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USE OF AIRBORNE LASER SCANNING DATA FOR MODELLING OF THE BOTTOM RELIEF IN A DESIGNED WATER RESERVOIR — CASE STUDY OF PIETRASZKI (KIELCE, POLAND)

While designing water reservoirs, especially those meant for recreation, apart from determining the resources and state of water purity in the catchment area, it is important to draw the course of the coastline and to recognise reservoir's bottom relief and its geometric parameters. The paper presents possibilities for the use of Airborne Laser Scanning (ALS) data in the morphological analysis of the bottom of the designed Pietraszki multi-purpose water reservoir which is located in the mouth section of the Sufraganiec river (5th rank) in Kielce. The source material consisted of 0.5 m resolution digital elevation model created by the MGGP Aero company on the basis of an ALS point cloud obtained in 2011. The bottom of the Sufraganiec valley was modelled with the use of SAGA GIS software which helped to draw reservoir's coastline and calculate its geometrical and morphological parameters.

The paper has proved that the DEM made from high-resolution Airborne Laser Scanning elevation data has been very useful for multidirectional morphological analysis of the bottom of the designed multi-purpose water reservoir Pietraszki, located in the outskirts of Kielce. There will be significant depth differences within the planned reservoir. The largest depth at the NWL will be at direct vicinity of the dam, regardless of its location, in the southwest of reservoir's area and will reach 4.2 m.

In practice, this analysis resulted in estimating the volume of ground masses that need to be moved in the investment area and in designing recreational zones along the reservoir's coastline. It has been proved that the use of ASL digital elevation model is fully legitimate for detailed modelling of reservoir's bottom and also for designing its coastline reach at two fixed water levels.

Key words: LiDAR, digital terrain model, water reservoir, bottom topography.

Introduction. While designing water reservoirs, especially those meant for recreation, apart from determining the resources and state of water purity in the catchment area, it is important to draw the course of the coastline and to recognise reservoir's bottom relief and its geometric parameters. For this purpose, detailed topographic maps, geodesic survey results and photogrammetric materials in the form of satellite images and aerial photographs are mainly used. In recent years, due to the development of remote sensing techniques, Airborne Laser Scanning (ALS) has emerged as a new source of high resolution elevation data (Affek 2014, Sailer et al. 2014). This data can be used to develop an elevation model that allows for very accurate morphometric modelling of the planned water reservoir, which is necessary to determine reservoir's capacity, spatial depth distribution, visualisation of bottom relief, designation of morphological profiles, as well as to plan necessary earthworks within its bottom and in the coastal zone. Literature enumerates many examples of the use of laser scanning data in geomorphological studies (Webster et al. 2006; Höfle, Rutzinger 2011; Bremer, Sass 2012; Bernardini et al. 2013; Migoń et al. 2013; Wójcik et al. 2013), including river valleys (Borkowski et al. 2006; Gołuch et al. 2009; Florek, Tylman 2013; Wierzbicki et al. 2013; Brach, Chormański 2014). In Poland, as part of the ISOK project (ISOK — IT system of the Country's Protection Against Extreme Hazards), ALS data is used to develop numerical models of river valleys and to assess hydrological hazards such as flood risk and flood reach (Kowalski 2013; Kurczyński, Bakuła, 2013; Pawłuszek et al. 2014). It has also been used to analyse bottom relief of natural water reservoirs, including the marine coastal zone (Dudzińska-Nowak, Wężyk 2006). However, this technique has not yet found much use in the design of artificial water reservoirs in Poland, including coastline modeling and bottom morphology.

Therefore the aim of this paper is to present the possibility of using ALS data for morphological analysis of a designed multi-purpose water reservoir named Pietraszki (Sufraganiec valley in Kielce, Poland).

Data sources and methodology. The present paper refers to a Digital Elevation Model (DEM) developed on the basis of an ALS point cloud which was made on 27 and 28 September 2011 by MGGP S.A (2011). 4 flights at an average height of 660 m were performed by Eurocopter 120 with LiteMapper LMSQ680i system. As a result, an average density of 28 points per square metre was obtained, which constitutes a much greater representation of the ground surface than in the ISOK standard (12 points per square metre). A resulting point cloud in LAS format was archived in 2000 Coordinate System (Zone 7), and in addition to the XYZ coordinates it was also classified according to the ASPRS standard (soil, vegetation: low, medium, high). A DEM in a GRID structure with 0.5 m resolution was prepared by the aforementioned company with TerraSolid software, using points classified as laying on ground and TIN (Triangular Irregular Network) interpolation method. This required careful filtering of other points representing non-ground objects (i.e. buildings, vegetation, noise). The vertical accuracy of the resulting model is characterized by an average error of m_z <0,15 m, while the horizontal by m_p<± 0,5 m. The assessment of altitude accuracy of the ALS DEM in relation to the height of the reference points presented on the base map sheets covering the study area indicates that a mean square error on the basis of the 1085 point pairs analysis was similar to the abovementioned value declared by the contractor.

The analytical procedure was performed with the use of SAGA GIS software (Conrad et al. 2015). The coastline course was defined by taking into account two levels of reservoir's fill — normal (224.0 m a.s.l.) and maximum (224.4 m a.s.l.). Next, terrain modeling was carried out, which consisted in removing the organic soils layer and bottom micro-leveling of the designed reservoir, while taking into account the relief of the valley floor with existing drainage ditches and natural depression areas, as well as the presence of thick organic soils. For this purpose, the map algebra modules were used (Tomlin 1990). In the area of organic soils, the DEM was lowered by their average thickness (0.3 m). Then, a DEM resampling procedure was performed twice from 0.5 m to 5 m and then again to 0.5 m. During reservoir's bottom modeling, the existing course of the Sufraganiec channel was preserved. While analyzing ground relative height changes, the volume of earth masses to be displaced was calculated, with the use of the Grid Volume tool. As a result of the operations performed, the final DEM of reservoir's leveled bottom was obtained, which was later subjected to further interpretation. The bottom profiles of the designed reservoir were determined with the use of Profiles from Lines tool, while bathymetric analyses — with Lake Flood and Hypsometry. The slope map of reservoir's bottom was generated according to the method described by Zevenbergen and Thorne (1987).

Study area. The designed water reservoir Pietraszki is one of the components of the Small Retention Program in the Świętokrzyskie voivodeship (Suligowski et al. 2009). It will be located within the administrative boundaries of Kielce, in the lower part of the Sufraganiec river catchment, which is a left tributary of the Bobrza River in the Nida River Basin (Figure 1). This river (5^{th} rank), with a length of 16.13 km and an average slope of 8.3 ‰, drains a forest-agricultural catchment with a downstream increase of urbanized areas contribution (Ciupa et al., 2015).

The area of the whole Sufraganiec catchment covers 61.98 km^2 and its area reaching the designed dam — 61.43 km^2. A double wing dam will be located in the ravine zone between Marmurek Mountain and Machnowica Mountain, in km 0 + 450 m of the river. Its length will be of 1162 m, and the crown level will be situated at 244.8 m a.s.l.

In the analysed section, the bottom of the Sufraganiec valley is lined with sand and river sands, while the terraces are formed by river sands with gravels. Underneath there are sands and silts that fill the fossil valley up to 40 m deep. Within the reach of the proposed water reservoir there are also organic deposits several dozen centimeters thick, where mud and peat-muck soils are distinguished. This section of the Sufraganiec channel is artificially shaped. Above the ravine, in the wide extension of the bottom of the valley (up to 1.2 km), numerous old river beds are found.

The agricultural value of this area is rather insignificant, while the rank of its natural valor — quite high, as evidenced by the fact that a part of it falls under numerous forms of protection (Chęcińsko-Kielecki Landscape Park, Kielce Protected Landscape Area and Special Protection Area Dolina Bobrzy).

The water reservoir will be supplied with the waters of the Sufraganiec river which flows mostly along the north-western edges of Kielce. Its flow regime can be defined as compound, with two maxima per year (spring: March-April and summer: June). During the summer floods high discharges are observed, being a hydrological result of a largely increasing share of impermeable areas in the western districts of Kielce. The average annual specific discharge value from the planned water reservoir's catchment area is 8.8 $dm^3 \cdot s^{-1} \cdot km^{-2}$, runoff coefficient — 39%, and runoff volume — 17.2 million m^3. An average annual streamflow of the Sufraganiec in the dam section reaches 0.544 $m^3 \cdot s^{-1}$, the lowest is 0.057 $m^3 \cdot s^{-1}$, and the highest is 15.53 $m^3 \cdot s^{-1}$ (Ciupa et al. 2015).

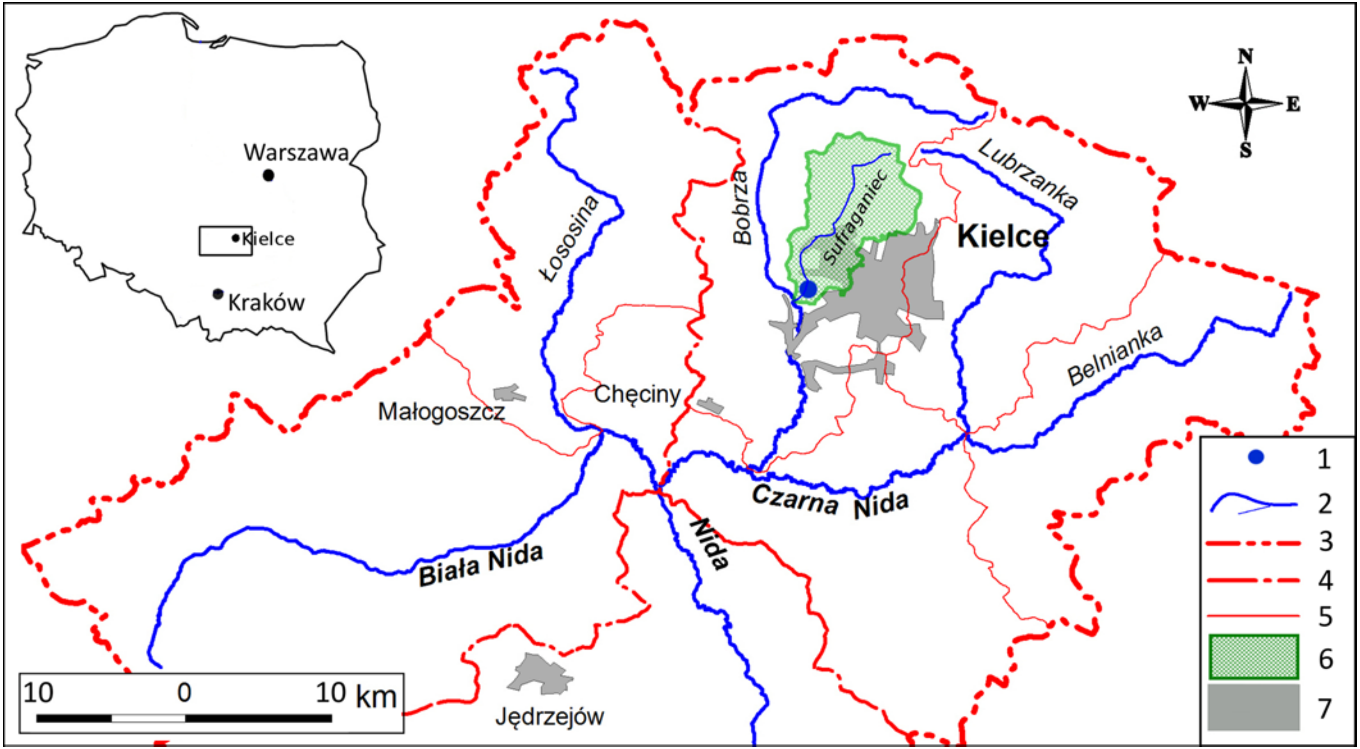

Fig. 1. Location of the designed Pietraszki water reservoir

Legend: 1 – location of the designed reservoir, 2 – rivers, 3 – II order water divide, 4 – III order water divide, 5 – IV and higher order water divides, 6 – Sufraganiec catchment, 7 – urban built-up area

The water quality status of the Sufraganiec in 2014 and 2015 did not indicate significant ecological hazards. Its water physicochemical status was ranked in the first water quality class, hydromorphological — in the 2nd, and biological — in the 3rd (WIOŚ 2015, 2016).

Results. Analysis of the DEM obtained from the ALS data allowed to define precisely the course of reservoir's coastline for two water levels — normal (NWL — 244.0 m) and maximum (MWL — 244.4 m) as well as its surface (Fig. 2). The length of the coastline (without the dam) is 2638 m at NWL and 2996 m at MWL, and the area of the planned reservoir is estimated at 68.92 and 74.37 ha respectively. The designed coastline of the future reservoir is moderately developed. The index of its compactness at the NWL is high (0.88).

The Sufraganiec riverbed is currently running through the area of the designed reservoir, and the ground elevation in its immediate vicinity is higher than in the distance (Fig. 2). This channel is a result of regulatory works, and the track of its original course is confirmed by the old river bed, clearly visible on its left side — up to 300 m. The land relief within the reservoir will be relatively insignificant. The largest depth (about 4 m) will be located near the dam — in the NW part of reservoir's bowl. In this zone, the ground elevation will be less than 241.0 m a.s.l. In the upper part of the reservoir, the ground elevation will exceed 243.0 m a.s.l. The bottom relief in a so-designed reservoir is characterized by the presence of drainage ditches over 1 m deep. As the reservoir is being set up also for recreation, it is important to ensure safety of its users and therefore to perform micro-leveling of reservoir's bottom relief, including the removal of the organic layer, and filling of ditches and hollows. For this purpose, the displacement of earth masses within the reservoir area was forecast, by means of the geo-information techniques discussed above (Fig. 3). The map analysis shows that the differences in altitude will vary from -0.6m (deepening) to +0.6m (overheap), and locally they can reach even higher values.

The volume of the humus layer requiring displacement beyond the reach of the tank will amount at 105 thousand m^3. This material can be used partly to strengthen the frontal dam and sow grass on its outer slope. The calculated balance of earth masses related to the planned micro-leveling works indicates that about 30 thousand m^3 of earth will need to be displaced but only within the reservoir area — without moving beyond its reach. As a result, the bottom of the tank will be leveled and adjusted for recreation (Fig. 4). In the middle part of the

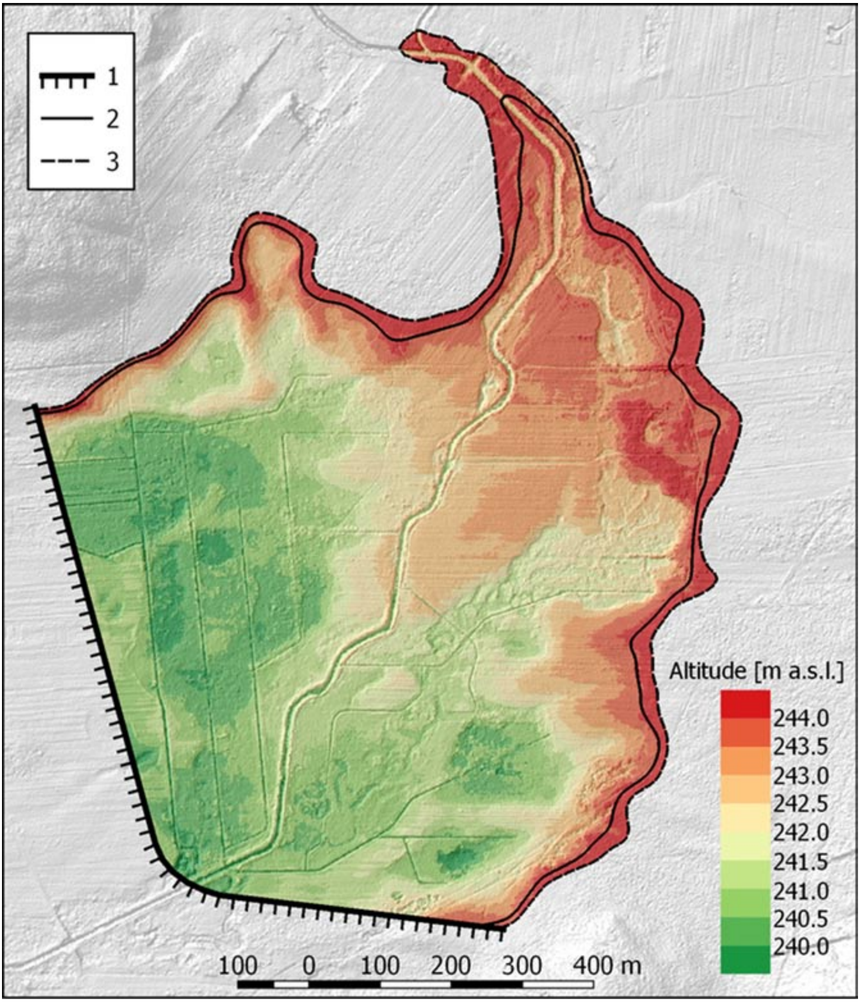

Fig. 2. Digital terrain model of the bottom of the Pietraszki reservoir based on Airborne Laser Scanning data
Legend: 1 – dam; coastline: 2 – at normal water level (NPP), 3 – at maximum water level (MPP)

reservoir the ground slope will range from 0 to 1 degree, in the coastal zone from 2 to 3, and it will only be steeper in the NW part (> 4).

With the use of the ASL data, several segments of different relief and width of the coastal zone (surface and underwater), exposures and resulting insolation were designated along the coastline of the reservoir

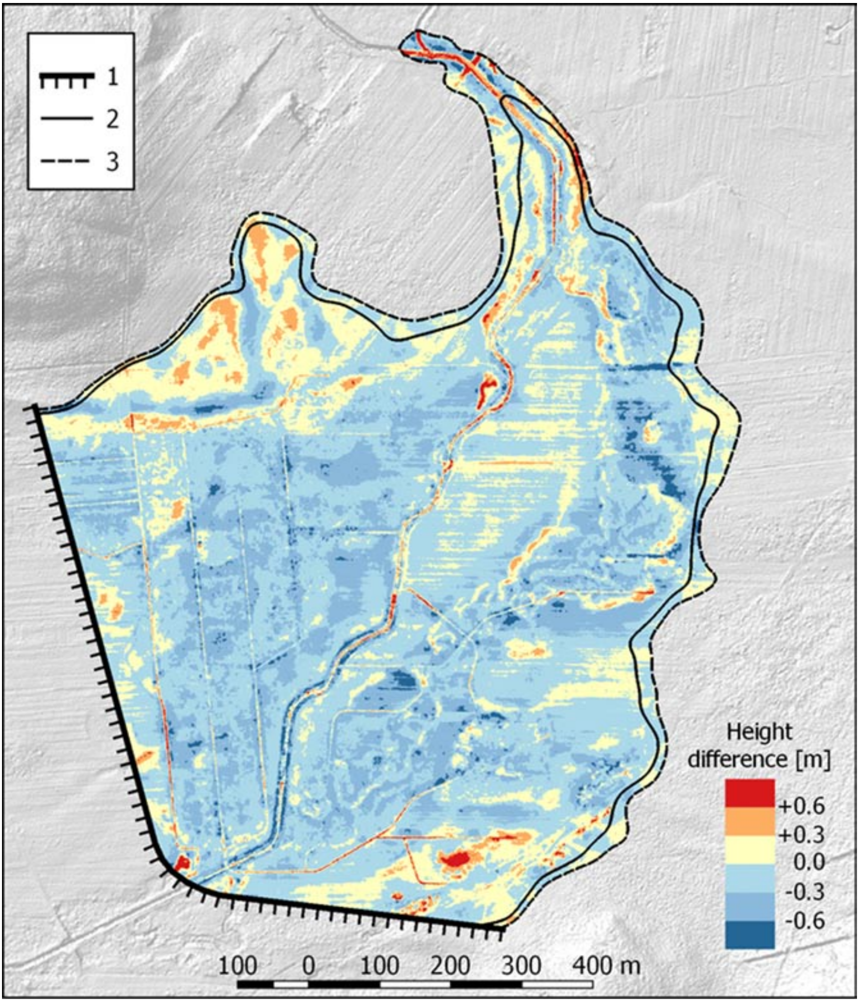

Fig. 3. Relative height changes (m) after removal of humus layer and ground micro-levelling. Legend as in Fig. 2

(Fig. 4). A few bays and small tips will be created, thus highlighting the scenic values of the landscape. From the northwestern outpost of the dam, in the NE direction along a section of about 350 m (A — in fig. 4), the shoreline will cross the lower slope of Machnowica Mountain. At this section, at a distance of 10 m from the shore, the reservoir will reach a depth of 0.6 m and at 20 m — already 1.6 m. These natural predispositions of the coastal zone could allow for location of a harbor

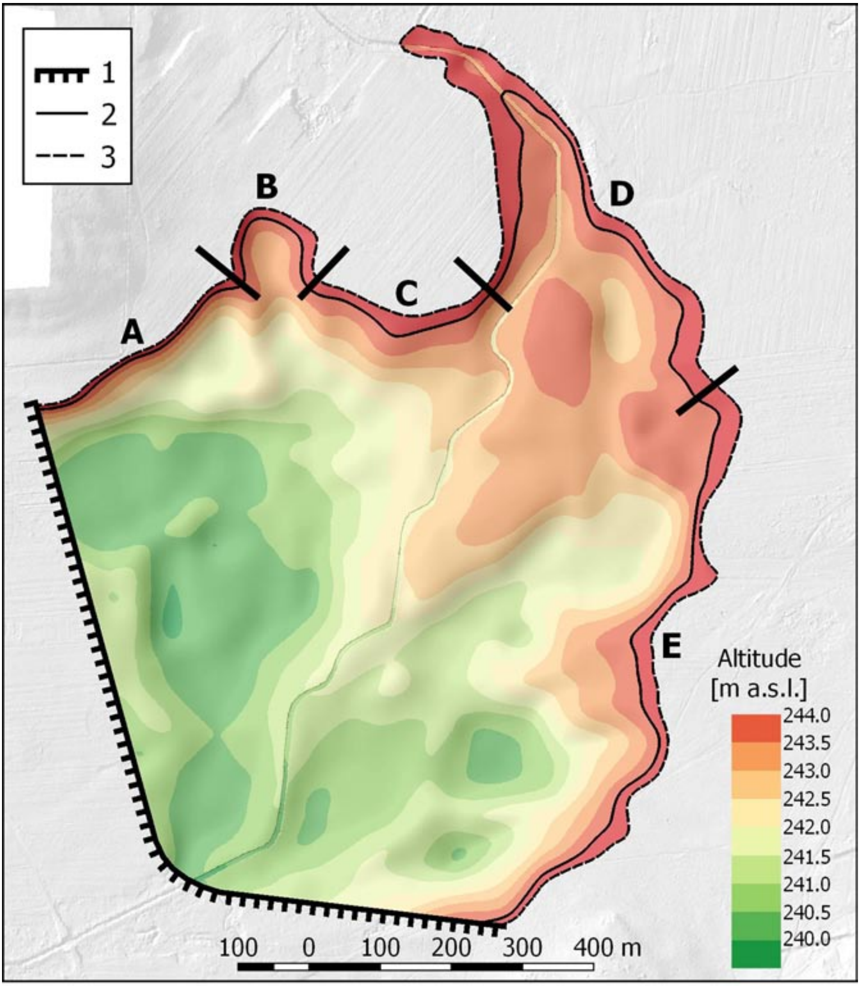

Fig. 4. Relief of the bottom of the Pietraszki reservoir after its micro-levelling
Legend as in Fig. 2

for floating equipment.

Another section (B), about 250 m long, will cover the largest bay within the planned reservoir — approximately 80 m wide. This bay can separate two recreation areas. The next C section of 300 meters with a much more developed coastline, broader surface and underwater areas, with an exposition in SE to SW directions, will be suitable to arrange beach and swimming zones. The fourth section of the coastline (D) of about 750 m, will be located in the water supply zone of the reservoir. It will be of small width and depth, which may favor the accumulation processes and as a result the formation of deltas and shallows. Water plants and fauna species associated with standing water will appear here. This area should be excluded from the recreational use. The last section of the shoreline (E), 950 m long, will run in the eastern part of the reservoir, and will be characterised by varying depths in the underwater zone (Fig. 4). In its large part it will be located along the forest border. This shall stimulate development of transport infrastructure (bicycle paths, walking routes) and accompanying tourism (fishing, rope park, etc.).

There will be significant depth differences within the planned reservoir. The largest depth at the NWL will be at direct vicinity of the dam, regardless of its location, in the southwest of reservoir's area and will reach 4.2 m. In this area, numerous are depths greater than 3.5 m (15% of the area at the NPP and 20% at the MPP) and therefore this part of the reservoir can be used for active forms of water tourism (canoeing, sailing). The upper part of the designed reservoir is characterised by low depths not exceeding 1.0 m. At the stage of technical design, it is possible to plan to build an island here.

The data from the DEM taking into account micro-leveling in the area of the designed reservoir were used to draw bathymetric and storage curves, which allowed to determine the basic parameters of the reservoir (surface area and volume) at two assumed — as well as at any — water levels (Ciupa, Suligowski 2015), enabling proper management of tank waters. The area of the water surface at the MWL is 74.37 ha and at the NWL — 68.92 ha, which allows to store 1 668 300 m^3 and 1 373 700 m^3 of water respectively. The results of this work have become the starting point for carrying out necessary hydrological calculations used in technical project analyses, in particular: the size of the flood reserve and the filling time of the reservoir. The reservoir's flood reserve will reach 294.6 thousand m^3, which means that the tank would be able to store the volume of a large flood wave caused by a heavy, several hour rainfall with precipitation sum of 50 mm. In turn, the filling time of the reservoir will be from 22 to 114 days, depending on the hydrological season.

Conclusions. The paper has proved that the DEM made from high-resolution Airborne Laser Scanning elevation data has been very useful for multidirectional morphological analysis of the bottom of the designed multi-purpose water reservoir Pietraszki, located in the outskirts of Kielce, in terms of:

• precise determination of the shoreline course at two water levels,

• modeling reservoir's bottom and determining the direction and magnitude of potential ground movements during earthworks to level uneven ground surface and thus to ensure safety of recreational users of the tank,

• developing a detailed bathymetric plan and identifying those parts of the reservoir that would be suitable for various forms of water tourism, depending on depths,

• determining 5 recreational zones of different purposes, on the basis of the bathymetric analysis and ground slope along the entire shoreline of the reservoir.

Reviewer — PhD A. V. Oreshchenko

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ВИКОРИСТАННЯ ДАНИХ ПОВІТРЯНОГО ЛАЗЕРНОГО СКАНУВАННЯ ДЛЯ МОДЕЛЮВАННЯ РЕЛЬЄФУ ДНА ПІД ЧАС ПРОЕКТУВАННЯ ВОДОСХОВИЩА — НА ПРИКЛАДІ ДОЛИНИ р. СУФРАГАНЦЯ (КЕЛЕЦ, ПОЛЬЩА)

В статті проілюстровані можливості використання даних лазерної аерофотозйомки (ЛАФЗ) для морфологічного аналізу запроектованого багатофункціонального водосховища Пєтрашка, розміщеного в гирлі річки Суфраганець в Кельцах (Республіка Польща). Фактичним матеріалом слугувала цифрова GRID-модель території з роздільною здатністю сітки 0,5 м, опрацьована фірмою MGGP Aero на основі хмари пунктів зі зйомки, здійсненої у 2011 році. Аналіз здійснено з використанням програми SAGA GIS, в якій виконано моделювання дна долини Суфраганця із визначенням берегової лінії майбутнього водосховища, а також його майбутніх основних геометричних та морфологічних показників.

Практичним результатом представленого в статті опрацювання, аналізу, моделювання є визначення об’єму ґрунту, який слід перемістити із запроектованого водосховища в процесі реалізації проекту, а також виділення прибережних рекреаційних смуг.

Вказано на необхідність застосування цифрової моделі території, створеної на основі даних ЛАФЗ, для детального моделювання берегової лінії, а також рельєфу дна проектованого водосховища при встановлених двох рівнях наповнення.

Ключові слова: LiDAR, цифрова модель рельєфу, водосховище, топографія дна.

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