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Research Article

MODEL FOR THE VOLUME-AREA-DEPTH RELATIONS OF MIDFIELD PONDS USING LIDAR

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ABSTRACT
Small midfield ponds have important functions in the hydrology and ecology of hummocky areas of Poland. Because of their sensitivity to meteorological conditions, their number and hydroperiod are altered as a result of climate changes and agriculture pressure. Accurate estimation of the pond area and storage capacities requires up-to-date high-resolution elevation data. In this paper, we developed 0.2 m and 1.0 m bare-earth DEMs from LiDAR data and compared them with DEMs obtained from old bathymetric maps. Then, we calculated A-h and V-h relations and compared them with the relations derived from simplified models describing the pond shape. The analyses showed that LiDAR data are also useful for detecting changes in the ponds morphometry.

Keywords: midfield pond, LiDAR, DEM

INTRODUCTION

Midfield ponds are numerous depressions observed on areas covered by ice during the last glaciation. Millions of such small depressional wetlands exist on the undulating terrain not only in Poland, but also in the northern part of Europe and North America (Drwal, Lange 1985, Büllow-Olsen 1988, Lutze et al. 2006, Sibbett 1999). In Poland, they are commonly referred to as *śródpolne oczka wodne*, in Northern America as *prairie potholes* or *sloughs* or *kettle holes* (Hayashi et al. 1998, Whittow 1984). Most midfield ponds are located in closed catchments without integrated drainage network. Such wetlands are usually small and shallow, with the depth of about one meter or lesser (Fiedler Zhang et al. 2009). Their size mainly depends on the size of melted dead ice bodies left by glacier (Drwal, Lange 1985), and they are often underlain by glacial till of very low permeability (Fiedler 2011, Winter, Rosenberry 1995). The water balance of such areas is mainly influenced by the meteorological conditions, including precipitation, snow cover distribution, evapotranspiration and water evaporation, runoff and groundwater exchange (van der Kamp, Hayashi 2009, Fiedler 2011). In spring, soon after snowmelt, the ponds reach their maximum annual extent. Conversely, in summer, a significant water loss is open water evaporation (Winter, Rosenberry 1995, Johnson et al. 2010, Fiedler 2011).

For water management in hummocky areas, it is important to model water flow and hydrological processes which changed the amount of water stored in pond over time (Major, Cieśliński 2015). Numerous studies have investigated the hydrological processes which influenced the water budget of midfield and midforest ponds (Millar 1971, LaBaugh et al. 1998, van der Valk A.G. 2005, Fiedler 2011, Korytowski, Szafrański 2014). For proper representation of water storage, the geometry of pond should be derived from a detailed bathymetry map. A practical approach for determining water volume V and area A is to measure the depth of water h and estimate A and V from predetermined area-depth (A-h) and volume-depth (V-h) relations. (Hayashi and van der Kamp

2000). Generalized forms of the above-mentioned relations have been used by some investigators in the mathematical modelling of lakes.

The objective of this paper was to evaluate the possibility of LiDAR (Light Detection And Ranging) data use for description of midfield ponds morphometry.

STUDY AREA

The study area is a portion of Gniezno Lakeland, in a north-eastern part of Wielkopolska Region. The site is located at φ – 52°53'N and λ – 17°28'E, which is approximately 60 km north-east of Poznań (Fig. 1). The study area is about 100 m in elevation and is covered by arable land. This area is within an undulated ground moraine from the last Baltic Sea glaciation. The investigated area is a hummocky landscape formed when melting blocks of dead ice were buried by a glacial drift. The collapse of drift into the aroused voids after ice blocks melted created numerous depressions. These depressions were filled with runoff and groundwater, resulting in midfield ponds that characterize the topography of the area. The project area is mainly covered by crops with very small bush areas.

According to data from Instytut Meteorologii i Gospodarki Wodnej, the average annual temperature is 7 °C and the average monthly temperatures range from -1 °C in January to 19 °C in July. The average annual precipitation is 520 mm and the average monthly precipitation ranges from 27 mm in February to 75 mm in July.

Three ponds marked as 6, 10 and 11 were chosen for a detailed analyses (Fig. 2).

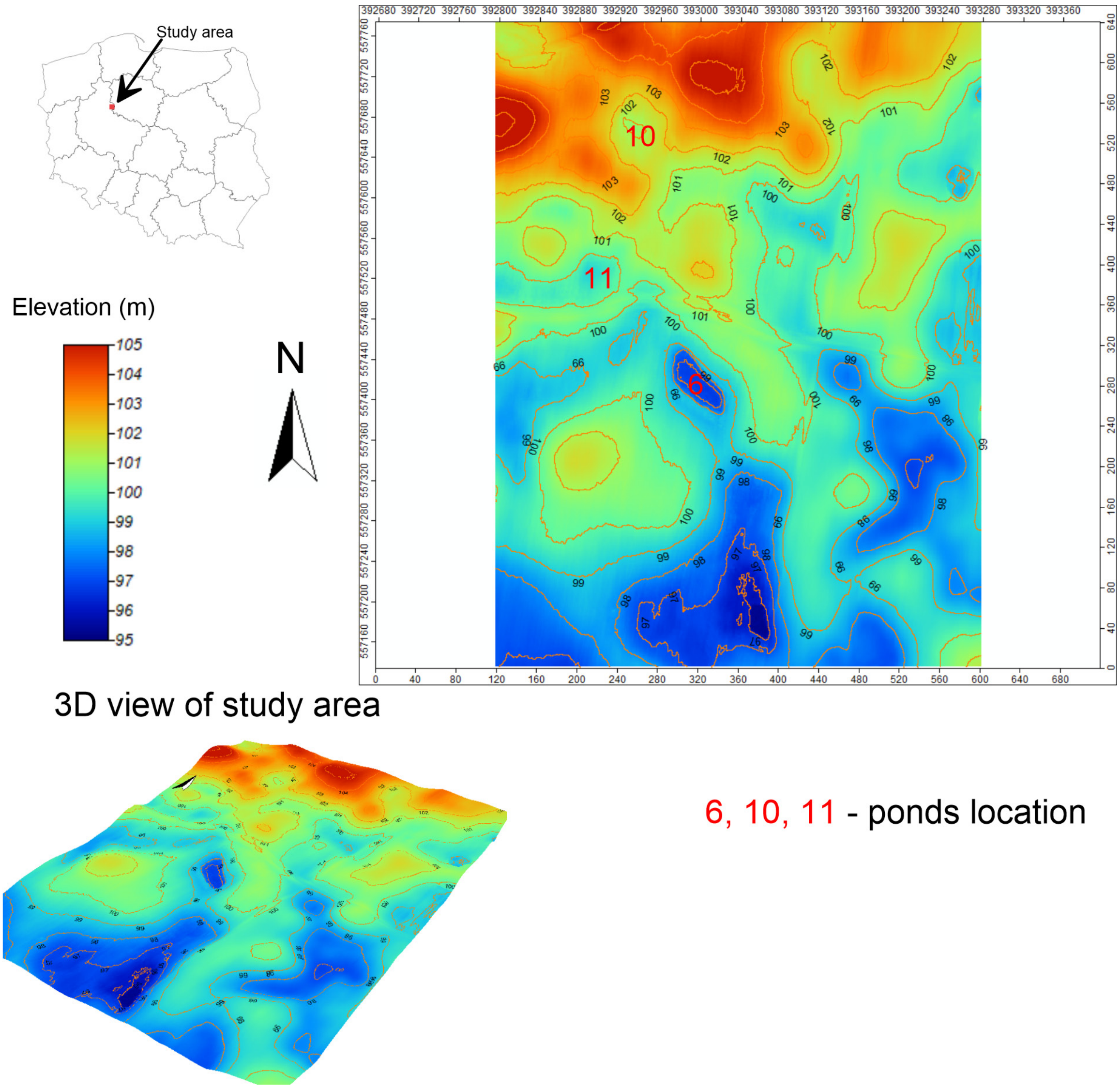

Figure 1. The study area

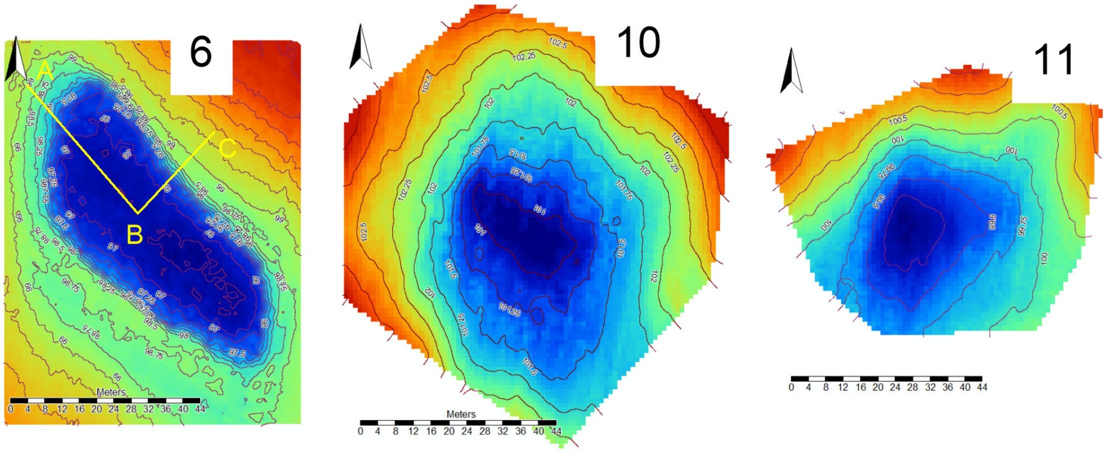

Figure 2. DEMs of midfield ponds 6, 10 and 11 for LiDAR data (A-B-C is section of pond 6).

METHODOLOGY

In this study, LiDAR data from Centralny Ośrodek Dokumentacji Geodezyjnej I Kartograficznej (CODGiK) were used. QGIS and SAGA software were used for spatial data processing (Conrad et al. 2015). Using the LiDAR data we derived bare-earth DEM. Point data were classified into following eight categories: “not classified”, “ground”, “low vegetation”, “middle height vegetation”, “high vegetation”, “buildings”, “noise”, “water” using the standard for LAS format. Point density is 4 pt/m^2 and mean elevation error is up to 0.2 m. Using all points classified as “ground”, a bare-earth DEMs were interpolated at 0.2 m and 1.0 m resolution via Delaunay triangulation.

In addition to the LiDAR dataset, we used bathymetric maps of ponds made in 1985 by Department of Land and Water Reclamation of PULS. The maps were converted to DEMs with 1.0m resolution via Delaunay triangulation. The DEMs were transformed to CS92 (EPSG: 2180) coordinates to fit LiDAR data.

The area-depth (*A-h*) and volume-depth (*V-h*) relations obtained from DEM were compared to the relations presented by Hayashi and van der Kamp (2000), which are based on the shape of simple symmetric basins formed by rotating a slope profile around the central axis:

$$A = s\left(\frac{h}{h_0}\right)^{2/p}$$

$$V = \frac{s}{(1 + 2/p)} \frac{h^{(1+2/p)}}{h_0^{\frac{2}{p}}}$$

where: A – pond area at height h,
V – pond volume at height h,
h_0 – unit depth,
s – scaling constant,
p – coefficient describing pond shape.

Coefficient p is dimensionless constant linking radius r of symmetric basin with depth. The larger p, the steeper are pond banks and bed is flatter (Fig. 3).

RESULTS

DEMs obtained from LiDAR data can have various resolutions. The comparison between the resolutions obtained from 0.2 m and 1.0 m DEM A-h and V-h relations for pond 6 are shown in Figure 4. As seen in Figure 2, the maximum depth of pond 6 is at 2.0 m and further calculations were conducted for this value. For both resolutions, the calculated values of pond area and volume are similar. The maximum volume deviation ΔV reach 1 m^3 and the maximum area deviation reaches 9 m^2. In order to evaluate the goodness of fit between the data points for both resolutions, root mean squared error (RMS) for volume V_{err} and area A_{err} is defined by:

$$V_{err} = \sqrt{\frac{1}{m}\sum_{i=1}^{m}(V_{0.2} - V_{1.0})^2}$$

$$A_{err} = \sqrt{\frac{1}{m}\sum_{i=1}^{m}(A_{0.2} - A_{1.0})^2}$$

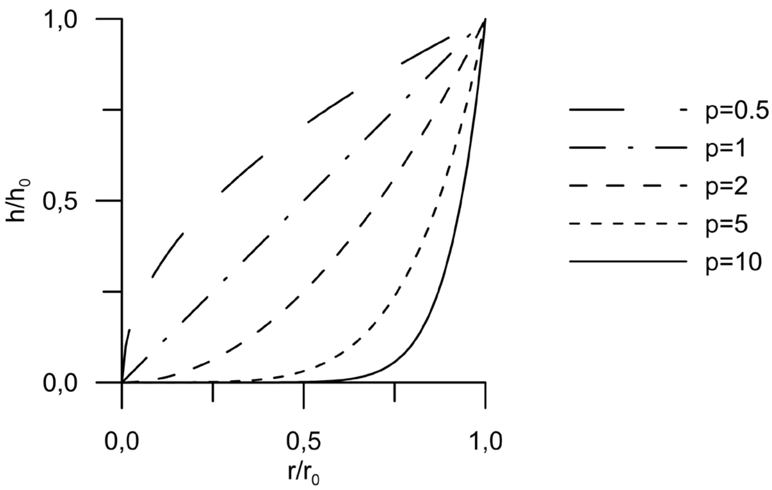

Figure 3. Slope profiles of pond for various *p*.

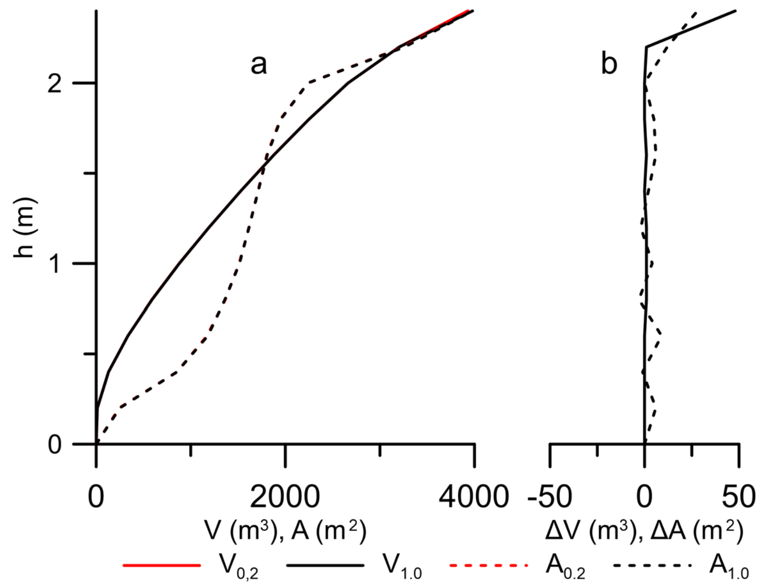

Figure 4. V-h and A-h relations of pond 6 for 0.2 m and 1.0 m DEM resolution and differences between calculated values of V and h

For area A_{err} amounts to 0.49 m^2 and for volume V_{err} equals 3.8 m^3. The errors are small, so 1.0m resolution DEM was chosen for further analyses. The analysis show that 1.0 m DEM, which is easily available from CODGiK, is enough to described pond morphometry.

Then, we compared the relations obtained for 1.0 m DEM from LiDAR to the relations calculated for bathymetric map of pond 6 made in 1985 (Fig. 5). We found that the bathymetric maps give significantly larger values of area and volume. The greatest difference of area $\Delta A = 1054$ m^2 is near the pond bottom and decreases with depth to value of 219 m^2. Conversely, the differences in pond volume grow with depth, reaching $\Delta V = 1166$ m^3 for fulfilled pond, which is about 30% of total pond volume. Bathymetric map shows the pond with very flat bottom and steep banks which also confirms the calculated values of *p* constant.

The calculated values of constant *p*, which described the link between the shape of pond and area-depth relation show the differences in the pond shape obtained from LiDAR and bathymetric data (Fig. 6). For LiDAR, data *p* is 2.9, while for bathymetric data it is much greater and equals 7.8. Bathymetric map of pond 6 gives more cylindrical shape of pond with flat bottom and steep banks than LiDAR data. It is a very important difference when calculating the water budget of ponds. We also have to remember that *p* constant assumed symmetrical shape of pond. Natural depressions have more complex and asymmetric shape (Fig. 6).

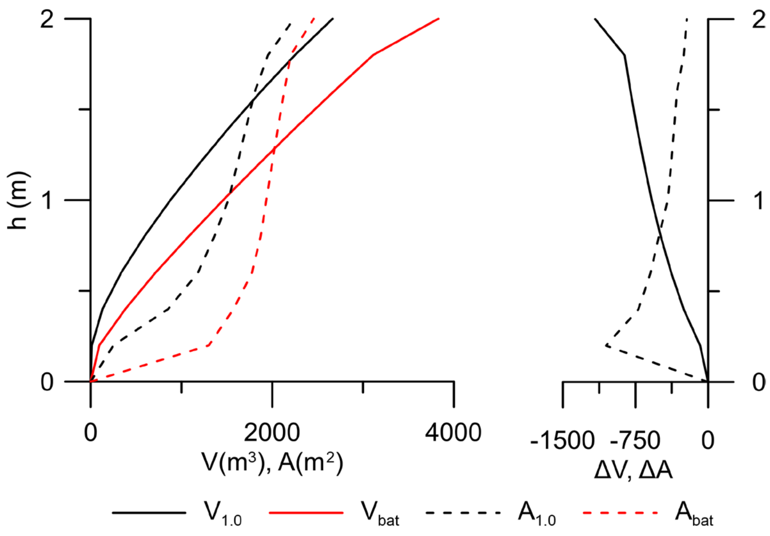

Figure 5. V-h and A-h relations of pond 6 for 1.0 m DEM resolution and bathymetric map and the differences between calculated values of V and h.

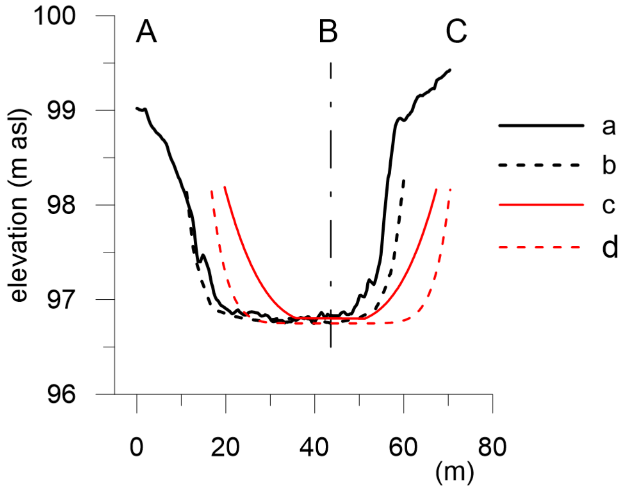

Figure 6. Slope profiles of pond 6 (a-profile from LiDAR data, b-profile from bathymetric data, c-simulated profile for p=2.9, d-simulated profile for p=7.8, A-B-C – profile see Fig. 2)

LiDAR also allows us to estimate temporal changes in morphology. Ponds 10 and 11 have been destroyed by the field owner and now there are only small depressions used as arable area. The bottom of pond 10 is around 0.6 m higher than before, and pond 11 it is even 1.1 m shallower in comparison to bathymetric maps (Fig. 7). The storage volume of these shallow depressions, which now cannot be called ponds, is about 30% of previous values.

CONCLUSIONS

The hydrological processes for hummocky areas are difficult to model. The use of LiDAR data can be a solution to the problem pertaining to the lack of detailed morphology of these areas. The LiDAR approach provides up-to-date and highly accurate elevation data. This allows to derive DEMs that capture detailed pond morphometry enabling us to determine midfield pond area and volume. This information is critical for calculations of water budget for pond. The LiDAR data used for analyses were collected for dry ponds. Topographical LiDAR systems cannot reliably penetrate water, so to estimate the water volume of pond between bottom and existing water surface we had to include empirical model. The formulas suggested by Hayashi and van der Kamp (2000) which describe relations depth-area-volume with use of one constant could be the solution to this problem.

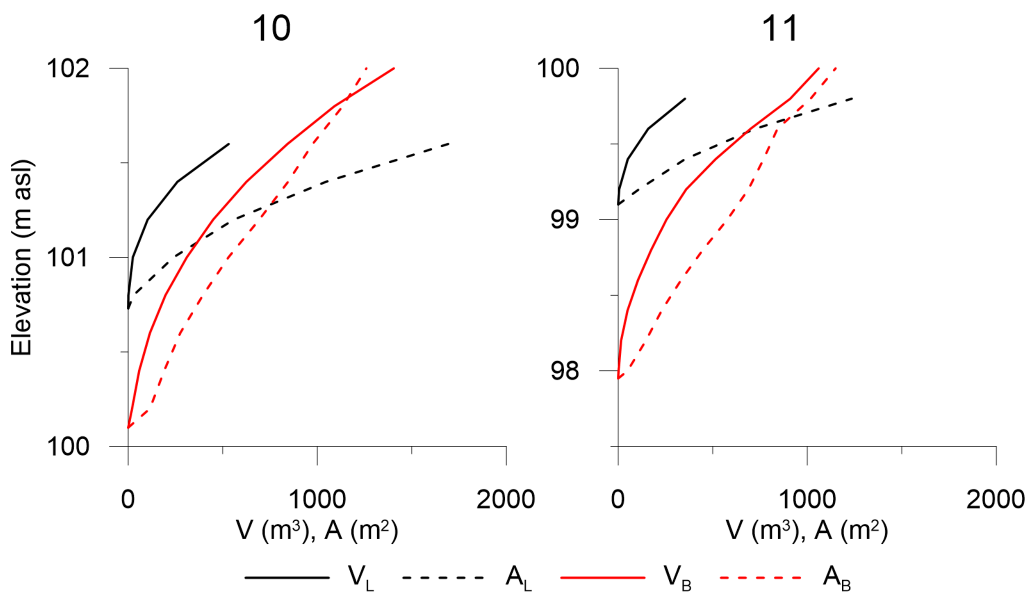

Figure 7. Values of volume (V_L) and area (A_L) of ponds 10 and 11 from LiDAR data vs. values calculated using bathymetric maps

Midfield ponds are generally small and shallow basins influenced by many stressors. The analyses of LiDAR data allow to detect temporal changes of such basins.

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