DOI: 10.1515/jwld-2017-0092
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Section of Land Reclamation and Environmental Engineering in Agriculture, 2017
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JOURNAL OF WATER AND LAND DEVELOPMENT
2017, No. 35 (X–XII): 259–264
PL ISSN 1429–7426

Available (PDF): http://www.itp.edu.pl/wydawnictwo/journal; http://www.degruyter.com/view/j/jwld

Received 16.03.2017
Reviewed 10.10.2017
Accepted 30.10.2017

A – study design
B – data collection
C – statistical analysis
D – data interpretation
E – manuscript preparation
F – literature search

The use of unmanned aerial vehicles (drones) to determine the shoreline of natural watercourses

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For citation: Wilkowski W., Lisowski M., Wyszyński M., Wierzbicki D. 2017. The use of unmanned aerial vehicles (drones) to determine the shoreline of natural watercourses. Journal of Water and Land Development. No. 35 p. 259–264. DOI: 10.1515/jwld-2017-0092.

Abstract

The aim of the paper was to study the possibility of using unmanned aerial vehicles (drones) to determine the shoreline of natural watercourses.

According to the Water Law, the shoreline is defined by: the edge of the shore if it is visible, and in other cases it is the boundary of persistent grass growth, or the line, which is determined on the basis of the average water level of a period of at least 10 years. The study included an analysis of the possibility of determining the shore line in all of these cases, using aerial photos obtained from an unmanned aerial vehicle (drone) on a particular stretch of the river Narew.

In order to determine the shoreline defined by the edge of the shore, a point cloud together with the necessary GIS tools were used to generate planes which then made it possible to determine that edge. Defining the shoreline using this method was done with an accuracy of ±0.21 m.

The study shows that the best results for determining the shoreline were obtained using either the edge of the shore or the line, which is determined according to the average water level of a period of at least 10 years.

Due to the very ambiguous course of the shoreline defined by the boundary of persistent grass growth, it would be advisable to eliminate this remove from the Water Law.

Key words: *image classification, orthophotomap, Shoreline, unmanned aerial vehicle*

INTRODUCTION

In substantive law, natural watercourses form separate cadastral parcels in the national land registry, whereas in terms of subjective law they are the property of the National Treasury in permanent management of organizational units or other legal entities. As with all cadastral parcels, watercourses also need to be registered in the cadastral system within defined boundaries. As with all cadastral parcels, also natural watercourses must be recorded in the system register within defined limits.

In accordance with the Water Law, the boundaries of natural watercourses are defined by the shoreline [Ustawa… 2001]. In this act of law, the shoreline of a watercourse, lake or other reservoir is defined by the edge of the shore if it is visible, and in other cases it is the boundary of persistent grass growth, or the line, which is determined according to the average water level of a period of at least 10 years [FELCENLOBEN 2012; MĄCZYŃSKA, KWARTNIK-PRUC 2016].

The Water Law states, that the shoreline can be determined based on a project proposed by the applicant, dividing the parcels covered by water from adjacent land.

The some natural watercourses in Poland have a defined shoreline on certain sections. This applies to the waters that are regulated as well as sections of watercourses, which are covered by regulation projects or where new natural watercourses are being formed. In this case, the determination of the shoreline is carried out together with the proceedings on the issue of water permits.

Due to the considerable amount of work and costs associated with the preparation of land division projects using current methods, the definition of the shoreline for all watercourses will require many years, even decades.

In publications concerning this subject there are many attempts to determine and monitor the shoreline using satellite imagery [VASSILAKIS *et al.* 2017] as well as unmanned aerial vehicles [FOODY 2002; KURCZYŃSKI *et al.* 2016; RATHINAM *et al.* 2007; WALKER, BLASCHKE 2008].

The problem of data processing also arises [JABARI *et al.* 2017; LALIBERTE, RANGO 2009; MICHAŁOWSKA, GŁOWIENKA-MIKRUT 2010; WALCZYKOWSKI *et al.* 2016].

Therefore, work is underway on testing the possibility of using unmanned aerial vehicles (drones) to determine the shoreline.

METHODS

DATA ACQUISITION AND PROCESSING

The data used in this study had been collected with the help of an unmanned aerial vehicle (drone). The flight was carried out close to the town of Różan, the total imaged area is about 4.8 km^2. The imaged area includes the Narew riverbed. In addition, data provided by Institute of Meteorology and Water Management (Pol. Instytut Meteorologii i Gospodarki Wodnej – IMGW) was also used in the study – the ordinates of the staff gauge zero in the national vertical datum as well as the average water levels at selected water gauges for the past 10 years.

The low altitude imagery data was obtained with the help of the UX5 platform, which can be classified as a mini UAV. This fixed-wing UAV can perform a fully autonomous flight at the desired altitude with a given longitudinal and transverse overlap between subsequent images. The UX5 has the ability to automatically control the start, flight and landing procedures. Images are obtained with the use of an automatic shutter release system within the camera. Flight safety is controlled automatically but there is the possibility of operator intervention by controlling the emergency safety procedures. Take off of the platform is only possible with the use of a mechanical launcher.

The device can acquire imagery from altitudes between 75 and 750 m with a ground resolution of 0.02 to 0.24 m [KĘDZIERSKI *et al.* 2014]. To acquire imagery data two cameras were used: the Sony NEX5R (range RGB) and the Sony NEX5T (NIR range). The photogrammetric flights were conducted in October 2016 with average imaging conditions, both from the altitude of 150 m. The technical details of both conducted flights are shown in Table 1.

Table 1. Technical specifications of the first and second flights

Parameter	Value
Ground sampling distance – GSD	0.05 m
Camera's focal length	f = 15 mm
Image size	4912×3264 pixels
Pixel size	x_r = 4.75 µm, y_r = 4.75 µm
Longitudinal overlap	p = 80%
Transverse overlap	q = 80%
Flight altitude above the terrain	h = 150 m

Source: own elaboration.

10 signaled ground control points and 3 independent checkpoints had been designed and measured on the imaged area. The coordinates of the ground control points were determined using the GNSS RTN kinematic measurement technique. These measurements were made using the mobile LeicaViva receiver. The coordinates of all of the points had been calculated with an average error of ±0.03 m. The adjustment process was conducted in the UASMaster software using bundle adjustment process.

As a result of this adjustment, the first RGB test block (camera SonyNEX5R) has an average error of a single observation equal to 5.0 microns (1.0 pixel). For the independent control points, the mean error for the X, Y and Z were all in the range of 0.03–0.15 m. As a result of the adjustment of the second test block in the NIR (camera SonyNEX5T) the average error of a single observation was 4.2 microns (0.9 pixel), while the mean square error of the independent checkpoints had mean values for the X, Y and Z in the range of 0.03–0.13 m.

In the next stage of data processing, the Digital Terrain Models were generated. These products were generated based on the extracted point cloud. The point cloud is generated on the basis of so called "dense matching" of individual stereograms included in the block. The models were generated using "detailed model" parameters, where the resolution of the mesh is equal to 27 x GSD. The next processing step was the orthorectification and mosaicing of imagery data obtained from the low altitude in the RGB and NIR range. The ground sampling distance of the resulting orthomosaics was equal to 0.05 m.

DETERMINING THE SHORELINE FROM A WELL DEFINED EDGE OF THE SHORE

Based on the acquired and properly processed data, the shoreline was determined using available GIS tools in accordance with the principles set out in the introduction to this paper. The following operations were performed to complete this task: generating contour lines, the classification of the image (using Erdas

Imagine) and indicating the intersection of two planes (ArcGis).

The edge of the shoreline (Fig. 1) is a contour line which can be generated on the basis of the digital terrain model derived from the flight. On the basis of data obtained from the unmanned aerial vehicle, using specialized software ErdasImagine 2013, contour lines were generated using the Ridge/Valley tool.

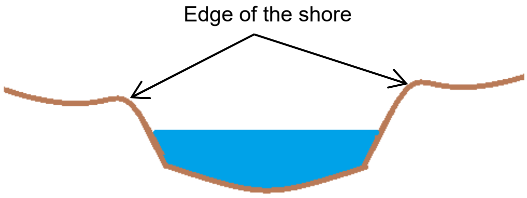

Fig. 1. Clearly visible edge of the shoreline; source: own elaboration

This tool generates contour lines based on a digital terrain model. The accuracy of the resulting image is dependent on the accuracy of the DTM and the chosen method of interpolation. The result of this operation is presented in the form of a raster image, and the detection of the shoreline based on such data requires the operator to select and vectorise one of the contour lines. This step is therefore completed in a semi-automatic manner.

In the case of the acquired images for the area in question, the process of generating the contour lines for the whole 4.8 km^2 area represented in the orthophotos takes about 5–6 minutes. The next stage – vectorisation of the selected contour line is more time-consuming and for the analyzed area required about 1.5 h. The result of vectorisation is a layer with a visible shoreline as described above.

As a result of completed measurement, an accuracy of ±0.21 m was achieved for the determination of the shoreline of the watercourse. The accuracy assessment of the method was based on the measurement of a perpendicular line segment between the points measured using GPS RTN – indicating a well defined edge of the shoreline – and those obtained from the model, using GIS tools (the location of measurement points is shown in Figure 2).

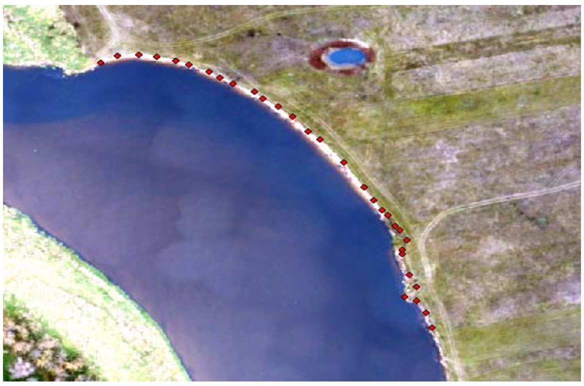

Fig. 2. Visualization of points which had been measured using the GPS RTN technique; source: own elaboration

DETERMINING THE SHORELINE AS THE BOUNDARY OF PERSISTENT GRASS GROWTH

The process of classification makes it possible to define the areas constituting the boundary of persistent grass growth adjacent to the watercourse, as indicated in the Water Law as one of the elements defining the boundary of a watercourse (Fig. 3). In this paper, supervised classification was conducted on imagery data obtained in NIR spectral channels using the Trimble's UX-5 system.

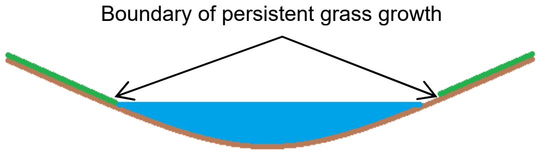

Fig. 3. Shoreline defined as the boundary of persistent grass growth; source: own elaboration

The minimum likelihood method was used to perform the classification, providing accurate results for detecting classes of objects with similar spectral characteristics. The choice of method was dictated by the fact that grassland vegetation typical of mesotrophic meadows with very slight variations was dominant in the analyzed area. In the immediate vicinity of the shore there were groups of shrubs, as well as single trees. On the image, the area of the watercourse was characterized by insignificant variations apart from locally occurring shallows. These were clearly visible on the image due the fact that they remained overgrown with vegetation.

For the purpose of the study, the following classes of objects were distinguished: forest, single trees, meadows and pastures, shrubs, bare ground, water. Training fields for all classes were selected on chosen fragments of the image and defined as: forests, single trees – 12 training fields, meadows and pastures – 18 training fields, shrubs – 10 fields, bare ground – 10 fields and water – 12 training fields. The selection of image fragments representing different classes and the association of image pixels to each object class was done based on field measurements and an orthophotomap.

The result of the automatic image mapping was compared with an orthophotomap and information obtained during field measurements. The Erdas 2013 Accuracy Assessment tool was used for this purpose. Based on information obtained directly in the field, the true coverage of 100 randomly selected points was defined and compared to the results obtained in the classification process [JENEROWICZ, WALCZYKOWSKI 2015].

The line of persistent grass growth obtained by the classification process shows a high convergence with the line of persistent grass growth indicated by the operator. There are, however, local differences due to shrubs and trees growing close to the shoreline, whose crowns cover the grass line. As a result, it was required to verify the generated line by means of field measurements.

The classification result was used to determine the line of persistent grass growth, the position of which was compared to a mean water level from at least 10 years in accordance with the rules of the Water Law. The result of the comparison was that, on some lengths, the boundary line defined using this method runs above the boundary line defined in accordance with the methodology in section "Determining the shoreline from a well defined edge of the shore". As a result, these sections should be removed and their course defined according to the data specified in the abovementioned section.

DETERMINING THE SHORELINE AS THE LINE OF INTERSECT BETWEEN THE WATER AND LAND

In this case ArcGIS software was used to determine the line being the intersect between the digital terrain model and the plane representing the water level generated on the basis of data obtained from IMGW. Data from IMGW consists of the ordinates of the staff gauge zero in the national vertical datum as well as the average water levels at selected water gauges for the past 10 years. The average height of the water surface is the ordinate of the specific plane. The line of intersection of the plane which defies the water level with the digital terrain model makes it possible to identify the shoreline of a watercourse, as shown in Figure 4.

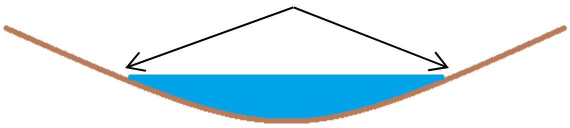

Fig. 4. Determining the shoreline as the line of intersect between the water and land; source: own elaboration

The line of intersection in the presented case was not generated automatically, its creation required the vectorisation of the line by the operator.

RESULTS

RESULTS REGARDING DETERMINING THE EDGE OF THE SHORELINE

The accuracy of determining the shoreline of the watercourse was conducted by comparing the results of determining the edge points of the watercourse shoreline using the method described above, involving the location of the designated GPS RTN points. In determining the accuracy of the points of the shoreline, which amounted to ±0.21 m, the points measured using the GPS RTN technology were adopted a flawless because the average position error of this technique was ±0.03 m.

RESULTS REGARDING DETERMINING THE SHORELINE AS THE BOUNDARY OF PERSISTENT GRASS GROWTH

The classification accuracy assessment for the orthophoto was carried out by comparing selected image fragments, for which their real coverage is known – grass (10 fields) with the results obtained on the basis of the supervised classification. The information about the actual state of grass cover of the 10 test fields was obtained during field inspection whilst performing the flight. The location of test fields was limited due to the nature of the studies to the area directly surrounding the watercourse. The assessment of the classification accuracy of the orthophotomap was done using the kappa coefficient and was equal to 0.7754 with a Overall Classification Accuracy of 70%. Incorrectly classified pixels were located on the water covered with water plants, as well as on trees growing on the banks of the water – their occurrence required verification in the field of the true line of persistent grass growth and incorporation of this information into the generated boundary. The line of persistent grass growth defined through classification was vectorized by the operator, and the course of this line was corrected for errors in the classification process due to the land cover. A fragment of the line of persistent grass growth is shown in Figure 5.

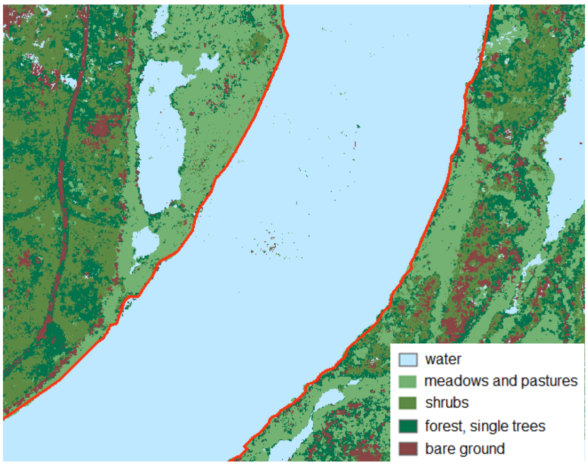

Fig. 5. Line of persistent grass growth (red); source: own elaboration

Analysis of the accuracy of the line determined using the method based on an aerial image was done by comparing the line determined by the method described in section "Determining the shoreline as the boundary of persistent grass growth" with the line of persistent grass growth obtained in the measurement process carried out by classical methods in the field. An offset was measured along a line perpendicular to the line formed by the classification and intersecting the line from the classical measurement at a right angle. The average point offset value was 0.29 m. However, some sections of this line were eliminated due to the conditions under the Water Law Act.

RESULTS REGARDING DETERMINING THE SHORELINE AS THE LINE OF INTERSECT BETWEEN THE WATER AND LAND

By implementing the method described in section "Determining the shoreline as the line of intersect between the water and land", it was possible to determine the shoreline as the intersection between the water level based on average staff gauge readings from a period of 10 years with a digital terrain model. The obtained result was compared to measurements taken in the field.

In practice, the location (x_i, y_i) of the points on the intersection which make up the shoreline generated based on the intersection between the digital terrain model and the plane defined by the actual water level on the day on which control measurements were taken (h). The difference between the average water level from a period of 10 years and the water level measured for control purposes was equal to 0.40 m and was taken into account in all further calculations. In practice, the coordinates of points of the intersection between the water level and the land were measured using the GPS RTN method. A comparison of the differences between these two gave an average accuracy of ±0.37 m.

DISCUSSION OF RESULTS

Certain errors occur when determining the shoreline using the method based on extracting the edge of the shore (as described in point "Determining the shoreline from a well defined edge of the shore") from contour lines generated from a point cloud – structures such as trees and shrubs are interpreted as terrain elements, for which contour lines are also determined. This introduces errors in the form of characteristic distortions generated on the final image. However, this type of distortions are easily detectable by the operator. In addition, when working with point clouds, the problem of image discontinuity can also be a problem.

In the method based on determining the shoreline as the boundary of persistent grass growth by performing a supervised classification, 90% of the achieved results are positive. According to the authors, however, this is the least accurate for determining the shoreline due to many ambiguities and uncertainties regarding the determined line. The line persistent grass growth is very dynamic, and depends in many cases on land use adjacent to the watercourse. Furthermore, if the water adjacent to the shoreline covers aquatic vegetation then the results of supervised classification will be wrong, as described in section "Results regarding determining the shoreline as the boundary of persistent grass growth".

According to the Authors, this criterion for determining the shore line as a line of persistent grass growth, due of its ambiguity, should not be used. Additionally, in agreement with the Water Law, the designated shore line should always be compared to the shoreline determined in accordance with the rules described in section "Results regarding determining the shoreline as the line of intersect between the water and land".

In the case that a shoreline defined by line of persistent grass growth lies above the line of the shore determined according to the average water level of at least 10 years, the shape of the shoreline should be defined in accordance with the rules described in section "Results regarding determining the shoreline as the line of intersect between the water and land".

The method of determining the shore line as the line of intersection between the water table from 10 year period with the adjacent land gives a mathematical definition of the watercourse's shoreline as a result of the intersection of a plane placed at a desired height with the digital terrain model obtained as a result of the conducted experiment. Control measurements of the actual shoreline taken in the field (in this case along the boundary between the water surface and the land) were compared with the boundary specified mathematically and confirmed a relatively high accuracy of shoreline detection using this method.

CONCLUSIONS

1. Data acquired using the unmanned aerial system (drone) made it possible to determine the shoreline of a natural watercourse using all three methods described in the Water Law.

2. Compact image-based digital cameras were used to provide low-altitude imagery data, which, unlike aerial photogrammetric cameras, are more sensitive to weather and lighting conditions, which in this case had been problematic for the development of topographic lines between flat terrain and terrain with trees and shrubs.

3. The best results for the shoreline were obtained when it was extracted based on the shore edge detection or the average water level from a 10 year period.

4. The greatest difficulties were incurred when determining the shoreline using the line of persistent grass growth criterion due to instances where vegetation was also growing beneath the water level, giving erroneous supervised classification results. These errors can only be removed by comparing the all classification results with field data. At the same time, according to the provisions of the Water Law, a comparison should be made of the course of the shoreline according to the criterion referred to in conclusion point "Results". The proposal eliminates those sections that lie above the shoreline that is the average water level from a period of at least 10 years.

5. According to the authors, amendments to the Water Law should be made due to:
- high ambiguity of the shoreline shape defined as the line of persistent grass growth, mainly due to the types of land use of the adjacent terrain;
- a need to eliminate those sections of the shoreline which run above the shoreline defined from the average water level from at least a10 year period.

Dofinansowano ze środków Wojewódzkiego Funduszu Ochrony Środowiska i Gospodarki Wodnej w Lublinie
Cofinanced by Voivodeship Fund for Environmental Protection and Water Management in Lublin

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Wykorzystanie bezzałogowych statków latających (dronów) do ustalania linii brzegowej cieków naturalnych

STRESZCZENIE

Celem pracy było określenie możliwości wykorzystania bezzałogowych statków latających (dronów) do ustalania linii brzegowej cieków naturalnych.

Z ustawy „Prawo wodne" wynika, że granicę linii brzegu stanowią: krawędź brzegu, jeżeli jest wyraźna, a w pozostałych przypadkach granica stałego porastania traw, albo linia, którą ustala się według średniego stanu wody z okresu co najmniej 10 lat. Badaniami objęto możliwości określenia linii brzegu we wszystkich przypadkach, wykorzystując zdjęcia lotnicze wykonane z bezzałogowego statku latającego (drona) na określonym odcinku Narwi.

W celu określenia linii brzegowej wyznaczonej przez krawędź brzegu wykorzystano chmurę punktów oraz narzędzia do wygenerowania płaszczyzn, z których wyznaczono tę krawędź. Uzyskano dokładność wyznaczenia tą metodą linii brzegowej, wynoszącą ±0,21 m.

Z przeprowadzonych badań wynika, że najlepsze rezultaty uzyskano, wyznaczając linię brzegu, gdy linię tę stanowi krawędź brzegu, lub linię średniego stanu wody z okresu co najmniej 10 lat.

Ze względu na bardzo niejednoznaczny przebieg granicy linii brzegu wyznaczonej jako linia stałego porastania traw, celowe byłoby wyeliminowanie tego kryterium z zapisu ustawy „Prawo wodne".

Słowa kluczowe: *bezzałogowy statek latający (dron), klasyfikacja obrazu, linia brzegowa, ortofotomapa*