www.czasopisma.pan.pl PAN www.journals.pan.pl

JOURNAL OF WATER AND LAND DEVELOPMENT
e-ISSN 2083-4535

Polish Academy of Sciences (PAN), Committee on Agronomic Sciences
Section of Land Reclamation and Environmental Engineering in Agriculture
Institute of Technology and Life Sciences (ITP)

JOURNAL OF WATER AND LAND DEVELOPMENT
2020, No. 46 (VII–IX): 84–96
https://DOI.org/10.24425/jwld.2020.134200

Available (PDF): http://www.itp.edu.pl/wydawnictwo/journal; http://journals.pan.pl/jwld

Received 08.01.2020
Reviewed 17.03.2020
Accepted 25.03.2020

Volume estimation of lakes and reservoirs based on aquatic drone surveys: The case study of Tuscany, Italy

Yamuna GIAMBASTIANI1) ✉, **Riccardo GIUSTI**1), **Stefano CECCHI**1),
Francesca PALOMBA2), **Francesco MANETTI**3), **Stefano ROMANELLI**3),
Lorenzo BOTTAI3)

1) CNR-IBE Italian Research Council – Institute of Bioeconomy, Area della Ricerca di Firenze, Via Madonna del Piano n. 10, Edificio D – Piano Primo, 50019 Sesto Fiorentino (FI), Italy
2) CNR-Ibimet Italian Research Council – Institute of Biometeorology, Florence, Italy
3) Consorzio LAMMA – Environmental Modelling and Monitoring Laboratory for Sustainable Development, Florence, Italy

For citation: Giambastiani Y., Giusti R., Cecchi S., Palomba F., Manetti F., Romanelli S., Bottai L. 2020. Volume estimation of lakes and reservoirs based on aquatic drone surveys: The case study of Tuscany, Italy. Journal of Water and Land Development. No. 46 (VII–IX) p. 84–96. DOI: 10.24425/jwld.2020.134200.

Abstract

Following flood events and cloudbursts alternating with long drought periods, interest grew in the reservoirs, lakes and water basins in the Tuscany region. In-depth studies are needed to understand the role of water bodies in territorial resilience to climate change. Water volume is the main information to be collected to quantify and monitor their capacity. In this study, a methodology was developed for the estimation of water volume, based on depth measurements taken by sensors with low detection time and costs that can quantify the resource on a regional scale. The depth measuring instrument was a portable sounder with 95 satellite positioning system (Deeper Smart Sonar PRO + (WI-FI + GPS). 204 water bodies were measured. The results indicate that depth is a fundamental parameter to be detected in the field, to obtain the volume with automatic and precise tools. The calculated volume correlates well with the real volume with an $R^2 = 0.94$. Elaboration of the results led to a model being developed to estimate the volume, knowing only the lake surface area. The database created can be used to conduct future studies on the dynamics of water resources in relation to climate change. It will also be possible to make comparisons with data obtained from satellite and LiDAR (light detection and ranging) surveys.

Key words: *deeper sonar, lake, pond, reservoir, volume model*

INTRODUCTION

In recent years, severe environmental phenomena have occurred in Tuscany with related disasters, deaths and extensive economic damage. These are attributable to extreme weather events and alteration of precipitation distribution: rainy periods alternating with extremely dry periods (e.g. ZOLINA *et al.* [2013]; BARTOLINI *et al.* [2014; 2018]). In addition, cloudbursts are increasingly frequent with destructive consequences on the territory and for the population [PRETI *et al.* 2017]. Flash floods have occurred throughout the region [San Polo (FI) – May 2018, Livorno – October 2017, the Albegna River (GR) – November 2012 and October 2014, Monteroni (SI) – August 2015], causing landslides, blocked roads and problems in agriculture. Prolonged drought has led to water shortages for agriculture and cities, with damage to crops and expensive supplies from long distances. Hill lakes and artificial reservoirs play an important role in tackling climate change, reducing the impact of extreme events and increasing the resilience of environments and affected elements [WATSON *et al.* 2016].

Reservoir embankments work similarly to fluvial check dams, retaining sediments [VERSTRAETEN, POESEN 2000], debris and reducing the mean slope of the hillside [PITON, RECKING 2017]. They also affect carbon retention and the carbon cycle [Lü *et al*. 2012]. Abundance and size distribution of lakes, ponds, and impoundments have a similar importance to large reservoirs [Downing, Duarte, 2009]. Large natural lakes or artificial reservoirs are not sufficient to meet the needs during extreme events. Their purpose is often for hydroelectric energy production [Fearnside 2016; Tullos *et al*. 2010].

The building of big dams to create large reservoirs leads to high impacts, in terms of hydrological [Chao *et al*. 2008; Graf 1999], ecological [Pokhrel *et al*. 2012] and social effects [Tilt *el al*. 2009]. Improving the control of outflows deriving from intense rainfall, means that water can be stored in reservoirs [Zhang *et al.* 2011], for use during periods of severe drought for crop irrigation [Molden *et al*. 2010; Mushtaq *et al*. 2006; Yang *et al*. 2019], civil use and to mitigate aridity for vegetation and wildlife [Stürck *et al*. 2014].

In addition, a lake influences the hydraulic risk by acting as an overflow basin and thereby improving the flood mitigation [Wang *et al*. 2011], protecting settlements and infrastructure downstream [Ming *et al*. 2007]. In order to best optimize flood mitigation, a hydrological study is needed for sizing of the spillway, based on the flow rate chosen for a given return time [Cummings *et al*. 2012]. Tuscany has many hill lakes, ponds and artificial reservoirs of small-medium size (Fig. 1). In Figure 1, there are areas with many small and medium hill lakes and reservoirs. These can affect water sustainability in the agricultural sector and flood mitigation. Small and medium-sized lakes create less impact than large dams. The figure also pinpoints the sites where recent disasters have occurred following heavy rains. In 2017, a severe drought hit the entire region.

Given the high number and variety, it is difficult to obtain information regarding the capacity of a reservoir and its state of maintenance, especially as regards silting and sedimentation [Baccari *et al*. 2008]. Silting represented an off-site damage of erosive phenomena and hydrogeological instability [Yang *et al.* 2019]. Sedimentation has a direct influence on the reservoir's water capacity, and therefore on the maintenance, cost and efficiency of the hydraulic works and mechanical devices of the artificial

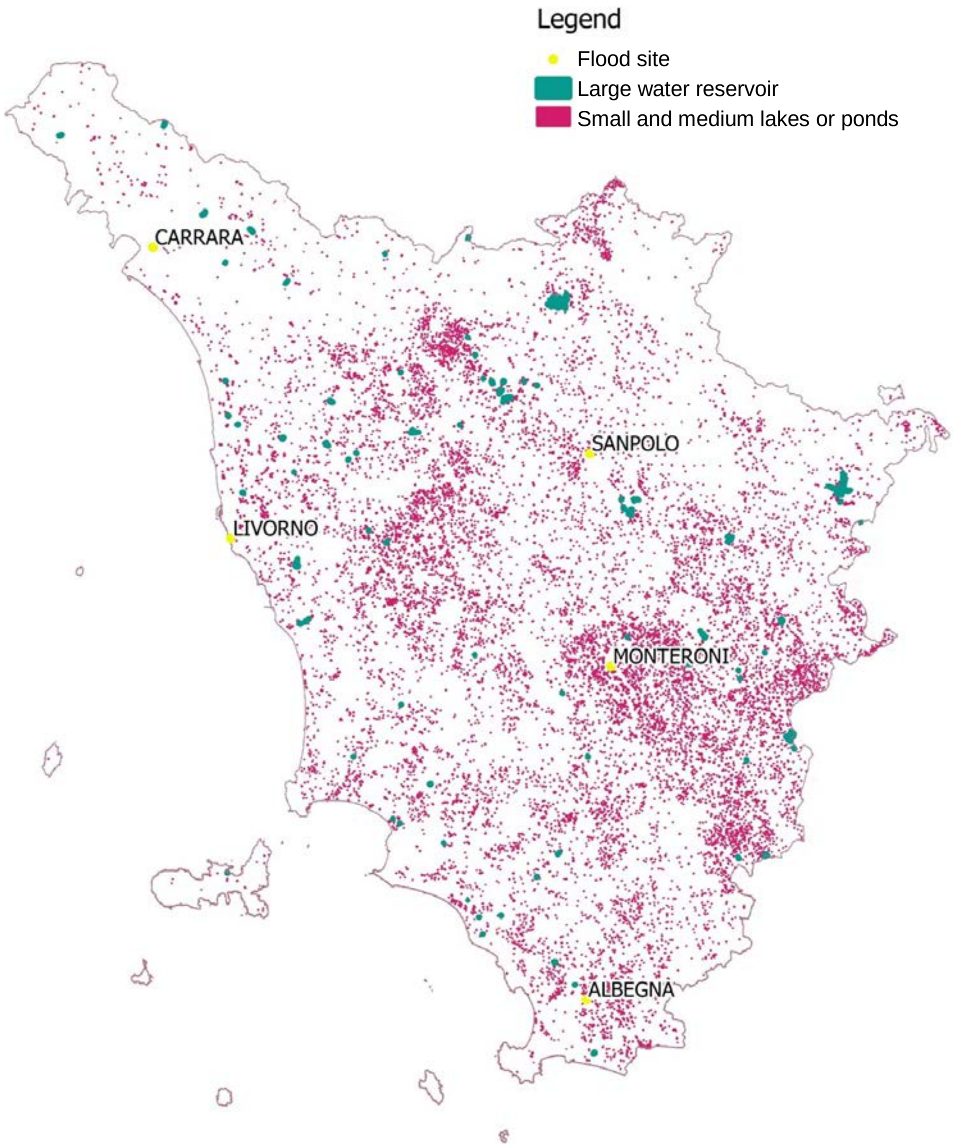

Fig. 1. Distribution of small and large water bodies in Tuscany; source: own elaboration

reservoirs. The accumulation of sediments increases the stress on the dam body and can also cause problems in the structure stability [IVANOSKI *et al*. 2019]. The silting can also generate serious problems on the tributary and effluent rivers, as well as on the water quality themselves and of the related ecosystems [SCHWEIZER, PINI PRATO 2003; STÜRCK *et al*. 2014]. In particular, direct consequence of sedimentation are the limitation of the capacity for regulating the outflows and the floods lamination, the obstruction and the loss of efficiency of the bottom discharges and of the gripping, filtering and derivation works [BAZZOFFI, VANINO 2009]. Causes the reduction of the water quantity for irrigation purposes in the agricultural sector [SOCCI *et al*. 2019]. In the case of reservoirs originating from river dams, sedimentation leads to geotechnical problems, causes the greater stress on the dam body, the abrasion of the artifacts, the lowering of the river bed downstream [BAZZOFFI 2008]. The volume is traditionally measured using a bathymetric survey [SHERSTYANKIN *et al*. 2006], which gives a precise result but with high costs and times. The measurement is carried out by an operator who travels the lake with a boat. It moves on a virtual square matrix and for each vertex of the matrix measures the depth by means of an echo sounder [HANSEN *et al*. 2017]. Several approaches have been proposed in the literature for estimating lake depth based on the interpretation of visible and near-infrared satellite data [BANWELL *et al*. 2012; GARAMBOIS *et al*. 2017; KRAWCZYNSKI *et al*. 2009; SIMA *et al*. 2013]. The reflectance of a water column is modulated to obtain the depth [TEDESCO, STEINER 2011]. Volume, average/maximum depth and other data for large dams can be collected by the managing authorities. These water bodies have a considerable impact and generally high hazard, so it is necessary to conduct in-depth studies and monitoring over time [TORRES-BATLLÓ *et al*. 2020]. Otherwise, field surveys or indirect estimates are necessary for small lakes, ponds and impoundments, for which no data on their capacity are available. In this paper, we propose a methodology to measure the volume of small and medium-sized lakes, i.e. those between 2000 and 50 000 m^2 of surface. Lakes and reservoirs of this type are numerous but information about volume is hard to find.

MATERIALS AND METHODS

BASIC ACQUISITION ON TUSCANY WATER BODIES

The first phase of the work concerned homogenization of the geographical data in regional databases (department archives, office of civil engineering and other relevant authorities). For each reservoir, a check was performed by means of photographic interpretation, in a GIS environment. From 2016 HD orthophotos (Tuscany Region), we verified the current state of the reservoir: existence, seasonality, shape modification, etc. Unknown reservoirs were collected by photographic interpretation through infrared orthophotos (Fig. 2), from which it is possible to easily distinguish water bodies from the rest of the territory. The water body takes on a dark blue-green colour that is easily distinguished from surrounding objects, such as buildings, woods, grassland, roads. This methodology was applied to complete our database and include lakes and other reservoirs that have never been surveyed. Methodology carried out to find unknown water bodies consist in examine all the Tuscany territory, watching NIR images at a range of scale between 1:200 and 1:4000. Water bodies take a dark colour, tending to green-blue. Thanks to their colour, it is possible distinguish the lake than other objects, usually reds (vegetation) and white-greys (buildings or fields). The number of perennial reservoirs detected was 16 248, for a total area of 5781.17 ha (Fig. 3). For each one, we quantified the surface by digitizing the geometry, 3446 have an area greater than 0.2 ha.

Fig. 2. Portion of orthophoto obtained with a near infrared sensor: Pontecosi dam on the Serchio River – Lucca province; data used: ‘Ortofoto 20 cm copyright 2016 Consorzio TeA’ OFC 2016 20 cm –32 bit colour – 4R 1G 2B NirRG Standard False Colour for vegetation studies; source: own elaboration

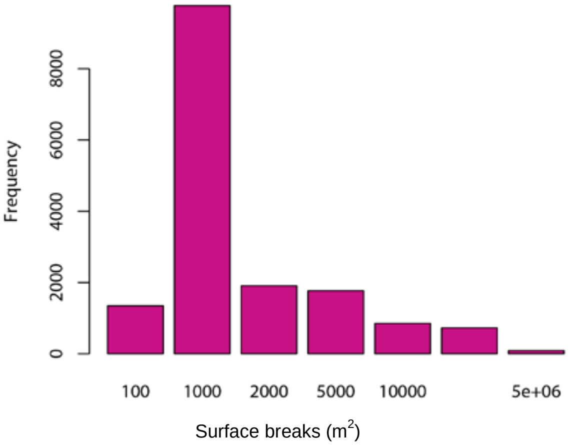

Fig. 3. Distribution based on the surface of the polygon of all lakes; source: own study

The most recurrent class is the small size (up to 1000 m^2). They are usually small reservoirs on farms for agricultural activities, such as fertilization and the fight against pathogens / with aqueous solutions. Farmers do not use the water contained in these reservoirs for irrigation, since it would not be enough to satisfy crop needs. However it is used to irrigate secondary crops. The reservoirs belonging to the following classes are those that play a major role in irrigation and provide many ecosystem services. In cases where they are deeper than 2 m, they can be used for forest fire fighting by means of a helicopter jack. 14 804 small reservoirs (up to 5000 m^2) have a total area of 1227.47 ha. 1581 medium-size reservoirs (between 5000 and 50 000 m^2) have a total area of 2015.41 ha. 93 large reservoirs (over 50 000 m^2) have a total area of 2538.29 ha.

WATER DEPTHS MEASURED IN THE FIELD

Once the general database had been updated, including all water bodies found in the region, direct field surveys were conducted in order to measure the depth of a sample of these. The sample size was not defined a priori. Surveys were conducted at all the properties that gave authorization for the measures. Most reservoirs are privately owned, so the generalities and contacts (e-mail or telephone) for each owner must be obtained. 204 reservoirs and lakes were measured (Fig. 4). The surface area of the 204 lakes (246.36 ha) was between 2000 and 50 000 m^2. There are 3353 reservoirs belonging to this class in the entire database for a total of 2581.57 ha. The measured sample is 6% of the number and 9.5% of the surface. The map shows that the sample is well distributed over the region. The different categories of morphology, geology and climate regime are well represented within the areas subject to

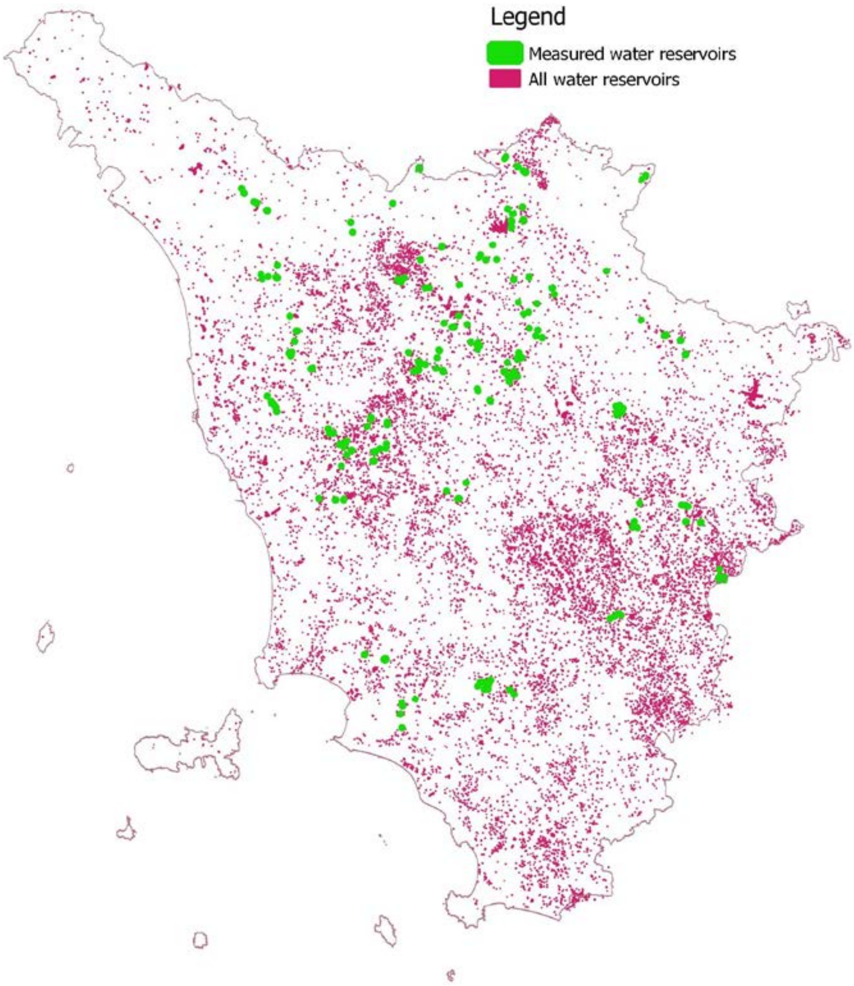

Fig. 4. Distribution of reservoirs measured during the field surveys; source: own elaboration

are excluded. The obtained sample was well distributed in the territory, representative of the sizes and types (morphology, geology). For each sample reservoir, the depths along the two main transects was measured, in relation to the surface (Fig. 5). Starting from this measurement it is possible to obtain a regression curve that represents the depth trend along the measured profile. Calculation of the water capacity of the reservoir is based on these measures.

The depth measuring instrument was a portable sounder with satellite positioning system (Deeper Smart Sonar PRO + (WI-FI + GPS). The Deeper can measure depth (max. 80 m, min. 0.6 m) through a sonic pulse with 290 kHz frequency and narrow beam (15° cone amplitude) – Fig. 6). It sends a double frequency sonic signal (290 kHz and 90 kHz) for different measurement cone size (15° – higher resolution and 55°). It is equipped with a water temperature sensor. A Wi-Fi connection is used to transfer data to a smartphone. The Wi-Fi range reaches up to 100 m. The Deeper PRO PLUS sonar has a highly accurate internal GPS receiver that allows the device to create bathymetric maps. Scan depth is from 0.7 m (2 ft) up to 80 m (260 ft). It can be launched with a fishing rod, or transported by boat. It is 65 mm in diameter and weighs 100 g. The rechargeable batteries are made of lithium polymers, providing 3.7 VGPS accuracy: 6 m. Each measure is provided with geographical coordinates in WGS84 reference system. Two measurements are taken every second. The instrument is transported by a radio-controlled aquatic drone that travels at 1.6 m per second and communicates by WI-FI via a smartphone equipped with a specific application that records the measurements (Photo 1). The results are automatically uploaded in the cloud, avoiding loss of data. The time for measuring depths along the two main transects varied according to the size of the reservoir, on average it was 18 minutes for each one, including walking time to the shoreline. An alternative in smaller lakes is using a fishing rod to launch and retrieve the instrument. The advantages of this are: transport of the equipment facilitated by the reduced weight, independence from the battery life of the aquatic drone and measurements without the need to directly reach the water/surface.

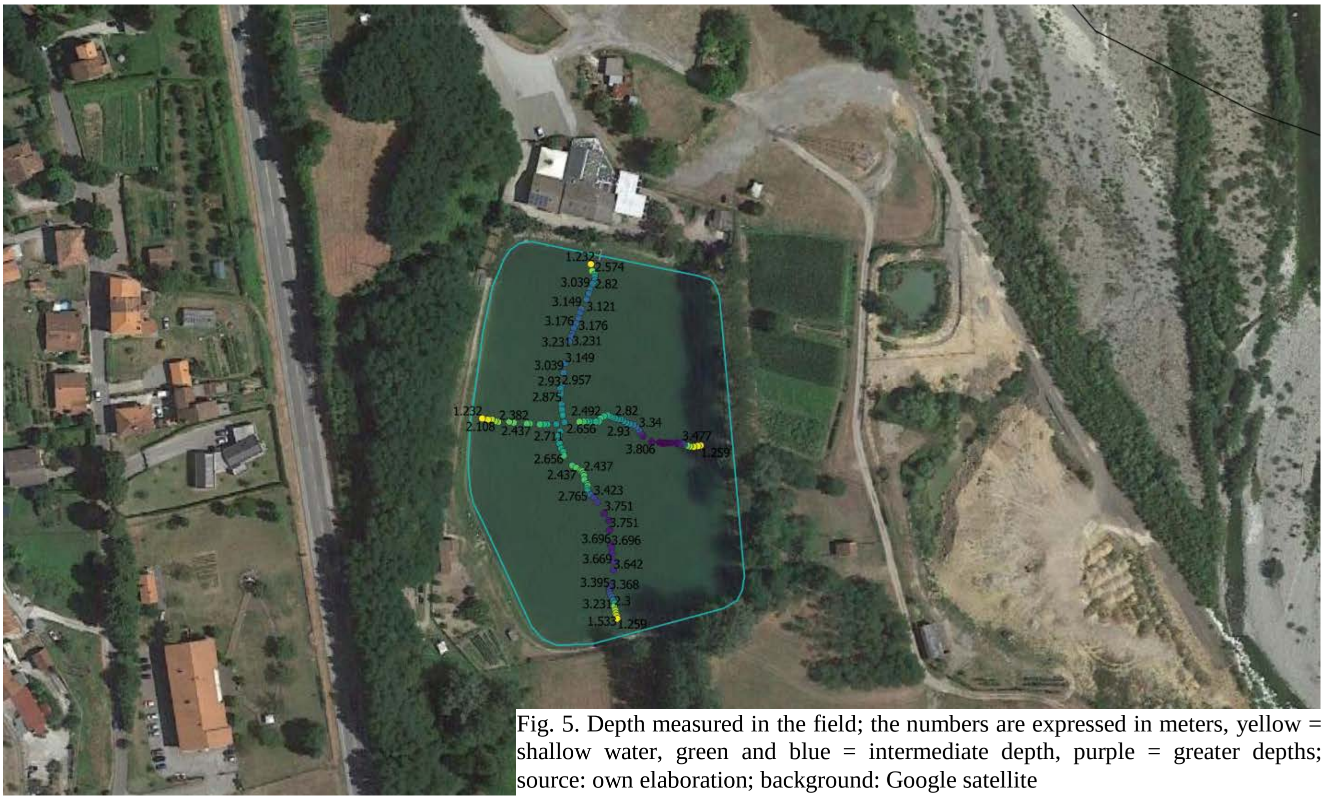

Fig. 5. Depth measured in the field; the numbers are expressed in meters, yellow = shallow water, green and blue = intermediate depth, purple = greater depths; source: own elaboration; background: Google satellite

Fig. 6. Sonic depth sounder used for field measurements; source: own elaboration

Photo 1. Radio-controlled aquatic drone used to transport the sonic sensor into the measured lakes (phot. *R. Giusti*)

ESTIMATION OF RESERVOIR CAPACITY

Storage capacity estimation (water volume) was performed using an automatic method based on the punctual depths obtained along the transects. Capacity was calculated for each one individually to obtain the water volume for each reservoir; we made a query, executed in GIS environment. The query steps are as follows:

- vector digitalization of each detected reservoir boundary is carried out, through photointerpretation of 20 cm resolution ortophotos;
- a grid of 0.5 m cells, related to the reservoir polygon, is created; for each cell a value is assigned a distance value, corresponding to the distance between the cell centroid and the shoreline;
- for each depth point detected along the transect, a regression model is calculated between depth and minimum distance from the shoreline; regression used is a fourth grade polynomial (Eq. 1); the independent variable coefficients vary for each reservoir;
- for each cell is assigned a depth calculate by the polynomial regression;
- the water volume in reservoir is the sum of each water column obtained multiplying the cell surface and the corresponding depth (Eq. 2).

$$h = a_1L^4 + a_2L^3 + a_3L^2 + a_4L + a_5 \tag{1}$$

Where: h = depth (m); L = the length (m) – shoreline distance is linear dimension; $a_{1\text{-}5}$ = polynomial coefficients

$$V = \sum_i^n h \cdot A \tag{2}$$

Where: V = volume (m^3); A = the cell size (m^2).

The regression model between depth and shoreline distance is based on a polynomial law, which best fits the lake profile. HOLLISTER and MILSTEAD [2010] applied this methodology in their study, providing good results for the determination of storage capacity. The R^2 correlation between estimated conical volumes (km^3) and "true" volumes (km^3), results in 0.95 [HOLLISTER, MILSTEAD 2010].

For each reservoir measured, we obtained the corresponding volume (Fig. 7). Once detected punctual depth, through the drone, all methodology flow is executable thanks an automatic query in GIS environmental. There permits an easy monitoring of the reservoir volume by some simply field activity.

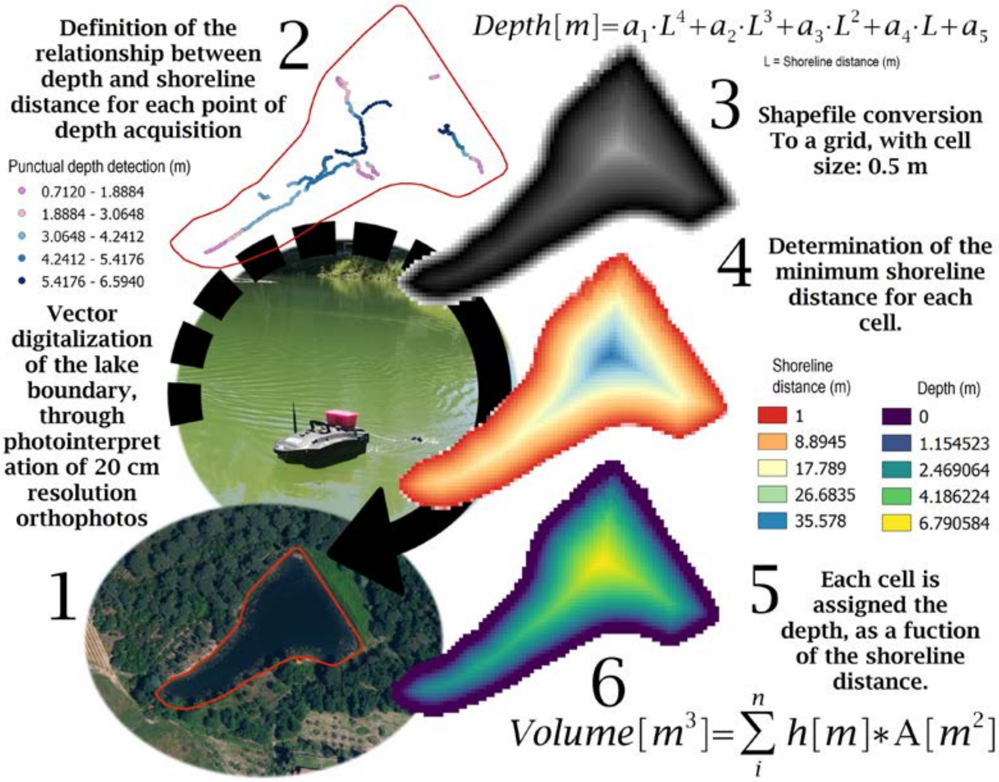

Fig. 7. Water reservoir volume estimation methodology conceptualization; h = depth (m), a = polynomial coefficients, L = length (m), V = water volume (m^3), A = cell size (m^2); source: own elaboration

DATA PROCESSING

During the data research phase, the volumes measured using traditional techniques were collected through high-level bathymetric surveys. These measures are considered "real volumes". Measurements were taken in the last 5 years, so were not influenced by silting or other modifications. The field surveys involved 55 reservoirs for which the real volume was available (Fig. 8). This allowed us to make comparisons, calibrations and establish the accuracy of the developed method. Subsequent elaborations concerned the comparison between the parameters detected in the field with variables collected by remote sensing, in order to find correlations that allowed the water capacity to be estimated with indirect systems, more rapidly and at a lower cost. The parameters used were: average slope and difference in altitude, measured through the processing of a DTM (digital terrain model). The DTM used is based on the regional technical map (scale 1:10 000); it is derived from the level curves and elevation points. Its structure is of 10×10 m cells and it contains the height above sea level. Processing of the DTM was conducted on a fixed distance buffer around the reservoir. Given the high variability in lake sizes in our database, the buffers were fixed at different distances (1 m, 7 m, 10 m, 15 m), to find relationships between surface size and the surrounding morphology [HEATHCOTE *et al*. 2015].

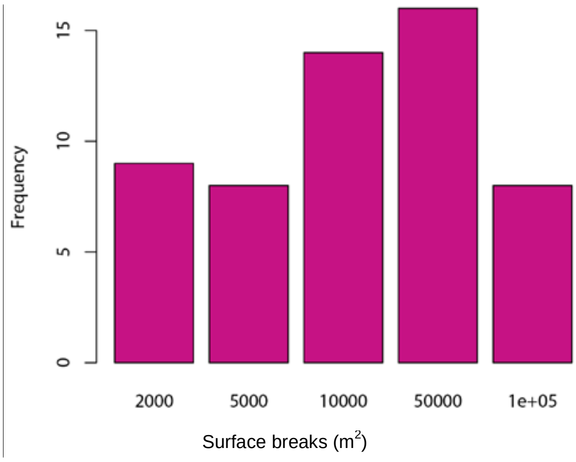

Fig. 8. Distribution of the lakes subject to comparison between the volume calculated with the methodology developed in this study and the real volume; source: own study

RESULTS

During the field activities, depth measurements were taken from 204 water bodies, distributed in the regional territory. There were 49 surveys, with a team consisting of 2 people. The analyzed sample is representative of the entire database, for the categories studied (Fig. 9). The created query was run with the data obtained, in order to estimate the capacity of each measured lake. Four were tagged as outliers and therefore discarded. In these cases, the estimated depth measurements were negative, due to query errors in the polynomial regression development. Polynomial regression well fit the relationship between depth and shoreline distance, R^2 (s) obtained from the regression vary about 0.68–0.87 range. The relationship between maximum measured depth and average depth of each reservoir was well correlated (Fig. 10). The two variables are well correlated ($R^2 = 0.93$) by a regression line ($y = 0.56x$). The relationship is significant (p-value: $<2.2\mathrm{e}^{-16}$). The regression line indicates that the average depth was frequently about half of the maximum depth. The high correlation index ($R^2 = 0.93$) demonstrated that the method works well for the volume estimation. The multiplication factor 0.56 (angular coefficient obtained from the modelling) indicates that the average water depth is about half the maximum depth. The distribution of regression residues is normal (Fig. 10). This indicates that the lake mean depth usually is

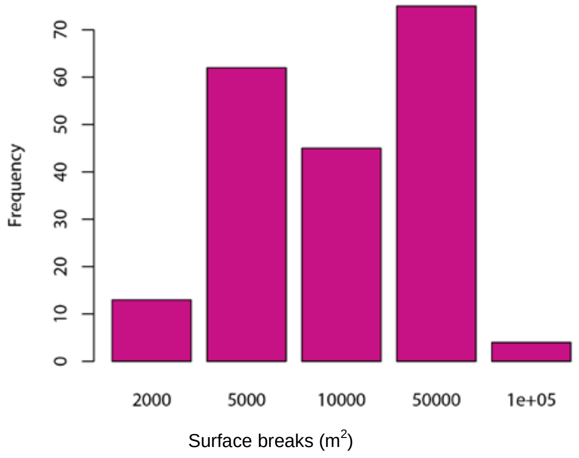

Fig. 9. Distribution of the measured water bodies; source: own study

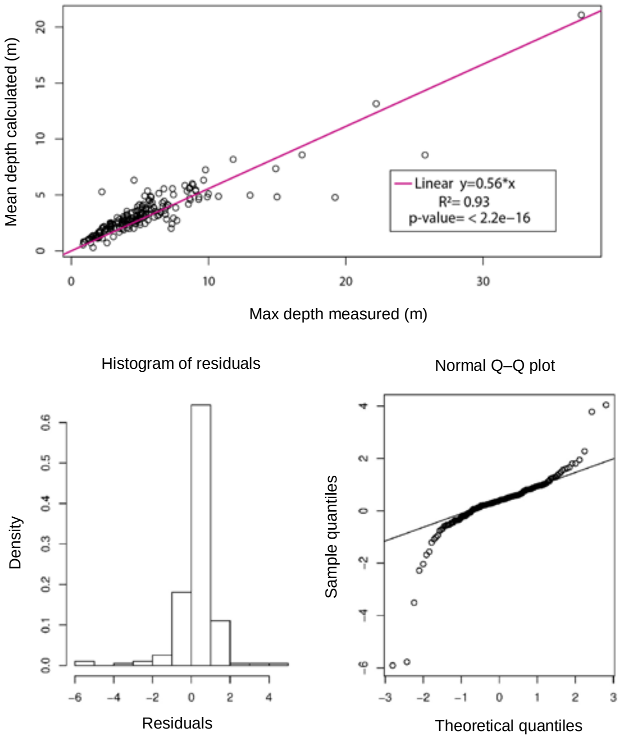

Fig. 10. Relationship between maximum measured depth and calculated average depth by dividing the query estimated volume and area of the lake polygon; source: own study

half of the maximum depth, and this depends in particular on the uniform shape of the lake. For larger lakes, the ratio between average and maximum depth is different from 0.5. This is mainly due to two reasons: during sampling the right maximum depth was not measured and the lake shape is not uniform.

The estimated volume was also well correlated with the surface area (Fig. 11); this relationship followed a linear trend. The model approximates the average depth at about 4.19 m, while the mean of the average water depths of the measured reservoirs is 3.25 m. The distribution of regression residues is normal. The estimated volumes, obtained with the polynomial model, were compared with the real volumes, on a sample of 55 reservoirs of different sizes (Fig. 12). The sample is representative of the size and type variability of the measured reservoirs (Fig. 7).

The high correlation (R^2 = 0.94 and p-value < $2.2e^{-16}$) between the two compared volumes indicated that the adopted methodology is correct. It generally tended to overestimate the water capacity by 1.4%. The results of the elaborations concern the relationships between parameters influencing the volume and morphological characteristics surrounding the reservoir. The parameter investigated was the maximum water depth. The analysis concerned the comparison between maximum depth and the average slope around the lake and the difference in elevation obtained relative to different buffer distances used. In addition, the type of reservoir was also discriminated, if excavated or formed by river dam or thalweg barrage. There are no significant relationships between these parameters, and the maximum water depth depends on non-morphological factors (Tab. 1).

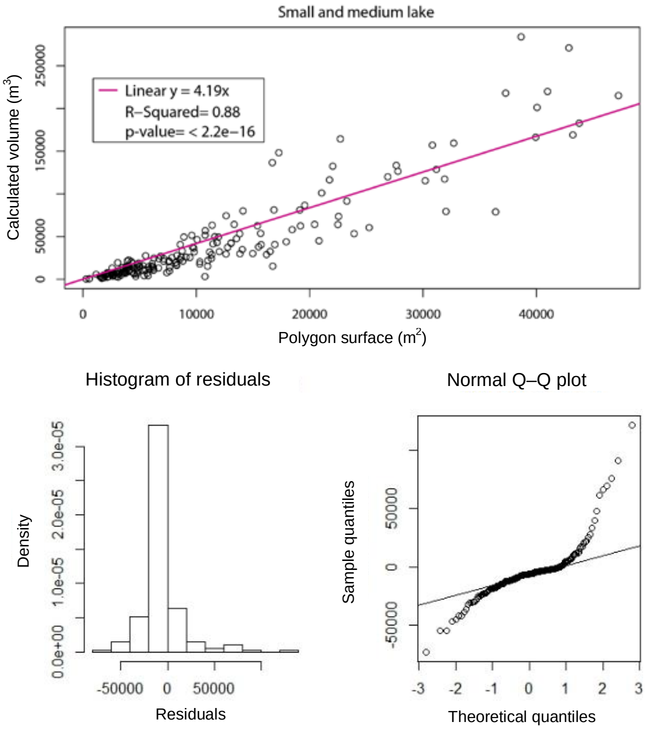

Fig. 11. Relationship between reservoir area and estimated volume; source: own study

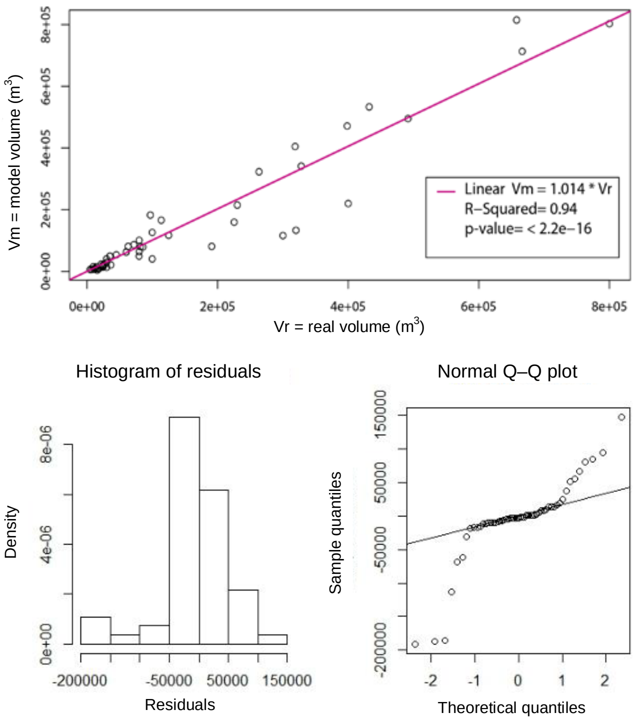

Fig. 12. Relationship between volumes calculated with the developed methodology and real volumes; source: own study

Table 1. Summary of correlation indices between maximum water depth and morphological parameters around the reservoir

Kind of reservoir	Maximum depth measured when difference of altitude at buffer width (m)								Mean slope on a 50-meter buffer	
	1		7		10		15			
	R^2	p-value	R^2	p-value	R^2	p-value	R^2	p-value	R^2	p-value
All	0.037	$6.27e^{-3}$	0.044	$2.99\ e^{-3}$	0.044	$2.99\ e^{-3}$	0.059	$5.54\ e^{-4}$	0.004	$3.98\ e^{-1}$
Small	0.050	$5.95\ e^{-2}$	0.089	$1.11\ e^{-2}$	0.127	$2.11\ e^{-3}$	0.143	$1.04\ e^{-3}$	0.079	$1.70\ e^{-2}$
Medium	0.066	$8.79\ e^{-2}$	0.060	$1.04\ e^{-1}$	0.055	$1.21\ e^{-1}$	0.037	$2.03\ e^{-1}$	0.009	$5.45\ e^{-1}$
Large	0.032	$1.26\ e^{-1}$	0.031	$1.34\ e^{-1}$	0.018	$2.54\ e^{-1}$	0.041	$8.17\ e^{-2}$	0.048	$5.99\ e^{-2}$
Digged	0.002	$6.92\ e^{-1}$	0.000	$9.42\ e^{-1}$	0.006	$5.08\ e^{-1}$	0.001	$7.65\ e^{-1}$	0.032	$1.12\ e^{-1}$
Barrage	0.179	$1.51\ e^{-3}$	0.282	$4.23\ e^{-7}$	0.332	$5.59\ e^{-9}$	0.428	$5.46\ e^{-13}$	0.192	$5.49\ e^{-4}$

Explanations: R^2 = coefficient of determination.
Source: own study.

DISCUSSION

The aim of this study was to develop a methodology for estimating the water capacity of lakes, hill lakes and reservoirs in general. Our target was mainly medium-sized water bodies, managed by private individuals or farms for crop irrigation, livestock watering, sport fishing and other recreational purposes. This type of water body plays an important role in the resilience of the territory to face drought periods [KHLIFI *et al*. 2010; NAPOLI *et al*. 2014], trap sediment [VERSTRAETEN, POESEN 2000], control soil erosion [ABEDINI *et al*. 2012; CASTILLO *et al*. 2007] and mitigate hydraulic risk [GRAF 1999; KHAN *et al*. 2011]. It is therefore necessary to collect information about how much water is contained in the water bodies. The main problems are the large number and small size, the high variability in geology and morphology, but above all the difficulty in estimating depth remotely [SIMA, TAJRISHY 2013], using satellite images or LiDAR data [HOLLISTER, MILSTEAD 2010]. Knowing the average depth, it is possible to easily obtain the volume, due to the wide availability of high-definition orthophotos from which to extract the surface area occupied by water.

The proposed methodology consists of taking measurements in the field, with appropriate tools, in order to obtain depth measurements along the main transects of the reservoir. From these the volume is obtained through an automatic procedure in GIS environment. In the literature, there are studies that have developed techniques for estimating reservoir capacity based on maximum depth and surface area. Some authors used data obtained from the IKONOS, MODIS [KRAWCZYNSKI *et al*. 2009] and ASTER [GEORGIOU *et al*. 2009] satellites to estimate lake depth, compared with data obtained from total station [MIHU-PINTILIE *et al*. 2014], multispectral satellite image [YANG *et al*. 2019], LiDAR [RODDEWIG *et al*. 2018] and LADS surveys [FINKL, VOLLMER 2016; FORFINSKI, PARRISH 2016; STUMPF, HOLDERIED 2003]. HOLLISTER and MILSTEAD [2010] implemented a methodology on the large lakes of New England. In our case study (Tuscany), where lakes are much smaller, the methodology has been slightly modified, mainly due to the greater uniformity in shape. The transverse profiles are modeled with a polynomial regression and are comparable to each other, even if they have different geometries. From the results obtained, the assumption that depth is strongly related to shoreline distance is verified [HOLLISTER, MILSTEAD 2010]. This shows a high shape regularity of the investigated reservoir, apart the four excluded, in according with SHELKE and BALAN [2017]. The estimated volumes are compared to the actual volumes for a sample of reservoirs. The correlation is high and we found an overestimation of 1.4% that can be considered acceptable (Fig. 12). No influences are been detected about the bottom silting process [VERSTRAETEN, POESEN 2002]. The overestimation is due to the calculation method. The estimate of the reservoir capacity through the portable sounder is a valid alternative to traditional bathymetric surveys [SCHMITT *et al*. 2008]. The main advantages concern the speed of the measurement. It is possible to estimate the volume of a 3–4 ha lake, taking no more than 20 min for the measurement and a few minutes of computer processing. This allows a rapid analysis related to documented changes in meteorological events, bank failures or water loss due to permeability problems. Furthermore, this approach allows periodic volume monitoring. The necessary equipment is readily available on the market at an affordable cost. The approach of shoreline distance based model, for estimation of the volume, is especially useful for management purposes, as it produces data in a short time and with a sufficient approximation.

Furthermore, it is possible to derive a model for estimating the volume, based on the water surface area. The two variables are well correlated with each other. The model "volume = coeff · surface" allows us to estimate the volume of large-size water bodies with sufficient precision, knowing only the surface area. However, this surface-based model is not applicable for the estimation of a single lake, as the approximations made lead to non-significant data. The linear model "volume = coeff · surface" cannot be used for all reservoirs, indiscriminately. On a regional scale, it is possible to create an estimation model of the lake surface, and thus obtain the entire water capacity by taking measurements only on a sample of lakes. Therefore, the approach supports the collection of useful data with little effort, and permits planning of the water capacity in the territory. For example, after this study, Tuscany authorities know the total volume of water storage, about 440 mln m^3, and 173 mln m^3 for only the small and medium size lakes. Assessments can be made on water availability for the dry season to manage water consumption by agriculture [POLISSAR, FREEMAN 2010]. Related to the effective water consumption by crops, there may be the need for maintenance or to fund the building of new reservoirs in order to make up the deficit. For the hydraulic risk it is possible to adopt mitigation strategies to keep water levels low and locate the most useful lakes for this purpose.

The size factor plays an important role. In artificial reservoirs, such as large basins for hydroelectric use, the water is very deep, determined by high dams [RĂDOANE, RĂDOANE 2005]. Figure 13 shows the relationship between area and volume for large reservoirs, but these are not the subject of this study, as the instruments used do not have autonomy and versatility to detect water bodies of this size. The regression shown is comparable in terms of trend, type and significance to that observed with the target reservoirs. However, the multiplication coefficient changes from 4.19 to 22.25. As stated above, this factor corresponds to the average depth used by the model to transform the surface area into volume. As the surface area of the reservoir increases, the water depth increases with a non-proportional trend. For large dams, parameters such as volume or depth are usually known. These structures are widely controlled and monitored due to their high hazard and environmental impact. It should also be considered that the smaller number makes any study or analysis more sustainable than hill lakes and small and medium-sized reservoirs. In order to improve the volume estimation model, based on the water surface area, it is necessary to insert a parameter in relation to the depth. There are some papers in the literature that propose methods for estimating the average and maximum

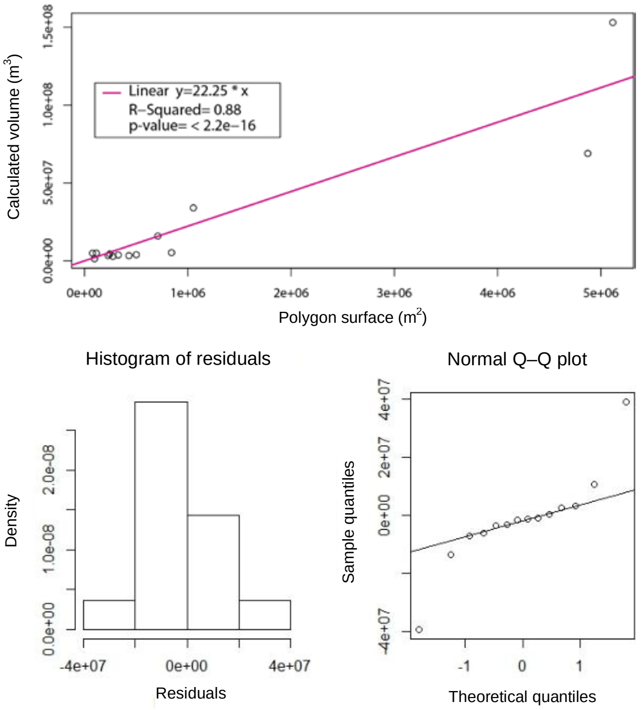

Fig. 13. Relationship between surface area and volume of large dams in Tuscany; source: own study

lake depth [Pistocchi, Pennington 2006], based on the morphology and topography of the surrounding land. The mean slope of the hillside, the difference between maximum and minimum altitude found around the lake are morphological parameters able to provide indications regarding the maximum water depth [Heathcote *et al*. 2015]. The results obtained in our study show non-significant relationships between the topographic parameters and maximum measured depth. We believe that the resolution of the DTM used is low (10×10 m), and therefore not correct for the processing performed [van Bemmelen *et al*. 2016]. Most of the water bodies in the region are artificial, built in the 1960s and 1970s. The sites were excavated to house the reservoir, and the embankments formed with the resulting soil. The size of the barrier is not based on the morphology of the slope, but depends on the excavation design and volume.

For each model in this work, we have made a cross-validation analysis. For model in Figure 10, the analysis shows that the model responds well, the regressions obtained coincides. The model well estimates the average depths of smaller lakes, those that supposedly have a more uniform shape (Fig. 14). The data are characterized by a high variability, as clearly showed from the data dispersion in the graph, in Figure 15. However, the model is able to provide a volume indication from the surface.

The models obtained from cross validation are sufficiently overlayed. The obtained model can be used effectively to obtain an estimate of the total volume, with an acceptable error (Tab. 2).

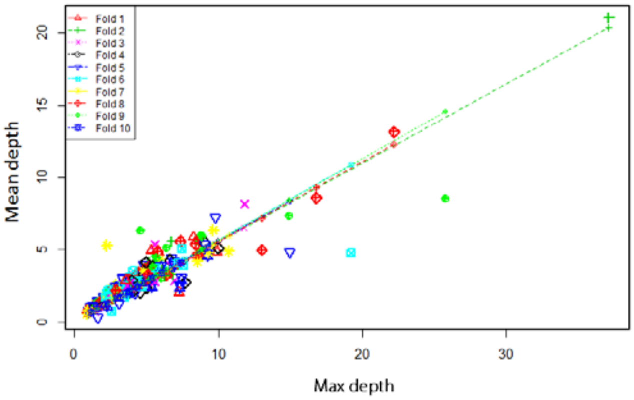

Fig. 14. Cross-validation analysis for model at Figure 10; small symbols show cross-validation predicted values; source: own study

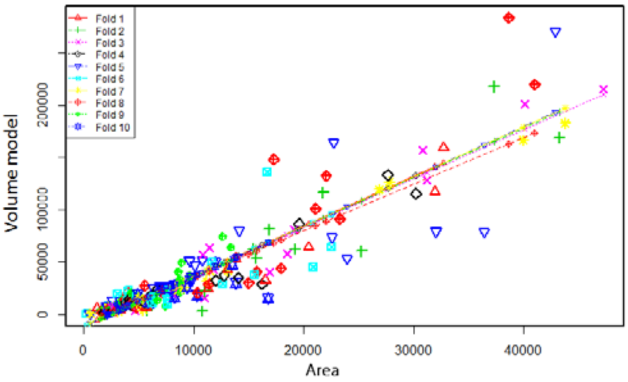

Fig. 15. Cross-validation analysis for the model at Figure 11; small symbols show cross-validation predicted values; source: own study

The model obtained from the correlation between the real volume and the volume estimated with the method proposed by this work, presents a high r^2. The cross validation shows that the models obtained by processing are well overlapped (Fig. 16). This allows us to support the effectiveness of the developed methodology, although we have found poor results in terms of error. Most of the lakes for which it is possible to find up-to-date information on the actual volume, are the large dams, those with greater irregularity of shape, which influence all the other models.

Table 2. Summary of the main errors calculated for the four models proposed by this work

Model	*ME*	*RMSE*	*MAE*	*MPE*	*MAPE*	*MASE*	Figure No.
Maximum depth measured vs. mean depth calculated	0.31	1.05	0.70	9.95	23.24	0.53	9
Polygon surface vs. calculated volume	–5 125.04	22 390.17	14 495.52	–82.23	90.24	0.40	10
Real model vs. model volume	–4 734.13	58 620.11	32 616.44	–27.93	43.96	0.23	11
Polygon surface vs. calculated volume (large dams)	–1 492 419.75	15 845 758.67	9 437 714.01	–59.96	84.55	0.35	12

Explanations: *ME* = mean error; *RMSE* = root mean squared error; *MAE* = mean absolute error; *MPE* = mean percentage error; *MAPE* = mean absolute percentage error; *MASE* = mean absolute scaled error.
Source: own study.

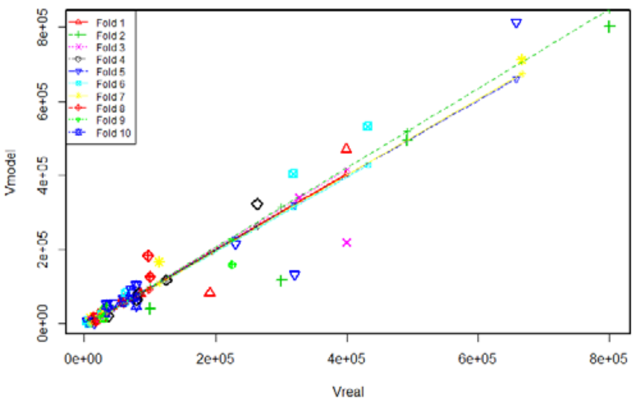

Fig. 16. Cross-validation analysis for the model at Figure 12; small symbols show cross-validation predicted values; source: own study

With the increase in the size of the lake there is a worse accuracy of the estimation model. This is due to greater variability, given the greater irregularity of the shape. However, the cross validation allows us to consider the model sufficiently accurate for the specific case study and allows us to confirm its effectiveness in estimating the volume of a large number of lakes (Fig. 17).

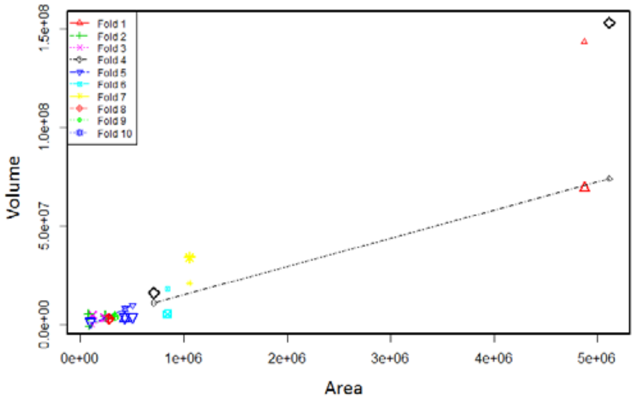

Fig. 17. Cross-validation analysis for the model at Figure 13; small symbols show cross-validation predicted values; source: own study

CONCLUSIONS

The data obtained allowed a methodology to be developed for the estimation of reservoir water capacity, based on the depth acquired by field surveys. With this methodology, it is possible to developed an estimation model of the water capacity knowing only the surface area, on a regional scale. The results have a low error when referring to large-scale studies, while it is not usable for estimating the volume of a single lake (lake surface approach). However, the max-depth approach works well, and allows the volume estimation with an acceptable error. The depth measurement sensor is quick and precise, and with simple tools, it is possible to obtain lakebed profiles in just a few minutes and with low costs. This approach is particularly useful for the management of water resources, allowing the availability in a large territory to be quantified and supporting mitigation processes to increase resilience in relation to extreme events as droughts and flashfloods [Dutta *et al*. 2019; Zhang *et al*. 2020]. Future studies can overcome some of the shortcomings in this work. It is the basis for the development of methodologies to estimate the capacity of reservoirs with indirect systems using remote sensing techniques. The data obtained with the field measurements represent the variability of lakes in Tuscany in terms of their size and type. It will be possible to process data and information obtained from satellite images, LiDAR surveys and other remote sensing techniques. Furthermore, the database will be used for monitoring the dynamics and silting rates [Moknatian, Piasecki 2020; Rădoane, Rădoane 2005] of the water contained in the reservoirs [Schmitt *et al*. 2008] in relation to climate change [Palmer *et al*. 2008].

REFERENCES

Abedini M., Md Said M.A., Ahmad F. 2012. Effectiveness of check dam to control soil erosion in a tropical catchment (The Ulu Kinta Basin). Catena. Vol. 97 p. 63–70. DOI 10.1016/j.catena.2012.05.003.

Baccari N., Boussema M.R., Lamachère J.M., Nasri S. 2008. Efficiency of contour benches, filling-in and silting-up of a hillside reservoir in a semi-arid climate in Tunisia. Comptes Rendus – Geoscience. Vol. 340. Iss. 1 p. 38–48. DOI 10.1016/j.crte.2007.09.020.

Banwell A.F., Arnold N.S., Willis I.C., Tedesco M., Ahlstrøm A.P. 2012. Modeling supraglacial water routing and lake filling on the Greenland Ice Sheet. Journal of Geophysical Research F: Earth Surface. Vol. 117. Iss. 4 p. 1–11. DOI 10.1029/2012JF002393.

Bartolini G., Grifoni D., Magno R., Torrigiani T., Gozzini B. 2018. Changes in temporal distribution of precipitation in a Mediterranean area (Tuscany, Italy) 1955–2013. Macromolecular Reaction Engineering. Vol. 10. Iss. 1 p. 1366–1374. DOI 10.1002/joc.5251.

Bartolini G., Messeri A., Grifoni D., Mannini D., Orlandini S. 2014. Recent trends in seasonal and annual precipitation indices in Tuscany (Italy). Theoretical and Applied Climatology. Vol. 118. Iss. 1–2 p. 147–157. DOI 10.1007/ s00704-013-1053-3.

Bazzoffi P. 2008. Erosione del Suolo in relazione alla redazione dei Piani di Gestione degli Invasi. Il modello FLORENCE e l'Atlante Italiano della Produzione di Sedimenti dai bacini Idrografici. Atti Convegno "Conservazione e Fertilità Del Suolo, Cambiamenti Climatici e Protezione Del Paesaggio" [Soil erosion in relation to the drafting of the Reservoir Management Plans. The FLORENCE model and the Italian Atlas of Sediment Production from Hydrographic Basins. In: Soil Conservation and Fertility, Climate Change and Landscape Protection]. Conference Proceedings. 10–11.12.2008 Roma. Rome. CRA-DAF p. 3–9.

Bazzoffi P., Vanino S. 2009. L'interrimento degli invasi ad uso irriguo nelle regioni meridionali: rilievi diretti, metodologie e modellistica [Burying of reservoirs for irrigation in southern regions: direct surveys, methodologies and modeling]. Rapporto I. Rome. Istituto Nazionale Di Economia Agraria p. 1–8.

Castillo V.M., Mosch W.M., García C.C., Barberá G.G., Cano J. A.N., López-Bermúdez F. 2007. Effectiveness and geomorphological impacts of check dams for soil erosion control in a semiarid Mediterranean catchment: El Cárcavo (Murcia, Spain). Catena. Vol. 70(3) p. 416–427. DOI 10.1016/j.catena.2006.11.009.

Chao B.F., Wu Y.H., Li Y.S. 2008. Impact of artificial reservoir water impoundment on global sea level. Science. Vol. 320(5873) p. 212–214. DOI 10.1126/science.1154580.

Cummings C.A., Todhunter P.E., Rundquist B.C. 2012. Using the Hazus-MH flood model to evaluate community relocation as a flood mitigation response to terminal lake flooding: The case of Minnewaukan, North Dakota, USA. Applied Geography. Vol. 32. Iss. 2 p. 889–895. DOI 10.1016/j.apgeog.2011.08.016.

Downing J.A., Duarte C.M. 2009. Abundance and size distribution of lakes, ponds and impoundments. In: Encyclopedia of Inland Waters. 469–478. DOI 10.1016/B978-012370626-3.00025-9.

Dutta N., Choudhury K.D., Nath S.S., Choudhury M.D. 2019. The water–level dependent inventory model developed to the reference of Sonbeel lake. Bulletin of Pure & Applied Sciences–Mathematics and Statistics. Vol. 38. Iss. 2 p. 615–624. DOI 10.5958/2320-3226.2019.00062.6.

Fearnside P.M. 2016. Environmental and social impacts of hydroelectric dams in Brazilian Amazonia: Implications for the aluminum industry. World Development. Vol. 77 p. 48–65. DOI 10.1016/j.worlddev.2015.08.015.

Finkl C., Vollmer H.M. 2016. Methods for investigating sediment flux under high-energy conditions on the Southeast Florida Continental Shelf using Laser Airborne Depth Sounding (LADS) in a Geographic Information System (GIS) Dataframe. Journal of Coastal Research. Vol. 33. Iss. 2 p. 452–462. DOI 10.2112/JCOASTRES-D-16A-00014.1.

Forfinski N., Parrish C. 2016. ICESat-2 bathymetry: An empirical feasibility assessment using MABEL. In: Remote Sensing of the ocean, sea ice, coastal waters, and large water regions. International Society for Optics and Photonics. Eds. Ch.R. Bostater Jr., S.P. Mertikas, X. Neyt, C. Nichol, O. Aldred. Vol. 9999 p. 999904. DOI 10.1117/12.2241210.

Garambois P.A., Calmant S., Roux H., Paris A., Monnier J., Finaud-Guyo, P., … Santos da Silva J. 2017. Hydraulic visibility: Using satellite altimetry to parameterize a hydraulic model of an ungauged reach of a braided river. Hydrological Processes. Vol. 31. Iss. 4 p. 756–767. DOI 10.1002/hyp.11033.

Georgiou S., Shepherd A., McMillan M., Nienow P. 2009. Seasonal evolution of supraglacial lake volume from aster imagery. Annals of Glaciology. Vol. 50. Iss. 52 p. 95–100. DOI 10.3189/172756409789624328.

Graf W. 1999. Dam nation: A geographic census of American dams and their large-scale hydrologic impacts. Faculty Publications. Vol. 35. Iss. 4 p. 1305–1311. DOI 10.1029/1999WR900016.

Hansen M., DeWitt N. T., Reynolds B.J., Links S. 2017. Archive of bathymetry data collected in South Florida from 1995 to 2015. (No. 1031). Geological Survey Data Series 1031. DOI 10.3133/ds1031.

Heathcote A.J., del Giorgio P. A., Prairie Y.T., Brickman D. 2015. Predicting bathymetric features of lakes from the topography of their surrounding landscape. Canadian Journal of Fisheries and Aquatic Sciences. Vol. 72. Iss. 5 p. 643–650. DOI 10.1139/cjfas-2014-0392.

Hollister J., Milstead W.B. 2010. Using GIS to estimate lake volume from limited data. Lake and Reservoir Management. Vol. 26. Iss. 3 p. 194–199. DOI 10.1080/07438141.2010.504321.

Ivanoski D., Trajkovic S., Gocic M. 2019. Estimation of sedimentation rate of Tikvesh Reservoir in Republic of Macedonia using SWAT. Arabian Journal of Geosciences. Vol. 12. Iss. 14 p. 1–15. DOI 10.1007/s12517-019-4583-x.

Khan S. I., Hong Y., Wang J., Yilmaz K.K., Gourley J.J., Adler R.F., …, Irwin D. 2011. Satellite remote sensing and hydrologic modeling for flood inundation mapping in Lake Victoria basin: Implications for hydrologic prediction in ungauged basins. IEEE Transactions on Geoscience and Remote Sensing. Vol. 49. Iss. 1 p. 85–95. DOI 10.1109/TGRS.2010.2057513.

Khlifi S., Ameur M., Mtimet N., Ghazouani N., Belhadj N. 2010. Impacts of small hill dams on agricultural development of hilly land in the Jendouba region of northwestern Tunisia. Agricultural Water Management. Vol. 97. Iss. 1 p. 50–56. DOI 10.1016/j.agwat.2009.08.010.

Krawczynski M.J., Behn M.D., Das S.B., Joughin I. 2009. Constraints on the lake volume required for hydro-fracture through ice sheets. Geophysical Research Letters. Vol. 36. Iss. 10 p. 1–5. DOI 10.1029/2008GL036765.

Lü Y., Sun R., Fu B., Wang Y. 2012. Carbon retention by check dams: Regional scale estimation. Ecological Engineering. Vol. 44 p. 139–146. DOI 10.1016/j.ecoleng.2012.03.020.

Mihu-Pintilie A., Romanescu G., Stoleriu C., Nicu I.C. 2014. Natural dam lakes from Cuejdiu watershed (Stânișoarei Mountains) – non-invasive methods used for bathymetric maps. In: Water resources and wetlands. Tulcea, Romania. Vol. 2 p. 130–137.

Ming J., Xian-guo L., Lin-shu X., Li-juan C., Shouzheng T. 2007. Flood mitigation benefit of wetland soil – A case study in Momoge National Nature Reserve in China. Ecological Economics. Vol. 61. Iss. 2–3 p. 217–223. DOI 10.1016/j.ecolecon.2006.10.019.

Moknatian M., Piasecki M. 2020. Lake volume data analyses: A deep look into the shrinking and expansion patterns of Lakes Azuei and Enriquillo, Hispaniola. Hydrology. Vol. 7(1), 1 pp. 22. DOI 10.3390/hydrology7010001.

Molden D., Oweis T., Steduto P., Bindraban P., Hanjra M.A., Kijne J. 2010. Improving agricultural water productivity: Between optimism and caution. Agricultural Water Management. Vol. 97(4) p. 528–535. DOI 10.1016/j.agwat.2009.03.023.

Mushtaq S., Dawe D., Lin H., Moya P. 2006. An assessment of the role of ponds in the adoption of water-saving irrigation practices in the Zhanghe irrigation system, China. Agricultural Water Management. Vol. 83(1–2) p. 100–110. DOI 10.1016/j.agwat.2005.10.004.

Napoli M., Cecchi S., Orlandini S., Zanchi C.A. 2014. Determining potential rainwater harvesting sites using a continuous runoff potential accounting procedure and GIS techniques in central Italy. Agricultural Water Management. Vol. 141 p. 55–65. DOI 10.1016/j.agwat.2014.04.012.

Palmer M.A., Reidy Liermann C.A., Nilsson C., Flörke M., Alcamo J., Lake P.S., Bond N. 2008. Climate change and the world's river basins: Anticipating management options. Frontiers in Ecology and the Environment 6 Frontiers in Ecology and the Environment. Vol. 6. Iss. 2 p. 81–89. DOI 10.1890/060148.

Pistocchi A., Pennington D. 2006. European hydraulic geometries for continental SCALE environmental modelling. Journal of Hydrology. Vol. 329. Iss. 3–4 p. 553–567. DOI 10.1016/j.jhydrol.2006.03.009.

Piton G., Recking A. 2017. Effects of check dams on bed-load transport and steep-slope stream morphodynamics. Geomorphology. Vol. 291 p. 94–105. DOI 10.1016/j.geomorph.2016.03.001.

Pokhrel Y.N., Hanasaki N., Yeh P.J.F., Yamada T.J., Kanae S., Oki T. 2012. Model estimates of sea-level change due to anthropogenic impacts on terrestrial water storage. Nature Geoscience. Vol. 5. Iss. 6 p. 389–392. DOI 10.1038/ngeo1476.

Polissar P.J., Freeman K.H. 2010. Effects of aridity and vegetation on plant-wax δD in modern lake sediments. Geochimica et Cosmochimica Acta. Vol. 74. Iss. 20 p. 5785–5797. DOI 10.1016/j.gca.2010.06.018.

Preti F., Guastini E., Penna D., Dani A., Cassiani G., Boaga J., …, Tarolli P. 2017. Conceptualization of water flow pathways in agricultural terraced landscapes. Land Degradation & Development. Vol. 29. Iss. 3. DOI 10.1002/ ldr.2764.

Rădoane M., Rădoane N. 2005. Dams, sediment sources and reservoir silting in Romania. Geomorphology. Vol. 71. Iss. 1–2 p. 112–125. DOI 10.1016/j.geomorph.2004.04.010.

Roddewig M.R., Churnside J.H., Hauer F.R., Williams J., Bigelow P.E., Koel T.M., Shaw J.A. 2018. Airborne LiDAR detection and mapping of invasive lake trout in Yellowstone Lake. Applied Optics. Vol. 57. Iss. 15 p. 4111–4116. DOI 10.1364/AO.57.004111.

Schmitt T., Mitchell N.C., Ramsay A.T.S. 2008. Characterizing uncertainties for quantifying bathymetry change between time-separated multibeam echo-sounder surveys. Continental Shelf Research. Vol. 28. Iss. 9 p. 1166–1176. DOI 10.1016/j.csr.2008.03.001.

Schweizer S., Pini Prato E. 2003. Sistemazione idraulica e variazione della diversità degli habitat fluviali: un approccio comparativo [Hydraulic arrangement and variation of the diversity of river habitats: a comparative approach]. Biologia Ambientale. Vol. 17. Iss. 2 p. 31–38.

Shelke S., Balan S. 2017. Analysis of bathymetry data for shape prediction of a reservoir. In: Proceedings of the International Conference on Data Engineering and Communication Technology. Eds. S. Chandra Satapathy, V. Bhateja, A. Joshi. Singapore. Springer p. 89–95.

Sherstyankin P.P., Alekseev S.P., Abramov A.M., Stavrov K.G., de Batist M., Hus R., …, Casamor J.L. 2006. Computer-based bathymetric map of Lake Baikal. Doklady Earth Sciences. Vol. 408. Iss. 1 p. 564–569. DOI 10.1134/S1028334X06040131.

Sima S., Tajrishy M. 2013. Using satellite data to extract volume–area–elevation relationships for Urmia Lake, Iran. Journal of Great Lakes Research. Vol. 39. Iss. 1 p. 90–99. DOI 10.1016/j.jglr.2012.12.013.

Socci P., Errico A., Castelli G., Penna D., Preti F. 2019. Terracing: From agriculture to multiple ecosystem services. In: Oxford Research Encyclopedia of Environmental Science p. 1–33.

Stürck J., Poortinga A., Verburg P.H. 2014. Mapping ecosystem services: The supply and demand of flood regulation services in Europe. Ecological Indicators. Vol. 38 p. 198–211. DOI 10.1016/j.ecolind.2013.11.010.

Stumpf R.P., Holderied K. 2003. Determination of water depth with high-resolution satellite imagery over variable bottom types. Limnology and Oceanography. Vol. 48 p. 547–556. DOI 10.4319/lo.2003.48.1_part_2.0547.

Tedesco M., Steiner N. 2011. In-situ multispectral and bathymetric measurements over a supraglacial lake in western Greenland using a remotely controlled watercraft. Cryosphere. Vol. 5. Iss. 2 p. 445–452. DOI 10.5194/tc-5-445-2011.

Tilt B., Braun Y., He D. 2009. Social impacts of large dam projects: A comparison of international case studies and implications for best practice. International Journal of ChemTech Research. Vol. 90(S) p. 249–257. DOI 10.1016/j.jenvman.2008.07.030.

Torres-Batlló J., Martí-Cardona B., Pillco-Zolá R. 2020. Mapping evapotranspiration, vegetation and precipitation trends in the catchment of the shrinking Lake Poopó. Remote Sensing. Vol. 12. Iss. 1, 73.

Tullos D., Brown P.H., Kibler K., Magee D., Tilt B., Wolf A.T. 2010. Perspectives on the salience and magnitude of dam impacts for hydro development scenarios in China. Water Alternatives. Vol. 3. Iss. 2 p. 71–90.

van Bemmelen C.W.T., Mann M., de Ridder M. P., Rutten M.M., van de Giesen N.C. 2016. Determining reservoir characteristics with global elevation data. Geophysical Research Letters. Vol. 43. Iss. 21, 11 p. 278–286. DOI 10.1002/2016GL069816.

Verstraeten G., Poesen J. 2000. Estimating trap efficiency of small reservoirs and ponds: Methods and implications for the assessment of sediment yield. Progress in Physical Geography. Vol. 24. Iss. 2 p. 219–251. DOI 10.1177/ 030913330002400204.

Verstraeten G., Poesen J. 2002. Using sediment deposits in small ponds to quantify sediment yield from small catchments: Possibilities and limitations. Earth Surface Processes and Landforms. Vol. 27. Iss. 13 p. 1425–1439. DOI 10.1002/esp.439.

Wang Y., Li Z., Tang Z., Zeng G. 2011. A GIS-based spatial multi-criteria approach for flood risk assessment in the Dongting Lake Region, Hunan, Central China. Water Resources Management. Vol. 25. Iss. 13 p. 3465–3484. DOI 10.1007/s11269-011-9866-2.

Watson K.B., Ricketts T., Galford G., Polasky S., O'Niel-Dunne J. 2016. Quantifying flood mitigation services: The economic value of Otter Creek wetlands and floodplains to Middlebury, VT. Ecological Economics. Vol. 130 p. 16–24. DOI 10.1016/j.ecolecon.2016.05.015.

Yang S., Chiang M., Chang C., Lin Y., Chien C., Kao I., Chang L. 2019. Building an intelligent reservoir operation decision support system for flood and sedimentation control. [3rd International Workshop on Sediment Bypass Tunnels]. [9–12.04.2019 Tampei-Tai].

Zhang B., Wu Y., Zhu L., Wang J., Li J., Chen D. 2011. Estimation and trend detection of water storage at Nam Co Lake, central Tibetan Plateau. Journal of Hydrology. Vol. 405. Iss. 1–2 p. 161–170. DOI 10.1016/j.jhydrol.2011.05.018.

Zhang Y., Zhang Z., Xue S., Wang R., Xiao M. 2020. Stability analysis of a typical landslide mass in the Three Gorges Reservoir under varying reservoir water levels. Environmental Earth Sciences. Vol. 79. Iss. 1, 42. DOI 10.1007/s12665-019-8779-x.

Zolina O., Simmer C., Belyaev K., Gulev S.K., Koltermann P. 2013. Changes in the duration of European wet and dry spells during the last 60 years. Journal of Climate. Vol. 26(6) p. 2022–2047. DOI 10.1175/JCLI-D-11-00498.1.