross-section as a result of erosion following snowmelt in 2013 (grid line every 0.5 m). Location of profiles as in Figure 4

CONCLUSIONS

• The application of the modern technology of laser scanning (TLS) permits the monitoring of the development of forms of gully erosion, even in forested gullies. The obtained measurement data enable very precise calculation of the volume of the resulting landforms with relatively complex spatial structure. The generated DTM also registers microforms and land topography. Moreover, the technology integrates spatial variables and develops a geometric 3D image at a scale of 1:1, accurately reflecting the actual object. The measurement methodology ensures high resolution of the obtained DTM and DSM of the studied objects.

• In the geoecosystems of loess gullies subject to rapid transformations, cyclical measurements permit the monitoring of the rate of the occurring processes and directions of further land relief transformations. Repeating the measurements in consecutive seasons permits the determination of both the spatial and temporal dynamics of the occurring changes.

• A slight drawback of the proposed measurement method is the necessity to perform multi-site measurements based on an established network of targets in forest areas. This involves frequent moving of sites, which extends measurement duration. Therefore, the success of the measurement campaign depends on the stability of the weather conditions, and particularly lack of precipitation. A high number of measurements also contributes to the time-consuming character of the development of DMT and DSM.

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STRESZCZENIE

Systemy wąwozowe, tworzące gęstą sieć rozcinającą pokrywę lessową w północno-zachodniej części Wyżyny Lubelskiej, są porośnięte lasami mieszanymi w typie grądów (ryc. 1). Na stromych zboczach wąwozów występuje wysoki drzewostan, głównie grab i lipa, zaś na płaskim dnie wąwozu rosną krzewy i byliny (ryc. 2 i 3). Porastające wąwóz zwarte i wielopiętrowe zbiorowiska leśne w zasadzie uniemożliwiają wykorzystanie technik teledetekcyjnych i urządzeń pozycjonowania satelitarnego (GPS) do monitoringu rozwoju form wąwozowych. Roślinność ta również utrudnia zastosowanie nowoczesnych narzędzi geodezyjnych, takich jak tachimetr laserowy, a także technologii naziemnego skaningu laserowego (TLS).

Podjęte badania w kontrolowanej zlewni wąwozowej mają na celu wypracowanie skutecznej strategii pomiaru natężenia erozji wąwozowej oraz zastosowanie technologii TLS do monitoringu tempa i kierunku rozwoju wąwozów zalesionych (ryc. 2). Do szczegółowych badań wybrano drugorzędową formę wąwozową, która od 15 lat stopniowo rozcina płaskie dno głównego wąwozu (ryc. 4). Początkowo wykonywano pomiary za pomocą taśmy mierniczej i klizymetru, a następnie dalmierza i tachimetru laserowego. Urządzenia te nie pozwalają na pomiar mikroform, dlatego w celu zwiększenia precyzji i efektywności pomiarów zastosowanego fazowy skaner laserowy. Rozpoznanie tempa rozwoju wtórnego wąwozu wykonano przy użyciu naziemnego skaningu laserowego 3D Leica HDS 7000. Badania terenowe w warunkach zalesionego wąwozu lessowego przeprowadzono w październiku 2012 i w kwietniu 2013 r.

W analizowanym okresie zaobserwowano szybki rozwój wtórnego rozcięcia dna wąwozu, głównie w wyniku spływów propluwialnych. Oszacowana przy użyciu TLS objętość analizowanej formy osiąga 1000 m^3, a jej podstawowe parametry wynoszą odpowiednio: długość ok. 160 m, szerokość od 2,6 m do 5,5 m, głębokość od 1,6 m do 4 m (tab. 1). Analizowane rozcięcie erozyjne zwiększa swoją kubaturę głownie w wyniku wzmożonej erozji wstecznej. W roku 2013 podczas roztopów doszło do cofnięcia progu erozyjnego o 22 m (ryc. 5). Przekrój poprzeczny górnego odcinka rozcięcia powiększył się od 1,7 m^2 do prawie 3 m^2 i zmienił kształt na skrzynkowy (ryc. 6).