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# A comparison of interpolation methods on the basis of data obtained from a bathymetric survey of Lake Vrana, Croatia

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## Abstract

The bathymetric survey of Lake Vrana included a wide range of activities that were performed in several different stages, in accordance with the standards set by the International Hydrographic Organization. The survey was conducted using an integrated measuring system which consisted of three main parts: a single-beam sonar Hydrostar 4300, GPS devices Ashtech Promark 500 – base, and a Thales Z-Max – rover. A total of 12 851 points were gathered.

In order to find continuous surfaces necessary for analysing the morphology of the bed of Lake Vrana, it was necessary to approximate values in certain areas that were not directly measured, by using an appropriate interpolation method. The main aims of this research were as follows: to compare the efficiency of 16 different interpolation methods, to discover the most appropriate interpolators for the development of a raster model, to calculate the surface area and volume of Lake Vrana, and to compare the differences in calculations between separate raster models. The best deterministic method of interpolation was ROF multi-quadratic, and the best geostatistical, ordinary cokriging. The mean quadratic error in both methods measured less than 0.3 m.

The quality of the interpolation methods was analysed in 2 phases. The first phase used only points gathered by bathymetric measurement, while the second phase also included points gathered by photogrammetric restitution.

The first bathymetric map of Lake Vrana in Croatia was produced, as well as scenarios of minimum and maximum water levels. The calculation also included the percentage of flooded areas and cadastre plots in the case of a 2 m increase in the water level. The research presented new scientific and methodological data related to the bathymetric features, surface area and volume of Lake Vrana.

## 1 Introduction

The methodology of bathymetric research has undergone many conceptual changes in the last few decades, especially since the mid 20th century and the appearance of the single-beam echo sounder. Rapid advances continued with the development of multi-beam sounders and laser systems (airborne laser sounding systems) which can gather high-density data samples and enable the development of a realistic underwater bottom model (Finkl et al., 2004; Ernsten et al., 2006).

The process of hydrographic measurement includes measurement and researching the configuration of the bottom of an ocean, sea, river, lake or any other water-related object on Earth (NOAA, 1976). The main goal of most such hydrographic research is to gain the exact data necessary to develop nautical charts featuring special details of types of navigational hazards. Other goals include gaining information crucial to the management and protection of coastal areas, exploitation of resources, scientific practices, national spatial data infrastructure, tourism purposes etc. (IHO, 2005). Contemporary bathymetry, as a field within hydrography, is the science of measuring depths and determining the physical properties of the underwater bottom on the basis of analysing data gained from recorded profiles. There are several different methods and techniques of bathymetric measurement, which depend on the complexity of the project (its final purpose, and the size of the area under research). The success of bathymetric measurement depends mostly on a detailed planning process, which in turn enables the organization and tracking of the measurement process from start to finish (IHO, 2005). During this particular research, the measurement plan included a wide range of activities and was performed in several phases according to the standards of the International Hydrographic Organization. The area surveyed included the whole of Lake Vrana, with a total surface area of 29 865 km$^2$ (Šiljeg, 2013). Lake Vrana is the largest, natural, freshwater lake in the Republic of Croatia, specific in its formation and hydrographic properties. This cryptodepression is an ecologically sensitive area, located in the Mediterranean part of Croatia (Zadar County) (Romic et al., 2003).

The lake is an important economic resource for the local community, but also provides a natural habitat for many bird species (Šikić et al., 2013). The waters of Lake Vrana are a specific, complex body, which also affected the bathymetric survey.

The bathymetric survey was performed using an integrated measuring system which included three main parts: an echo sounder Hydrostar 4300, GPS devices Ashtech Promark 500 and a Thales Z-Max. The data measured was transferred into computer form using the Juniper System-Allegro controller and Fast Survey program package. The survey was performed for several reasons: to enable optimal water level maintenance, to classify the lake bottom, to develop bathymetric maps, and to enable better management and protection of natural resources, flora and fauna etc. The primary purpose was the development of a bathymetric map.

Since the terrain formations in the natural environment feature a high level of complexity, most scientists opt for research via the development and analysis of digital terrain models (Dikau et al., 1995; Bishop and Shroder, 2000; Millaresis and Argialas, 2000; Wilson and Gallant, 2000; Tucker et al., 2001; Shary et al., 2002; Chaplot et al., 2006; Wilson, 2011). Today, most of the data gathered is point-related, regardless of rapid developments in technology. This means that the data collected features specific values for a certain variable only for specific $x$ and $y$ coordinates. In order to find continuous surfaces, which are necessary for the process of research and understanding of our environment, some values need to be approximated for spaces which are not measured directly. This is done using various methods of interpolation (Collins and Bolstad, 1996; Hartkamp et al., 1999; Hu et al., 2004; Naoum et al., 2004; Li and Heap, 2008; Erdogan, 2009). The final result in the interpolation method is the model that approximates or simplifies the Earth's surface. Each method produces a different result, so the main challenge is to determine the characteristics of errors and variability of approximated values by comparing and testing different interpolation methods (Šiljeg, 2013).

This research chose the most appropriate methods based on eight statistical parameters: minimum value, maximum value, range, sum value, mean value, variance and

SD. Of these, SD, or mean quadratic error, is especially worth mentioning, since it is the most used method world-wide for determining the precision of digital terrain models (Yang and Hodler, 2000; Aguilar et al., 2005). In addition to analyzing parameters, interpolation methods were compared on the basis of high-fidelity, two-dimensional and three-dimensional graphic representations of data sets. Volume comparison methods were also used, by employing various algorithms, as well as methods for calculating and comparing profiles (Pribičević et al., 2007; Medved et al., 2010).

In order to compare the accuracy of the interpolation methods, the method of cross-validation was used. Most authors suggest using this method in order to achieve a successful evaluation of accuracy (Cressie, 1993; Smith et al., 2003; Webster and Oliver, 2007; Hofierka et al., 2007).

The main aims of this research are as follows: (1) to compare the efficiency of 16 methods of interpolation; (2) to determine the most appropriate interpolators for the development of a raster model of the lake, on the basis of data gained by bathymetry and by using the cross-validation method; (3) to calculate the surface area and volume of the lake and to compare the results between the raster models; (4) to develop the first bathymetric map of Lake Vrana (Fig. 15); (5) to develop a scenario for changes in water level; (6) to calculate the percentage of flooded areas in the Nature Park and the flooded plots in the Pakoštane cadastre, in the case of a 2 m rise in the water level.

## 2 Research methods

### 2.1 Plan for the bathymetric survey

In order to perform a bathymetric survey, it is necessary to have a detailed plan, which enables tracking research development and the organization of the research from start to finish. The plan included a wide range of activities and was structured in a number of phases: (1) determining the exact research area, (2) determining the purpose of the bathymetric survey, (3) application of the survey method (techniques, accuracy, referential horizontal and vertical geodesic system, equipment, etc.), (4) determining the time frame (short or long), (5) gathering various secondary data (aerial photos, data from the cadastre, information on the water level, salinity, temperature, etc.), (6) considering limiting factors (budget, logistics, etc.) and (7) data processing (conversion, filtering, interpolation methods, etc.).

### 2.1.1 Survey area

The waters of Lake Vrana are a specific and complex system, and this affected the selection of methods for the bathymetric survey. The area included Lake Vrana in its entirety, with a surface area of 29 865 km$^2$.

The lake is characterized by (Šiljeg, 2013):

1. A high percentage of shallow water – over 65 % of the lake's surface features a water depth of −1.76 m, while the deepest is −3.73 m (in relation to the water level of +0.42 measured using a Prosika rod).
2. Low vertical dissection – the absolute vertical difference over the entire area of the lake is only 3.46 m. More than 90 % of the lake's bottom features a slope inclination of 2°;
3. Low water transparency, especially during even the slightest winds;
4. Lush vegetation (grass) on the lake's bottom and the surrounding shoreline (*Phragmitetalia*);
5. Significant seasonal oscillations in the lake's water level.
6. Coverage of parts of the lake's bottom by poorly connected sediments.

Based on these characteristics, some complex, more efficient techniques, such as measuring using a multi-beam echo sonar, or laser sonar, would have been inappropriate, considering the morphology of the bottom. The percentage of the recorded bottom would increase greatly in relation to recordings from a single-beam sonar, but the cost of the survey and amount of data acquired would significantly increase as well. After consideration, it was clear that the most efficient solution was bathymetric measurement and the use of a single-beam ultrasound device.

### 2.1.2 Purpose of the survey

The bathymetric survey of Lake Vrana was performed for a number of reasons: in order to enable optimal management of the water level, to classify the lake's bottom, to create a bathymetric map, and to enable better management and protection of the lake's flora, fauna etc. The primary purpose of the research was to enable the development of a bathymetric map. Another important point was to test possibilities regarding the optimal water level. This process implies all the hydro-technical measures and infrastructure that facilitate a deliberate change in water distribution, which in turn enables the more efficient management of natural water resources, protection from water hazards and prevention of water pollution (Kuspilić, 2008). The water regime includes the entire dynamics of constant change, both the quantitative and qualitative aspects of water, and the dynamics between the water and surrounding area (Kuspilić, 2008). Inconsistent management of the water regime has caused some extreme changes in the water level, salinity, temperature, oxygen levels etc. As a result, the lake has been poorly exploited for other purposes: tourism, water resource management, biodiversity, ecological activities etc. This culminated in a series of negative consequences in 2012, when a record number of fish died (URL 1).

An optimal water regime can only be achieved if the amount of water in the lake is known at any moment, and if Prosika channel has a regulatory water infrastructure, as well as an efficient drainage ditch used to regulate the water level, depending on the season.

The data measured and evaluated enable the development of hydrological and hydro-technical studies which would result in an optimal water level, ensure a biological minimum and economical water minimum, and optimize the water system (Ožanić, 2002; Kuspilić, 2008). In order to determine the volume of the lake, it was necessary to map the lake's bottom, gather data required for the development of the digital terrain model, and make a topographic map of the lake's bottom and shoreline relative to its optimal water level, thus creating a sound basis for future activities.

### 2.1.3 Equipment used

An inflatable Hondawave boat was used for the bathymetric survey (Fig. 1). The vehicle is 3.85 m long, and belongs to Lake Vrana Nature Park. The boat was the optimal vehicle due to its small dimensions and economical engine, and because it was easy to install the surveying equipment on it.

The bathymetric measurement was performed using an integrated measuring system (Fig. 4), which included three main components: a Hydrostar 4300 sonar, GPS devices Ashtech Promark 500 and a Thales Z-Max. These were connected via the RTK controller Juniper System-Allegro, which enabled real-time connection and data registration in the FastSurvey programme. This enabled recording of the sonar coordinates and corresponding depth. The programme automatically recalculated the coordinates from the GPS into the local projection coordinates. The selected projection was the universal transversal Mercator, Gauss–Krüger shape with a central meridian of 15, a factor of scale change of 0.9999 and a false easting of 5 500 000. The Bessel 1841 ellipsoid was used.

Two GPS devices were also used: a base or referential device, which was positioned according to precisely determined coordinates, and a rover device, which was used in the work area (Figs. 2 and 3). A data-exchanging connection was established between them via a UHF radio transmitter, which would also have been possible via various GSM devices. The distance between the base and referential devices had to be determined in advance, in order to achieve an adequate degree of precision. This was named the base line and its maximum value was 50 km. The distance between the base GPS and the UHF transmitter had to be a minimum of 10 m.

Since the UHF signal was rather weak throughout the lake, three base points were determined using the Ashtech Promark 500 and CROPOS system: (1) coordinates $\lambda = 5\,541\,365.709$, $\varphi = 4\,865\,017.188$ m – 2.02 m a.s.l. in the northeast section of the Nature Park (Crkvine), (2) coordinates $\lambda = 5\,543\,197.353$, $\varphi = 4\,861\,981.8633$ m – 36.69 m a.s.l. in the western parts of the Nature Park (Martina Draga, Draga), (3) coordinates $\lambda = 5\,548\,694.214$, $\varphi = 4\,860\,958.663$ m – 62 m a.s.l. in the eastern part of the Nature Park (Kamenjak – Torovi – Mernjača). They were connected by a benchmark and measuring rod at the Prosika location. A base GPS device was set at those points, depending on the phase of the survey, and connected to a UHF transmitter (with all components) in order to achieve a connection (signal) with the mobile GPS installed on the inflatable boat.

For measurement purposes, a wooden support was made and installed on the inflatable boat (Fig. 1). A dual-frequency probe was fixed to this support with a rover GPS device submerged 20 cm below the water level (Fig. 2). This arrangement was necessary due to the shallow water of the lake and low water level at the northwest end. Since the Hydrostar 4300 sonar supports depth recording simultaneously at two frequencies, the survey was conducted at two frequencies: low – 30 kHz and high – 200 kHz.

The bathymetric survey was performed according to the previously established profiles, which were planned in the AutoCAD program, on a geo-referential cartographic surface (Croatian base map and digital orthophoto to the scale 1 : 5000). The basic measuring profiles were planned perpendicular to the slope of the terrain, in a northeast-southwest direction. The planned lines of the survey, (basic bathymetric profiles) ensured good coverage and high resolution in the research area. The survey also included several transversal profiles which intersected with the main profiles, enabling the comparison and control of the measured depths.

Within the borders of the shoreline of Lake Vrana, 375 basic lines (profiles) were planned. The distance between adjacent profiles was set at 200 m, which corresponds to the desired mapping resolution to the scale 1 : 30 000.

### 2.1.4 Time frame

The time frame, and the first day of the survey were determined by the water level and obligations of the team. The water level is important since is it impossible to register a depth of more than 0.5 m by transducer. Weather conditions are important for navigation and the quality of data registration (Fig. 4). Wind, rain, waves and cold, for example, are usually limiting factors. Weather reports and water level oscillations were continuously observed from the production of preliminary plans in November 2010 until the beginning of the survey.

The measurement process was conducted in two phases (Fig. 6): (1) from 10–12 May 2012, and (2) from 7–9 June 2012.

The first phase took two days, and included a survey of 14 351 km$^2$ of the northern part of Lake Vrana. The total length of the measured profiles was 71.3 km, and the total amount of points gathered was 5643 (2248 gathered on the first day, and 3395 during the second). Weather conditions were ideal for navigation and surveying. The water level measured at the Prosika station was 0.42 cm. The limiting factors for the survey in this part of the lake were the dense grassy vegetation on the bottom, the shallow water and the lush surface-level vegetation which hindered navigation. Measurement was cancelled in these parts, based on previously established profiles, while the shallow water was measured using a plumb-line. As a result, this survey cannot be classified as systematic. It is nevertheless very important in relation to the part of the lake that was measured, since the terrain there is flat or minimally inclined. An acceptable level of interpolation is possible in areas featuring an irregular layout of profiles.

The second phase featured negligible limiting factors, so the survey was conducted according to plan. The water level at the Prosika station was 0.37. A total area of 15 514 km$^2$ was surveyed in the southern part of the lake. The total length of the measured profiles was 82.5 km, and the total amount of points gathered was 7208 (3582 during the first day, and 3626 during the second).

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### 2.1.5 Processing the bathymetric data

The data obtained from measurement was transferred to a PC via the Juniper System-Allegro controller and the Fast Survey programme package for further processing and interpolation. During measurement, the controller creates a separate file with information regarding the point coordinates, time obtained, and depth recorded. Data processing included filtering out noise, calibrating the checked depths to a common referential level, and, interpolation. The filtering process was implemented according to a programme which enabled the removal of errors in the data registry (Fabulić, 2012). Records of water depth were calibrated in relation to the Prosika benchmark and measuring rod ($R = 2.0949 - 0$ measuring rod $= -0.057$).

Since parts of Lake Vrana are quite difficult to survey, measurements taken by ultrasound showed some background noise. In simple terms, the ultrasound beam bounces off the first obstacle it encounters, so the echo sounder calculates the distance to that obstacle and represents it as a depth measurement. However, such obstacles are not always on the bed of the lake, and indeed, random noise may be generated by floating matter, plankton, fish, or vegetation (Pribičević et al., 2007). These sounds need to be filtered and reduced in order to obtain correct, usable data. An additional caution is necessary when filtering such data. Low frequencies (30 kHz) cannot penetrate the dense, complex, "sedimentary" vegetation which forms the new bottom. As a result, low frequency measurement did not yield adequate results, since it could not properly determine the density of the silt or vegetation, or the boundary between the rocky and muddy bottom. Therefore it was used only during the first day of the survey. Another deficiency recorded using the low frequency was significant leaps in profiles, especially in places where the frequency penetrated the vegetation and muddy deposits. This also indicated significant differences in the levels of muddy deposits. In order to perform a more detailed analysis, a sediment profiler should be used, featuring a frequency of up to 15 kHz, which could be used to gain detailed information regarding the lake's bottom (Lafferty et al., 2005; Pribičević et al., 2007). Since the lake is shallow, and water transparency during the survey was good, it was relatively easy to determine the features of the lake's bottom and differentiate vegetated from non-vegetated areas.

## 3 Research results

### 3.1 Interpolation of data gathered from the bathymetric survey

In order to generate continuous areas necessary for research and knowledge of the bottom of Lake Vrana, it was necessary to approximate values in areas that were not sampled directly. This was done using various interpolation methods.

The main aims of this part are as follows:

1. To compare the effectiveness of sixteen interpolation methods
2. To determine the most appropriate interpolators for the purpose of developing a raster model of the lake, on the basis of bathymetric data, by using the cross-validation method
3. To calculate the surface area and volume of the lake, and to compare differences in the calculation between raster models.

The effectiveness (quality) of interpolation methods was analyzed in two phases. In the first phase, 12 851 points were used to develop a model of the lake and compare interpolation methods. The second phase covered 30 233 points. Using the ArcGIS extension within the Geostatistical Analyst programme, interpolation parameters were automatically optimized for each interpolation methods (Table 1).

Four parameters influenced the quality of the output deterministic methods results: distance exponent, number of neighbours, distance, and number of sectors. The number of neighbours which influenced an approximated point was set at 15. The criteria for distance used a circular search zone with a defined distance radius. All methods, except local polynomial methods, featured a radius of 3619.9 m (Table 1).

Geostatistical methods are more demanding to process, since they require semi-variogram modeling and the appertaining defining parameters.

The first phase showed that all the used methods of interpolation showed satisfying results, and were adequate for developing digital terrain models of the lake, since they had similar parameter values (Table 2). The main reason for this is the slight difference in depth values, low vertical dissection of the lake's bottom and minimal percentage of elements with sudden leaps in height. The range of value for SD, considering the automatically optimized parameters, was between 0.197 and 0.249. According to all parameters, the best method was ordinary cokriging (0.197). The reasons for that were: the principle of the method's process ($\mu =$ known stationary mean value, taken as a constant for the entire research area and calculated from the median data value) and the maximum range between the depth values (only −3.46). The mean value for the entire area was −1.763.

Since most authors point out that the quality of stochastic methods depend on the choice of criteria regarding semi-variograms, a comparison was made between the criteria automatically determined by software and those manually determined for the ordinary cokriging method. The two most common theoretical models were tested: spherical and Gauss (Table 3). The purpose of manually assigning criteria is to find out the minimum deviation and minimum value for SD. In the case of the spherical model, the minimum value of SD was the distance of 1800 m (0.221). Unlike the automated software process, finding the minimum value of SD manually is more difficult and time-consuming (it requires inputting the parameters of interpolation repeatedly until the minimum value is found).

Table 3 shows that the output results regarding the SD do not reveal significant differences. For example, the difference between automatic and manually found SD in the case of the spherical model for 12 851 points is 0.011. However, it is notable that the maximum error in the approximation for the same model is 0.208 m greater (2.238).

According to Malvić (2008), a decrease in distance also decreases the deviation, since the values of closer points are more similar than the values of more distant ones.

The decrease in deviation should decrease the SD calculated from the differences in the measured and the approximated values. However, the quality of approximation in other parts of the model might be questioned. By testing using ordinary kriging, the conclusion was that the decrease in distance affected the SD positively, and negatively affected it in areas that were not included in the direct measurement. The values obtained in such areas greatly surpassed the values of the surrounding measured points. For example, a semi-variogram for Lake Vrana was made, which was used to compare 30 233 points. The determined distance was 1200 m, and the SD for 12 851 points was 0.298. For the distance of 12 000 m, the SD was 0.471. In the case of the first distance (1200 m) the lowest value of depth for the entire model was −5.21 m (the lowest measured depth was −3.73 m). As much as 0.246 $\text{km}^2$ of the model's surface fell within the category of −3.73 to −3.21 m (Fig. 7). This result implies a serious error that would create an increase in the volume of the lake. The second distance (12 000 m) did not feature any values above −3.578. This example shows that SD can be an unreliable parameter when taking the values of the entire model into account.

Points gathered by the bathymetric survey did not include the entire surface of the lake, since the echo sounder could not gather data in areas above −0.5 m. Since that resulted in a lack of data at the edges of the lake, the modeling toolset poorly extrapolated the surfaces (Fig. 7).

Visually compared, the methods generally show the greatest differences in the smoothness of isobaths, which is logical since the differences between the chosen parameters are essentially negligible. A more detailed analysis indicates the results of certain methods (appearance of continuous surfaces at micro levels).

In order to develop a digital model of the lake that would enable various simulations, such as changes in the water level, it is necessary to consider the data that refers to the surrounding terrain (height data, gathered by aero-photogrammetry). The combination of precisely obtained data on heights and depths enables the interpolation for the areas that were not directly included in the survey. The output results turned out well, since the lake features mostly low, flattened shores.

Due to curious output results in the first phase, the comparison of methods of interpolation was repeated for 30 233 points within the Lake Vrana Nature Park (Table 4). Of those points, 12 851 were depths (bathymetrically measured points), and 17 832 were elevations (points with $x$, $y$ and $z$ values gathered by aero-photogrammetry). Statistic indicators were calculated only for the bathymetrically gathered points. The output results were quite different. The use of elevation points, which are necessary to develop a good digital terrain model of the lake and its surroundings, showed numerous deficiencies in most of the interpolation methods, clearly visible in Table 4 and Fig. 8.

Ordinary cokriging turned out to be the best method of interpolation according to all relevant parameters (Table 4). Figure 8 clearly shows the characteristic of the simple kriging method, when the range of elevation is 307.23 m, in which case the mean value for the entire area is 38.02 m. Along with the ordinary cokriging method, satisfactory results were obtained from the inverse distance weighting method, RBF – multi-quadratic and ordinary kriging. The SD according to all three methods was less than 0.5 m.

The differences between the four methods of interpolation are obvious in the two-dimensional (Fig. 12) and three-dimensional graphic representations. Figures 9 and 10 show the more vertically dissected part of the lake, with an AB profile, and a length of 1500 m, which was used as a further testing sample for the four best interpolation methods. The profile line was drawn so as to cover 6 bathymetrically measured points.

After drawing the profile line, it was necessary to calculate the intersection for the defined profiles based on the regular network generated by the interpolation, i.e. to convert the two-dimensional profiles into 3-D lines which feature $x$, $y$ and $z$ values.

This approach enabled comparison of the profiles, a clear representation of the interpolated lake's bottom and the detection of deviation between the bathymetrically measured points and those approximated by the model. Figure 11 shows a difference in the interpolation method of deterministic (inverse distance weighting, ROF – multi-quadratic) and geostatistical methods (ordinary kriging, ordinary cokriging).

The final result of comparing methods of interpolation using ArcGIS expansion Geostatistical Analyst is to obtain a regular spatial network or grid. Usually, the greatest

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problem is deciding between greater spatial resolution or pixel size (Hengel, 2006). In this case, the software optimized the pixel size at 40 m. The spatial resolution corresponds to McCullagh's (1988) method of determining pixel size. The size was calculated using a grid calculator and the method of point sample analysis (Hengel, 2006). On the basis of 12 851 points and an area of 29.865 km$^2$, a spatial resolution of 24.2 m was generated. This method (McCullagh, 1988) was not chosen due to a disproportionate ratio between the distance of the profiles and the points measured in them. Due to the high density of the sampling within a profile (10 m), but also due to variability in the elevation of the neighboring points, a problem known as the "Prussian helmet" occurs (Šiljeg, 2013). The grid was later used as input data for the purpose of developing a three-dimensional representation. In addition, it can be used to develop various maps to show contours, lake terrain, grid models, slope, etc.

### 3.2 Surface area and volume of the lake

The final phase of bathymetric research involved calculating the lake's surface area and volume. Volume can be defined as the amount of water which occupies a certain space between the surface and the bottom of the lake, measured in cubic units. Today, the process of calculating such numbers has sped up significantly due to technological improvements (Diolaiuti et al., 2005; Ahmed, 2010). Many programmes are available that can display and compare the results of measurement and calculation. The output results of a certain analysis depend on the method of data gathering, dissection of the lake bottom of the lake density and distribution of points, spatial resolution (pixel size), algorithms and the interpolation method used.

The volume of a lake can be efficiently calculated by a regular grid obtained by using a certain interpolation method. The calculation process was relatively simple, since the number of pixels was known (18 714), as well as the surface ($40 \times 40 = 1600\,\text{m}^2$) and the height ($z$) within the coordinate system. A pixel in this case represents a three-dimensional object (cube or a quadratic prism) based on which the volume can be calculated.

In order to compare it with other algorithms, the volume was calculated for the regular spatial grid, obtained by the ordinary cokriging interpolation method. The volume amounted to 49 783 536 $m^3$. This method yielded good results, since the difference between the result and the arithmetic mean for three rules (trapezoidal, Simpson's and Simpson's 3/8) was 293 143 $m^3$ (Table 5). The output results of volume calculation depend primarily on the spatial resolution; the lower the resolution, the more precise the calculation, because the leaps in values between pixels become less.

In order to calculate the volume, three more complex Newton–Cotes formulae were used, integrated within the Surfer program: (1) the extended trapezoidal rule, (2) the extended Simpson's 1/3 rule and (3) the extended Simpson's 3/8 rule (Press et al., 1988). Newton–Cotes formulae are very useful and provide a direct technique for approximately calculating an integral by numerical methods and algorithms (their use results in various degrees of errors in the final calculation) (Medved et al., 2010). They are used to calculate the surface area and volume of various shapes. Simpson's rule approximates an integral by the Lagrange polynomial which passes through three points, while the trapezoidal rule approximates by the Lagrange polynomial passing through two points (Palata, 2003).

Table 5 shows calculated values for the volume derived from Newton–Cotes formulae, applied to five different methods of interpolation. Since every method displays a certain level of error in the approximation of the volume, arithmetical means for the three methods were also calculated.

The border of the lake for all the models was an isobath at 0.4 m, obtained by interpolating bathymetrically measured depth data and terrain elevation data obtained by aero-photogrammetry. The isobath was converted into a polygon, which was used to determine a raster model within the borders of the polygon. Table 5 also shows that the surface, perimeter and volume of the lake, regardless of the formula used, greatly depend on the model developed by interpolation.

The surface area of Lake Vrana, according to official records, is 30.2 $km^2$ (JUPPV, 2010). However, none of the written sources mention the process used to calculate the surface area, the water level included, what year, month, or methods and techniques used. It is known that the surface area of the lake changes constantly and that it is conditioned by the water level and shape of the surrounding terrain. In the period from 1948 to 2007, the lowest water level was 12 cm (0.003 mnm), measured in 1990 and 2008. The highest was 241 cm (2.24 mnm), measured in 1974 and 1994. The mean value was 0.81 mnm (JUPPVJ, 2010). The water level is influenced by major factors such as inflow, drainage and evaporation, but also by complex hydrological and hydraulic effects such as water balance, salt and fresh water content, sea tides and other factors influencing changes in sea level (JUPPVJ, 2010). The annual oscillation of the water level measured at the Prosika station is 193 cm.

The surface area of Lake Vrana, in relation to its water level (which annually oscillates by 1.93 m) varies by almost 4 km$^2$. Therefore, it is not the same if the surface is measured when the water level is 2.41, or 0.12 m (Table 6).

The surface area can be obtained by manual vectorisation based on a geo-referential digital orthophoto (29 412 km$^2$). The process is relatively simple, and the contour of the lake is represented by the border between the water and land, defined by subjective visual approximation. However, 4.6 % of the lake's surface area is covered in dense vegetation (*Phragmitetalia*), which makes determining the surface area a more complex task. Considering the limitations of the aforementioned method, the research employed previously stated methods for determining the lake's surface area.

The total surface area of the lake is 30.815 km$^2$, calculated based on the 0.81 m isobath (mean water level in the observed period from 1947 to 2007) obtained by interpolating data on an elevation of the surrounding terrain and depth of the lake. The interpolation method provided good results, because most of the lake's shore is flattened. featuring mild slopes and almost no anomalies in data values obtained by bathymetric survey and aero-photogrammetry. The method was also tested by field work, using a precise GPS. The device was used to record information on the most distant borders of the lake at six randomly chosen locations. Since the interpolated border of the lake was transferred into GPS, it was easy to determine the deviation.

The average width of the lake is 2201.4 m (minimum 262.26 and maximum 3469.31 m). The average length of the longitudinal profiles is 8765.43 m (minimum 1843.55. and maximum 13 245.34 m). These values were obtained by analyzing 68 transverse (northeast-southwest) and 17 longitudinal (southeast-northwest) profiles at 200 m intervals (at the water level of 0.4 m).

Since the surface area and water level of Lake Vrana change throughout the year, this research visualized the annual water level oscillation (a scenario was made in the northern part, outside the Nature Park, in case the Jasen water pump stopped working) (Fig. 13). A section of the flooded habitats and cadastre plots within the Nature Park were also determined (Table 7), at the water level of 2 m (Fig. 14).

The water level map at 2 m was overlaid with the map of habitats for Lake Vrana Nature Park to the scale of 1 : 5000. The map was made in accordance with the rules of National Croatian Habitat Classification and comprises 30 classes of habitats (Jelaska, 2010). A habitat is defined in the Statute of Nature Protection (OG 70/05, 139/08 and 57/11) as a unique functional unit of an ecological system, determined by its geographical, biotic and abiotic features (URL 2). A sudden change in the water level can change the ecological features of a particular habitat, affecting the flora and fauna of Lake Vrana Nature Park. The analysis concluded that almost half the habitats are endangered if the water level rises to 2 m. The highest level of threat (100 %) relates to Illyrian-Sub-Mediterranean river valley meadows. and the lowest level (1 %) relates to brambles. It is worth noting that 52.7 % of the endangered areas are consolidated arable lands with monoculture crops (cereals), while 18.3 % (37.8 ha) are complex mosaics of crops.

Lake Vrana Nature Park is divided between 4 cadastre municipalities: Pakoštane, Radašinovci, Murter-Betina and Banjevci. Most of the arable areas are inside the Pakoštane cadastre. The total number of cadastre plots that are within the Nature Park and belong to the municipality of Pakoštane is 1530. Most are used for intensive agricultural purposes. The northern part of the Park features horticultural plants with multiannual crop rotations. Plants include mostly hybrid species. Various agro-technical methods are used in order to produce a better level of crop success, as well as fertilizers and chemical components for plant protection (JUPPVJ, 2010). In the northwestern lake area, there is a mixed culture of olive fields, vineyards. horticulture and some cereal crops (JUPPVJ, 2010). Should the water level rise by 2 m, it would partially or completely threaten 45.94 % (703) of the cadastre plots. In the northern part of the Park (a flatter area), flooding would threaten the entire area, a total of 136 cadastre plots. In the northwestern part, flooding would mostly threaten areas at a lower elevation. These areas have been more susceptible to flooding in the past, as is evident from the specific shape of the field parcels (especially in the northwestern part). The parcels there are narrow (10 m on average) and extremely elongated (150 m). The inclination of these parcels (2–5°) is perpendicular to the lake. Similar parcels are also characteristic of fields found in the delta of the River Neretva (Glamuzina, 1986; Faričić et al., 2005).

## 4 Discussion and conclusion

The results of this research show that the output results of the digital terrain modelling and corresponding analyses depend on the data gathering methods, density of samples, interpolation methods, terrain features (mostly vertical dissection), pixel size and algorithms applied. The main aim of this research was to find out the most appropriate interpolation methods and spatial resolution necessary to calculate the surface area and volume of the bottom of the lake, and to analyze it adequately. In the research, 16 methods of interpolation were compared; 8 deterministic and 8 geostatistical. Of the five most common methods for gathering elevation data and comparing interpolation methods, two sets of data were used (depth and elevation). They were obtained by various methods, techniques and procedures: bathymetry and aero-photogrammetry. The conclusion is that there is no universal method of interpolation which shows the best results in both sets of data, since the output results depend on the data gathering method. For example, an optimal method for developing a DTM of the lake's shore was developed, but it turned out to be inadequate for developing a DTM of the lake's bottom. In addition, regardless of the fact that certain authors point out either deterministic or geostatistical methods as more advantageous, it is important to note that there is no single best interpolation method, since they are all conditioned by spatial and temporal components. This means that the result of the comparison and selection of the best method are in fact provisional and dependent on time and space components, the technology used to gather and process data, and the area of research.

The fact that geostatistical methods of interpolation employ mathematical functions and the probability theory was one of the reasons for hypothesizing that geostatistical methods would be better interpolators. This was proven, but the research also showed that the differences between geostatistical and deterministic methods were negligible. The multi-quadratic function, as the globally most commonly accepted method, was proven to be the best radial basic function, but also one of the best deterministic interpolation methods in general.

In order to develop a digital model from the bathymetrically gathered data, 16 interpolation methods were compared in two phases. In the first phase (which used 12 851 bathymetrically measured points), all the methods compared showed good results, due to the low vertical dissection of the terrain. By using the method of cross-validation and analyzing statistical parameters, the conclusion was that the best results were yielded by the simple cokriging method (the SD was 0.197). The range of the SD for all 16 methods was between 0.197 and 0.249. Due to characteristic issues with output results and the problem of extrapolating data in the first phase, the process of comparing interpolation methods was repeated for the sample of 30 233 points within Lake Vrana Nature Park. The output results in the second phase were notably different, and the majority of methods applied showed imperfections. According to all the statistical parameters, the best method of interpolation was ordinary cokriging. Along with ordinary cokriging, good results were shown by the inverse distance weighting method, ROF – multi-quadratic method and ordinary kriging. The SD for all three methods was less than 0.5 m. These methods were compared by graphic representation, calculation and comparison of the profiles, surface area and volume of the lake. The conclusion was that there were no significant differences between the statistical indicators in deterministic or geostatistical methods, whether the parameters were determined automatically or manually. However, by testing the ordinary kriging method, the conclusion was that the reduction in the distance positively affected SD, but negatively affected approximation in the areas that were not included in the direct survey. The interpolated values in those areas turned out to be much greater than the values actually measured at the surrounding points.

Based on the optimal method of interpolation, the lake's surface area, perimeter and volume were calculated at the water level of 0.4 m. The surface area of the lake is 29 865 $\mathrm{km}^2$, the perimeter is 35 851 km and the volume is 50 076 679 $\mathrm{m}^3$. During the bathymetric survey, the conclusion was that a low frequency (30 kHz) could not penetrate the very thick, intertwined "sediment" vegetation which formed the new bottom of the lake. Another problem with low frequency is occasionally significant leaps in profiles, especially in places where the frequency managed to penetrate the vegetation or mud. In order to perform a detailed analysis, a sediment profiler with a frequency of up to 15 kHz should be used to gain detailed information about the layers on the lake's bottom (Lafferty et al.,2005; Pribičević et al., 2007).

All the analyses and conclusions derived can be used for further research on data gathering methods, interpolation methods, methods of spatial resolution selection and methods of digital terrain analysis. In any future research of Lake Vrana, it would be useful to extend the profiles during the survey, if a single beam sounder is used, so that the distance between the profiles is no greater than 50 m. In that case the relation between the profiles and the data gathered from the profiles (every 10 m) would be much more proportional. In addition, it would be useful to compare the results of the development of the lake's bottom model using single beam, multi-beam and laser sounder techniques. It is important to note that the more efficient techniques, such as multi-beam ultrasound or laser measurement, might not yield significantly better results due to the morphology of the bottom and the relatively high percentage of dense, native vegetation. The portion of the bottom surveyed would increase in relation to the portion surveyed with the single beam sounder, but the costs of such research would drastically increase, as well as the amount of data yielded for the processing. In that case, processing stations would have to be employed as well. This research used a desktop computer with an i7 processor and 6 GB RAM to process 12 851 points measured during the survey, but performance was slower. A frequency of under 15 kHz is recommended for future research, in order to determine the density and volume of sediments. Since 4.6 % of the lake's surface is covered in dense vegetation, it was difficult to determine the exact borders. The dense vegetation prevents sounders from effectively reaching the surface. In order to avoid extrapolation in the bordering areas, the research employed elevation data obtained by aero-photogrammetry and stereo-restitution, where the average distance between the elevation points was 90 m. If future interpolation projects aim at higher level of precision in the bordering areas, it will be necessary to reduce the distance between the elevation points. Recommended methods include aerolaser or aero-photogrammetry. In this case, the distance between the points should be less during stereo-restitution (maximum 10 m).

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**Table 1.** Parameters of interpolation methods.

| IM* | Power | Model | Range | Sill | Nugget | Lag | Distance | NL* | NS* |
|---|---|---|---|---|---|---|---|---|---|
| IDW | 2 | | | | | | 3619.90 | | 1 |
| LP | 1 | | | | | | 228.20 | | 1 |
| CRS | 12.3 | | | | | | 3619.90 | | 1 |
| SWT | 17.7 | | | | | | 3619.9 | | 1 |
| MQ | 0 | | | | | | 3619.90 | | 1 |
| IMQ | 0 | | | | | | 3619.90 | | 1 |
| OK | | Spherical | 8496.40 | 0.591 | 0.227 | 886.11 | 10 633.32 | 12 | 4 |
| SK | | Spherical | 2453.10 | 0.496 | 0.088 | 394.96 | 4739.52 | 12 | 4 |
| UK | | Spherical | 10 058.80 | 0.000 | 0.031 | 886.11 | 10 633.32 | 12 | 4 |
| DK | | Spherical | 2395.60 | 0.767 | 0.223 | 388.72 | 4664.64 | 12 | 4 |
| OCK | | Spherical | 6461.03 | 0.560 | 0.191 | 886.11 | 10 633.32 | 12 | 4 |
| SCK | | Spherical | 2451.89 | 0.496 | 0.087 | 394.88 | 4738.56 | 12 | 4 |
| UCK | | Spherical | 8496.35 | 0.000 | 0.030 | 886.11 | 10 633.32 | 12 | 4 |
| DCK | | Spherical | 2394.07 | 0.768 | 0.221 | 388.57 | 4662.84 | 12 | 4 |

[*] IM – interpolation method, NL – number of lags, NS – number of sectors.

**Table 2.** Cross-validation of method results.

| IM | Number of points measured | Minimum value (m) | Maximum value (m) | Range (m) | Value sum (m) | Mean value (m) | Variance (m$^2$) | SD (m) |
|---|---|---|---|---|---|---|---|---|
| IDW | 12 851 | −1.748 | 2.265 | 4.013 | −67.424 | −0.005 | 0.062 | 0.249 |
| LP | 12 851 | −1.702 | 2.100 | 3.802 | 79.836 | 0.006 | 0.049 | 0.222 |
| CRS | 12 851 | −1.702 | 2.239 | 3.941 | −48.410 | −0.004 | 0.052 | 0.229 |
| SWT | 12 851 | −1.707 | 2.234 | 3.941 | −49.528 | −0.004 | 0.052 | 0.228 |
| MQ | 12 851 | −1.736 | 2.273 | 4.009 | −23.102 | −0.002 | 0.065 | 0.255 |
| IMQ | 12 851 | −1.743 | 2.159 | 3.902 | −68.307 | −0.005 | 0.055 | 0.234 |
| OK | 12 851 | −1.737 | 2.030 | 3.767 | 19.950 | 0.002 | 0.054 | 0.232 |
| SK | 12 851 | −1.701 | 2.177 | 3.877 | −8.482 | −0.001 | 0.050 | 0.223 |
| UK | 12 851 | −1.827 | 1.948 | 3.775 | 51.824 | 0.004 | 0.057 | 0.239 |
| DK | 12 851 | −1.664 | 2.143 | 3.807 | −3.060 | 0.000 | 0.051 | 0.225 |
| OCK | 12 851 | −1.660 | 2.060 | 3.720 | 11.443 | 0.000 | 0.051 | 0.226 |
| SCK | 12 851 | −1.526 | 2.007 | 3.533 | −6.873 | −0.000 | 0.038 | 0.197 |
| UCK | 12 851 | −1.827 | 1.949 | 3.776 | 51.825 | 0.004 | 0.057 | 0.239 |
| DCK | 12 851 | −1.535 | 2.022 | 3.557 | −6.678 | −0.000 | 0.041 | 0.203 |

**Table 3.** Comparison of manually and automatically determined parameters of the interpolation method.

| Model | Range | Sill | Nugget | Lags | Distance | NL* | NS* | SD | MPE* |
|---|---|---|---|---|---|---|---|---|---|
| Spherical (CAD*) | 8496.4 | 0.591 | 0.227 | 886.11 | 10 633.32 | 12 | 4 | 0.232 | 2.030 |
| Spherical (MD*) | 1777.9 | 0.418 | 0.027 | 150.00 | 1800.00 | 12 | 4 | 0.221 | 2.238 |
| Spherical (CAD*) | 6337.5 | 0.477 | 0.302 | 886.11 | 10 633.32 | 12 | 4 | 0.238 | 1.948 |
| Gauss (MD*) | 133.8 | 0.042 | 0.048 | 20.00 | 240.00 | 12 | 4 | 0.220 | 2.235 |

NL – number of lags, NS – number of sectors, SD – standard deviation, MPE – maximum prediction error, CAD – criteria automatically determined, MD – manually determined.

**Table 4.** Cross-validation method results.

| IM | Number of points measured | Minimum value (m) | Maximum value (m) | Range (m) | Value sum (m) | Mean value (m) | Variance ($m^2$) | SD (m) |
|---|---|---|---|---|---|---|---|---|
| IDW | 30 233 | −1.748 | 4.372 | 6.120 | 1169.497 | 0.091 | 0.199 | 0.446 |
| LP | 30 233 | −2.142 | 4.809 | 6.951 | 1793.793 | 0.140 | 0.234 | 0.484 |
| CRS | 30 233 | −117.351 | 46.197 | 163.548 | 487.438 | 0.038 | 1.825 | 1.351 |
| SWT | 30 233 | −4.134 | 2.881 | 7.016 | 60.581 | 0.005 | 0.107 | 0.327 |
| MQ | 30 233 | −1.925 | 2.618 | 4.544 | 360.547 | 0.028 | 0.087 | 0.294 |
| IMQ | 30 233 | −87.722 | 40.884 | 128.607 | 464.898 | 0.036 | 1.298 | 1.139 |
| OK | 30 233 | −1.700 | 5.551 | 7.250 | 1738.313 | 0.135 | 0.228 | 0.478 |
| SK | 30 233 | −1.740 | 2.363 | 4.103 | 186.282 | 0.014 | 0.085 | 0.291 |
| UK | 30 233 | −1.662 | 10.137 | 11.799 | 2329.834 | 0.181 | 0.343 | 0.586 |
| DK | 30 233 | −5.977 | 4.267 | 10.245 | 1828.414 | 0.142 | 0.562 | 0.750 |
| OCK | 30 233 | −1.314 | 2.280 | 3.594 | 543.563 | 0.042 | 0.057 | 0.239 |
| SCK | 30 233 | −1.656 | 2.338 | 3.995 | 211.185 | 0.016 | 0.066 | 0.258 |
| UCK | 30 233 | −1.665 | 10.136 | 11.802 | 2331.259 | 0.181 | 0.343 | 0.586 |
| DCK | 30 233 | −8.972 | 4.976 | 13.949 | 1944.773 | 0.151 | 0.570 | 0.755 |

**Table 5.** Volume, surface and perimeter of Lake Vrana at 0.4 m water level.

| Water level (0.4 m) | Interpolation method | | | | | |
|---|---|---|---|---|---|---|
| | IDW | MQ | OK | OCK | NaN | TIN |
| Trapezoid rule ($m^3$) | 49 512 560 | 50 839 235 | 48 904 436 | 50 077 481 | 50 007 961 | 50 108 329 |
| Simpson's rule ($m^3$) | 49 523 461 | 50 822 602 | 48 902 952 | 50 070 506 | 50 008 506 | 50 107 823 |
| Simpson's 3/8 rule ($m^3$) | 49 516 428 | 50 821 012 | 48 906 375 | 50 082 051 | 50 011 883 | 50 105 204 |
| Arithmetic mean ($m^3$) | 49 517 483 | 50 827 616 | 48 904 587 | 50 076 679 | 50 009 450 | 50 107 119 |
| Surface ($km^2$) | 29.521 | 30.009 | 29.493 | 29.865 | 29.897 | 29.857 |
| Perimeter (km) | 36.619 | 36.703 | 34.290 | 35.851 | 35.918 | 36.118 |

**Table 6.** Perimeter and surface area of Lake Vrana at various water levels, for the most suitable (OCK) interpolation method.

| Water level (mnm) | | Perimeter (km) | Surface area (km$^2$) |
|---|---|---|---|
| Maximum[*] | 2.24 | 38.541 | 33.064 |
| Mean | 0.81 | 38.338 | 30.815 |
| Minimum | 0.03 | 34.974 | 29.177 |

[*] Within Lake Vrana Nature Park.

**Table 7.** Percentage of flooded habitats at the water level of 2 m.

| NKS_DESCRIPTION | Flooded area (ha) | Total area of the habitat in the NP (ha) | Percentage (%) |
|---|---|---|---|
| Complex mosaic of crops | 37.8 | 206.3 | 18.3 |
| Illyrian-Sub-Mediterranean river valley meadows /Mediterranean halophytic *Juncus* species | 32.6 | 34.9 | 93.4 |
| Mixed evergreen forests and holm oak maquis | 15.6 | 696.3 | 2.2 |
| Brambles | 6.6 | 685.9 | 1.0 |
| Shore uncovered or rarely covered by vegetation | 4.4 | 6.3 | 70.9 |
| Illyrian-Sub-Mediterranean river valley meadows | 2.6 | 2.6 | 100.0 |
| Tree lines at the edges of cultivated areas | 2.1 | 7.2 | 29.5 |
| Brambles/Thermophile flooded underbrush | 1.2 | 3.5 | 34.9 |
| Thermophile flooded underbrush | 0.6 | 1.2 | 50.0 |
| Aleppo pine plantations | 0.6 | 65.6 | 0.9 |
| Tyrrhenian-Adriatic limestone | 0.6 | 1.0 | 60.3 |
| Consolidated arable land with monoculture crops (cereals) | 0.6 | 1.1 | 52.7 |
| Man-made or industrial habitats | 0.5 | 11.2 | 4.6 |

**Figure 1.** Hondawave inflatable boat with wooden support.

**Figure 2.** Rover GPS and dual-frequency probe.

**Figure 3.** Base GPS and UHF antenna.

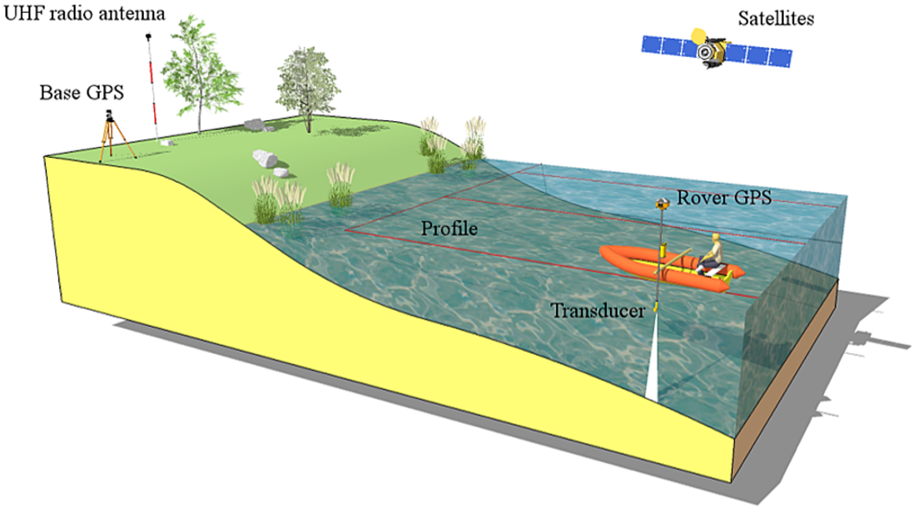

**Figure 4.** Integrated measuring system – combination of GPS-RTK and a sonar.

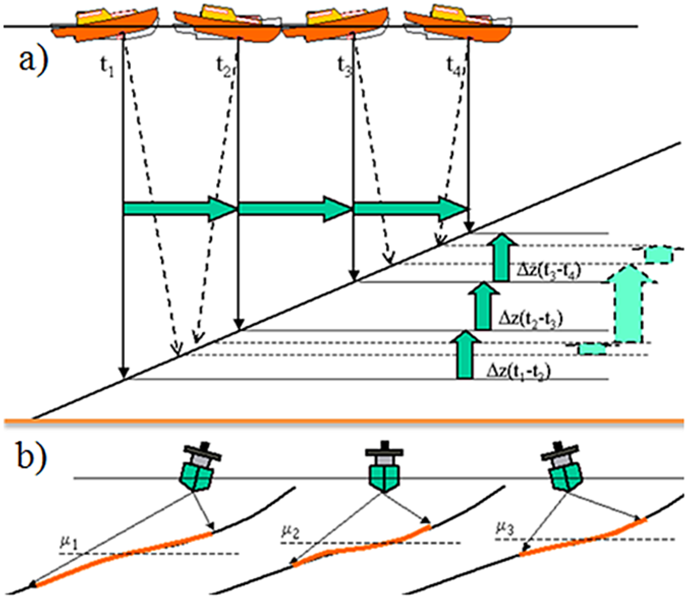

**Figure 5.** The effect of frontal **(a)** and dorsal **(b)** waves on data registration (Clarke, 2003).

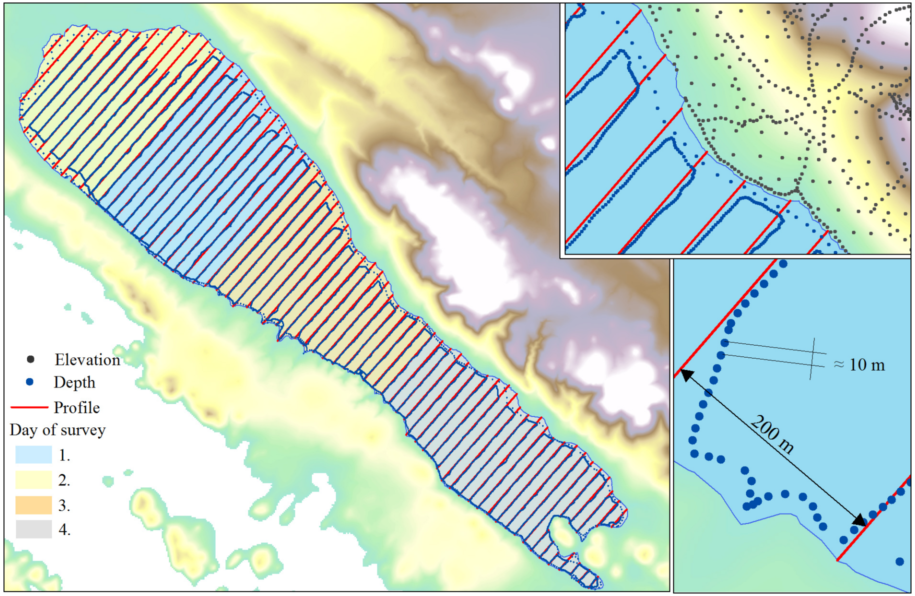

**Figure 6.** The phases and plan of the bathymetric survey.

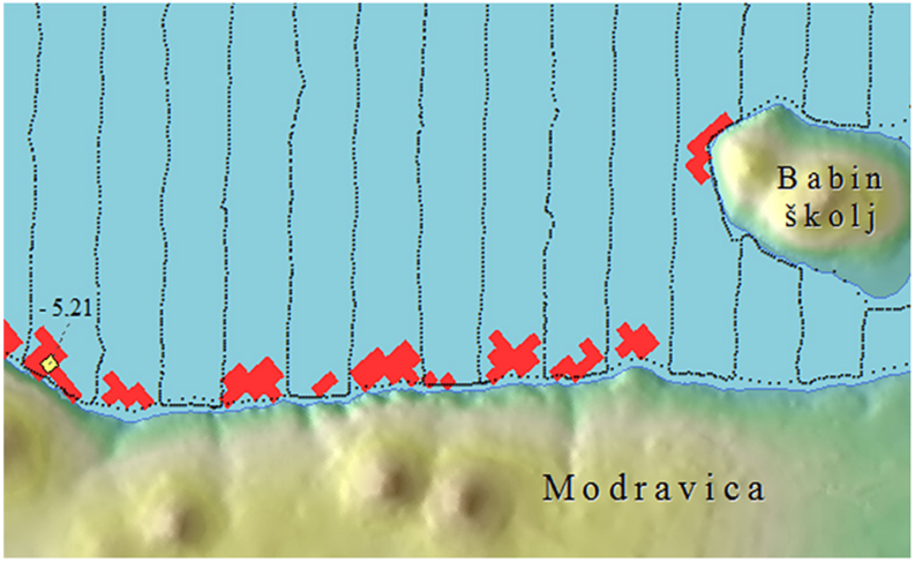

**Figure 7.** Areas that were not directly measured during the survey.

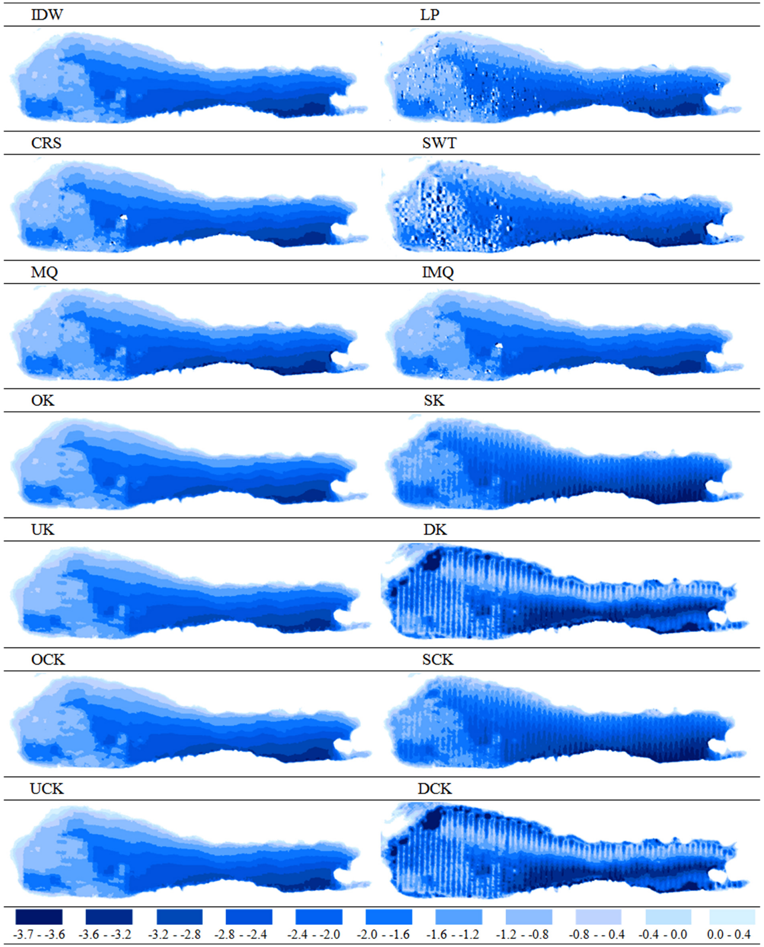

**Figure 8.** Bathymetric maps (30 233 points).

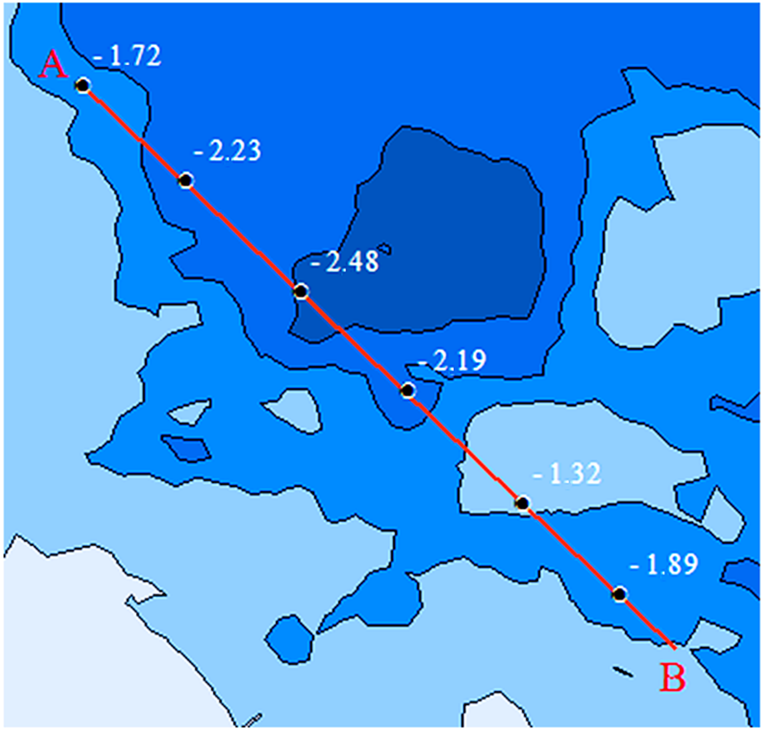

**Figure 9.** Profile display, contour map.

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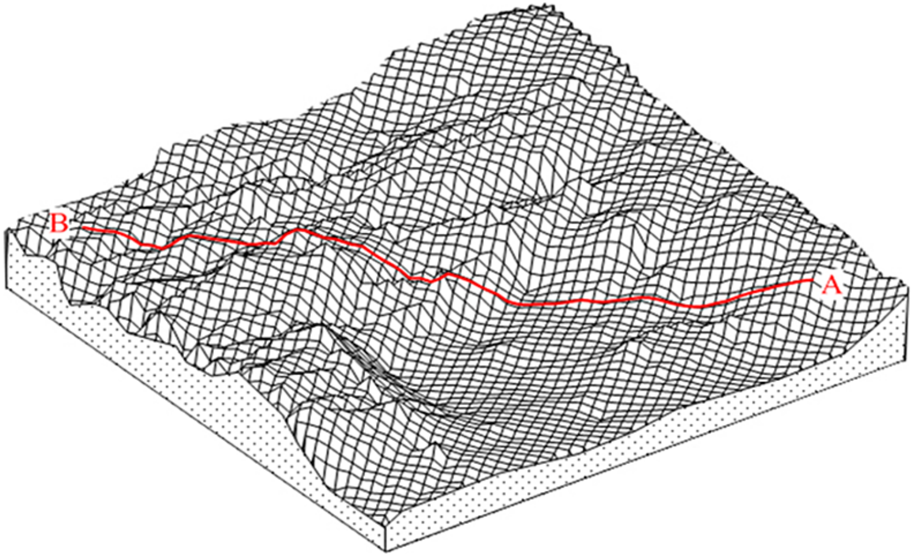

**Figure 10.** Profile display, three-dimensional model.

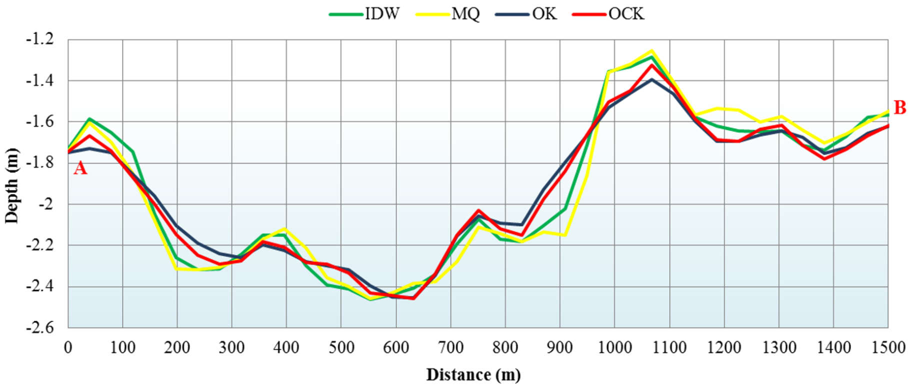

**Figure 11.** Differences in profile for the four best interpolation methods.

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Bathymetric survey of Lake Vrana, Croatia

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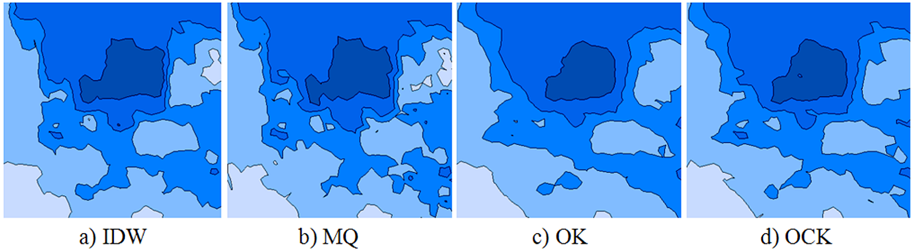

**Figure 12.** Representation of contours in part of the lake.

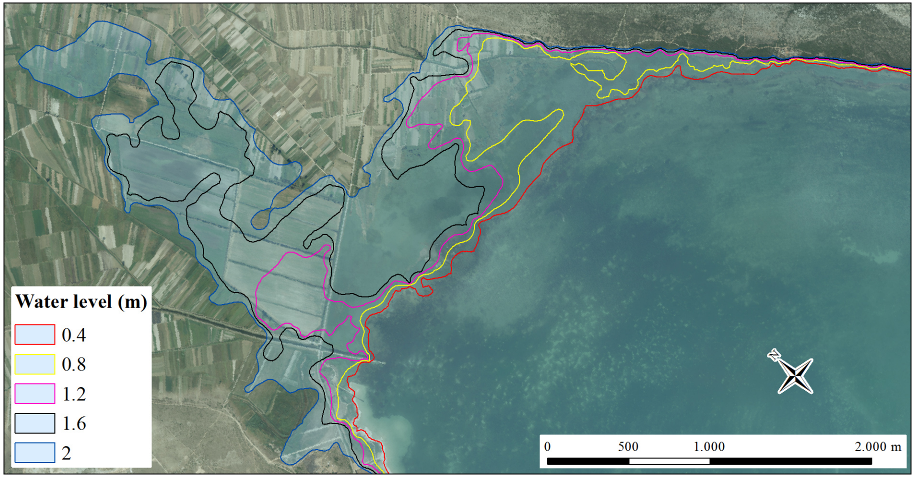

**Figure 13.** Annual water level oscillation in the northern part of Lake Vrana Nature Park (probable scenario in case the Jasen water pump stops working).

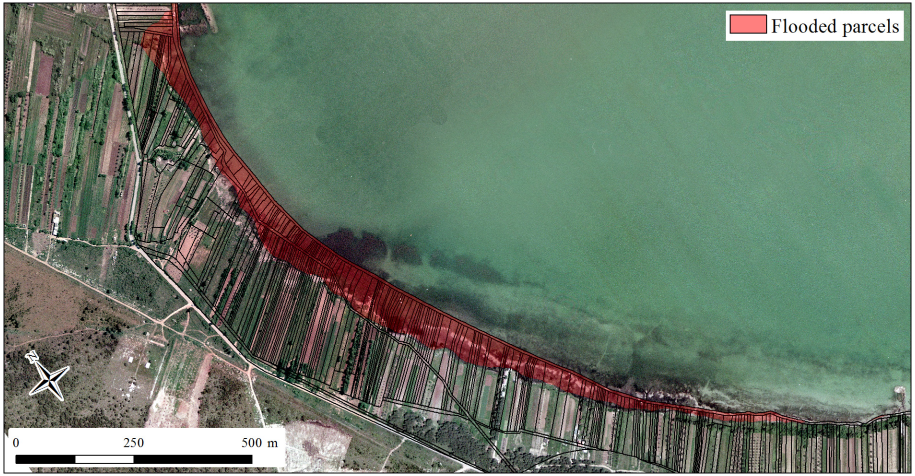

**Figure 14.** Flooded agricultural parcels in the Pakoštane cadastre at a water level of 2 m (north-western section of the Park).

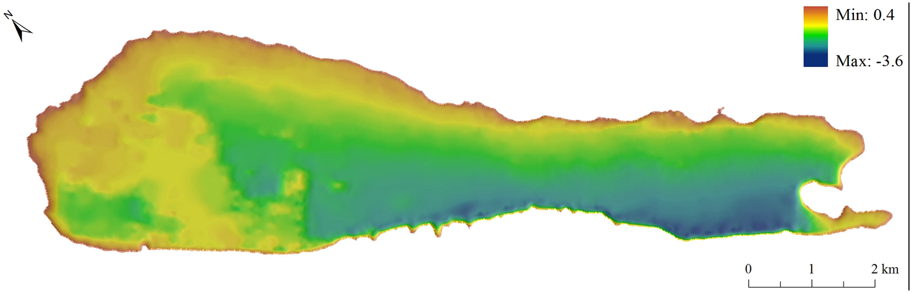

**Figure 15.** Bathymetric map of Lake Vrana.