

# Vindšachta Water Reservoir – Using GIS Tools for a Comparison of Storage Capacity in 1887 and 2014

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**Abstract.** This article focuses on an analysis of the storage capacity of Vindšachta water reservoir in Štiavnické Bane, Banská Štiavnica district, at two points in time: 1887 (old) and 2014 (current). The analysis was performed using an old bathymetry map dated 1887 and current data from sonar surveying (2014). The analysis was performed by comparing water volumes calculated from digital elevation models of the reservoir bottom for each year, using an area-storage capacity curve. During the period between the two years, the water volume decreased to 85% of the initial storage capacity (from 335 000 m<sup>3</sup> to 285 000m<sup>3</sup>).

**Keywords:** water volume change, GIS, sonar surveying, old maps

## 1 Introduction

The study focuses on an assessment of current water storage capacity and water surface area in 2014, comparing it with the status in 1887, using an area-storage capacity curve and the creation of bottom profiles for potential further use in a CAD environment, for the purposes of designing and maintaining the water reservoir. This analysis was performed at Vindšachta old artificial water reservoir in the district of Banská Štiavnica, Slovakia.

The topic of water reservoir bottom morphology mapping is currently of interest worldwide (Childs et al., 2003; Boddy and Ganske, 2005; Jordan et al., 2005; Kress et al., 2005; Ceylan et al., 2011) and also in Slovakia (Pauk, 1997; Kočický et al., 2002). Mapping of a water reservoir bottom can be performed with a set of various methods

based on echo-sounding data collection to provide bottom elevation and depth data. Processing the data can be performed in a GIS environment to obtain models of the water reservoir bottom in raster format (Childs et al., 2003; Elçi et al., 2009) or vector TIN model format (Cross and Moore, 2014). Visualization of the water reservoir bottom morphology can be performed using an elevation map or depth map, or it can be described using cross-sections (Ceylan et al., 2011; Fуска and Bárek, 2015).

Water reservoir management requires data on siltation development, regular updating of bathymetry data and also the identification of negative development trends and proposed countermeasures. A change in the water storage capacity or assessment of the current water volume in general is necessary for various water management purposes in relation to the water reservoir (Cross and Moore, 2014).

# Umjetno jezero Vindšachta – Primjena GIS-a za usporedbu kapaciteta 1887. i 2014. godine

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**Sažetak.** U radu se analizira kapacitet umjetnog jezera Vindšachta u mjestu Štiavnické Bane u okrugu Banská Štiavnica, u dvama navratima: 1887. (povijesno stanje) i 2014. (trenutno stanje). Analiza je provedena upotrebom stare batimetrijske karte iz 1887. i podataka izmjere sonarom 2014. godine. Uspoređeni su volumeni vode izračunani iz digitalnih modela dna jezera za svaku godinu, upotrebom krivulje kapaciteta u odnosu na površinu. Volumen vode smanjio se na 85% početnog kapaciteta (s 335 000 m<sup>3</sup> na 285 000 m<sup>3</sup>).

**Ključne riječi:** promjena volumena vode, GIS, izmjera sonarom, stare karte

## 1. Uvod

Tema ovog istraživanja je procjena trenutnog kapaciteta i površine vode u 2014. te usporedba sa stanjem iz 1887. upotrebom krivulje kapaciteta u odnosu na površinu i izradom profila dna u svrhu potencijalne buduće upotrebe tih podataka pri održavanju umjetnog jezera upotrebom CAD-a. Istraživanje je provedeno na povijesnom umjetnom jezeru Vindšachta u okrugu Banská Štiavnica u Slovačkoj.

Kartiranjem morfologije dna umjetnih jezera bave se mnogi u svijetu (Childs i dr., 2003; Boddy i Ganske, 2005; Jordan i dr., 2005; Kress i dr., 2005; Ceylan i dr., 2011), kao i u Slovačkoj (Pauk, 1997; Kočický i dr., 2002). Kartiranje dna jezera može se provesti različitim metodama koje se temelje na prikupljanju podataka sonarom kako bi se

dobili podaci o obliku dna i dubini. Podaci se mogu obraditi GIS-om kako bi se dobili modeli dna jezera u raster-skom obliku (Childs i dr., 2003; Elçi i dr., 2009) ili vektorskom formatu TIN (Cross i Moore, 2014). Vizualizacija morfologije dna jezera može se provesti upotrebom karte visina ili dubina ili se pak može opisati upotrebom presjeka (Ceylan i dr., 2011; Fuska i Bárek, 2015).

Upravljanje umjetnim jezerom zahtjeva podatke o zagađenju muljem, redovito ažuriranje batimetrijskim podacima te utvrđivanje negativnih trendova razvoja i predlaganje protumjera. Promjena kapaciteta vode ili procjena trenutnog volumena vode općenito su potrebni za različite svrhe upravljanja vodom u jezeru (Cross i Moore, 2014).

Kapacitet umjetnog jezera i površina vode na određenoj razini mogu se opisati krivuljom kapaciteta s

A description of water reservoir storage capacity and water surface area at a given water level elevation can be provided using an area-storage capacity curve (Issa et al., 2015). Other authors refer to this method as an ‘area and capacity curve’ (U.S. Bureau of Reclamation, 1987), or ‘elevation-area and elevation-capacity curves’ (U.S. Department of the Interior, 2001). In Slovakia, the term ‘bathygraphic curve’ is generally used. An area-storage capacity curve can be presented in table or graph form.

The calculation of the water surface area and water storage capacity (water volume) for each part of the area-storage capacity curve is based on the prismatic calculation method. The process consists of calculating partial volumes of water between two contours; partial volume is calculated from the average contour area (upper and lower contours of the section of water depth examined) multiplied by the elevation difference of those contours {Equation 1}. The contour area can be obtained by planimetry (for paper maps), GIS, or CAD using a contour map. The total water volume up to the required water level elevation is calculated as the sum of partial volumes up to the required water level elevation {2} (Jurík et al., 2011).

$$v_{n,partial} = \frac{S_{n-1} + S_n}{2} \Delta H = S_{average} \Delta H [m^3] \quad \{1\}$$

$$v_{n,total} = \sum_{n=1}^i v_{n,partial} [m^3] \quad \{2\}$$

Calculation of the water volume can also be performed using a water reservoir bottom DEM, where the calculation of the water depth map involves subtracting the reservoir bottom elevation from the water level elevation (Írvem, 2011). This principle was also used to calculate Vindšachta water reservoir’s area-storage capacity curve, but the process was automatized by using a script to provide a fast and accurate way of analysing the GeoTIFF DEM of the water reservoir bottom.

## 2 Materials and Methods

### 2.1 Development of the Water Reservoir Bottom

The storage capacity of water reservoirs constantly changes as the result of various processes that affect the reservoir bottom. Erosion processes that occur in the watershed cause the siltation of water reservoirs (Halaj et al., 2013). Siltation is estimated to cause 0.5-1.0% annual loss of reservoir capacity (White, 2010). Erosion and particle transfer are functions of soil type and are affected strongly by the soil water regime (Igaz et al., 2012). Water reservoir bank erosion caused by wind-driven waves leads to shore erosion (Pelikán and Šlezinger, 2015).

Pánek et al. (2007) states that landslides carrying debris also play an important role. These processes and sediment accumulation cause a wide range of negative effects, the most significant being the loss of usable volume and storage capacity, gradual siltation and damage to the outlet structures (monks or pipelines) and effects on the biota and ecological water quality (Ahmed and Sanchez 2011, Pradhan et al. 2011). However, pollution caused by various human activities is far more dangerous to the environment (Policht-Latawiec et al., 2015) as sediments ultimately contaminate the reservoir with many potential chemical and biological substances from urban, agricultural and industrial land (Apitz et al., 2005). These changes may induce significant negative impacts on the use of water reservoirs (Marková and Hubáčiková, 2015).

### 2.2 Study Area

Vindšachta water reservoir is located near Štiavnic-ké Bane village, in the district of Banská Štiavnica, Slovak Republic (Fig. 1). With other reservoirs in the region, it is inscribed in the UNESCO World Heritage List as a technical monument in a mining area (“Historic Town of Banská Štiavnica and the Technical Monuments in its Vicinity”). Construction work began on 21 July 1712. The dam crest is 237 m long, 15.2 m high, and 13.5 m wide, while the water surface area is 46,800 m<sup>2</sup> (Hydroconsult, 1991). Vindšachta is the largest reservoir in the reservoir cascade system (Bakomi – Vindšachta – Evička). It currently functions as a facility for leisure activities and carp fishing, and is also used by the Slovak Fishing Union (Hydroconsult, 1991).

### 2.3 Input Data from 1887

Conditions in 1887 are documented in the map “Calculation of the water volume of Lake Vindšachta” created by János Tezényi under the supervision of mining engineer József Tizshez, from a field survey performed in 1887 (Tirscher and Tezényi, 1887). This map in the scale 1:1000 was scanned with 600 dpi resolution. The contours were semi-automatically vectorised in R2V software (R2V User’s Manual, 2008), and elevation was added as an attribute of each contour. A correction of the elevation system from the Adriatic to the Baltic elevation system,  $H_{Balt.} = H_{Adriat.} - 0.41$  m, was required. For Slovakia, the elevation difference is between -0.40 and -0.42 m, due to the greater disproportion between old and modern surveying (Pravda and Kusendová, 2007). Later, the vector was georegistered to the S-JTSK coordinate system in ArcMAP 10.2 (Fig. 2), using identical points from orthophotomaps made by Eurosense in 2006 and

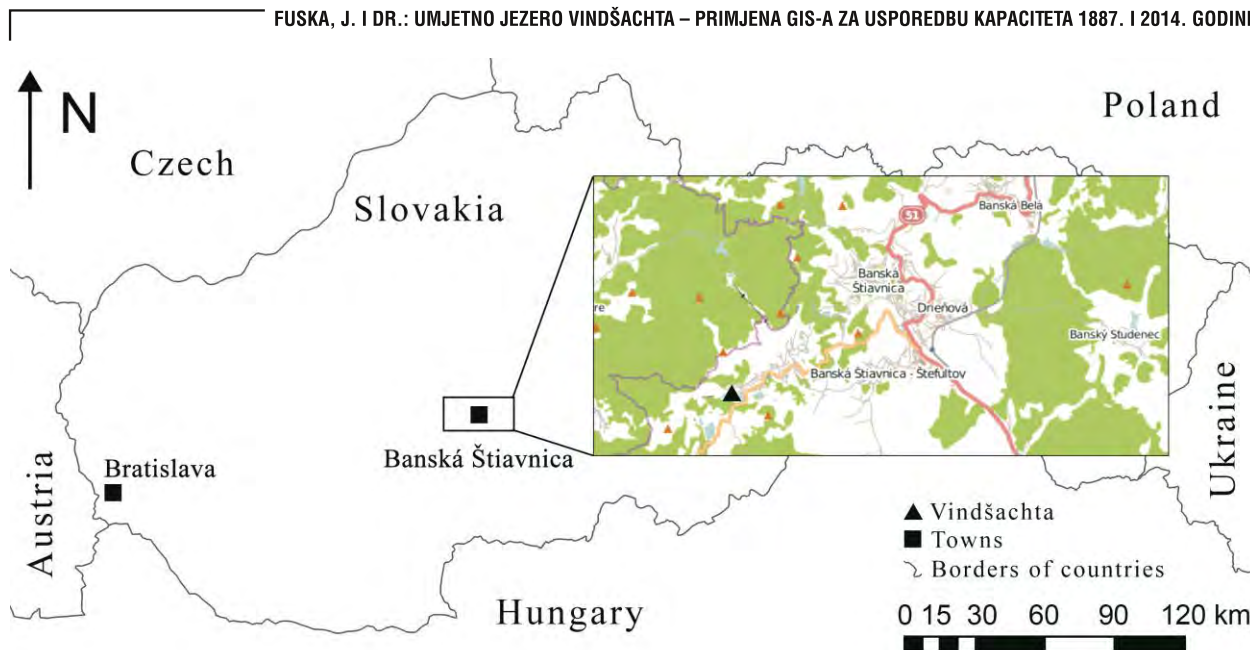


Fig. 1 Location of Vindšachta water reservoir

Slika 1. Položaj spremnika za vodu Vindšachta

obzirom na površinu (area-storage capacity curve, Issa i dr., 2015). Drugi autori tu metodu nazivaju krivuljom površine i kapaciteta (area and capacity curve, U.S. Bureau of Reclamation, 1987) ili krivuljama visina-površina i visina-kapacitet (elevation-area and elevation-capacity curves, U.S. Department of the Interior, 2001). U Slovačkoj se obično upotrebljava termin bati-grafska krivulja. Ta se krivulja može prikazati tablično ili grafički.

Računanje površine vode i kapaciteta jezera (volumena vode) za svaki dio krivulje kapaciteta s obzirom na površinu temelji se na metodi računanja prizmi. Postupak se sastoji od računanja djelomičnih volumena vode između dviju izobata; djelomični volumen računa se iz srednje površine izobata (gornje i donje izobate dijela dubine koji se istražuje) pomnoženog s razlikom dubina tih dviju izobata {1}. Površina izobata može se dobiti planimetrijski (za papirnate karte), ili s pomoću GIS-a ili CAD-a upotrebom karte s izobatama.

Ukupni volumen vode do potrebne razine vode izračunava se kao zbroj djelomičnih volumena do potrebne razine vode {2} (Jurík i dr., 2011).

$$v_{n,partial} = \frac{S_{n-1} + S_n}{2} \Delta H = S_{average} \Delta H [m^3] \quad \{1\}$$

$$v_{n,total} = \sum_{n=1}^i v_{n,partial} [m^3] \quad \{2\}$$

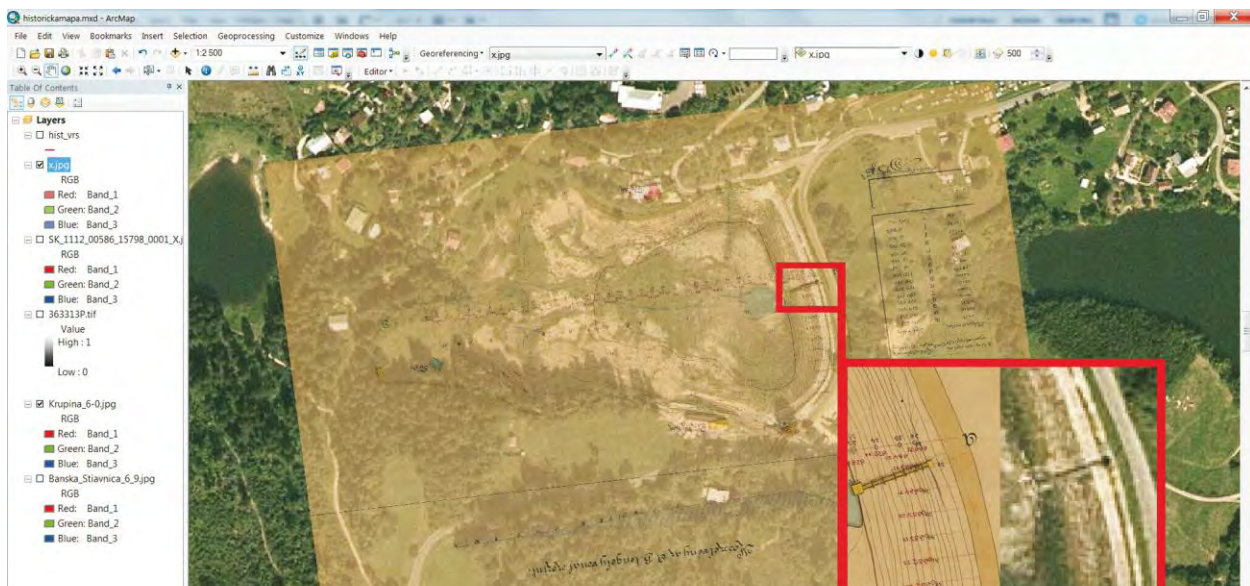
Volumen vode može se izračunati i s pomoću digitalnog modela dna, pri čemu računanje dubine vode znači oduzimanje visine dna od visine vode (Irvem,

2011). Taj je princip primijenjen pri računanju krivulje kapaciteta u odnosu na površinu jezera Vindšachta, no postupak je automatiziran skriptom za brzo i točno analiziranje digitalnog modela dna jezera u spremljenog u formatu GeoTIFF.

## 2. Materijali i metode

### 2.1. Razvoj dna umjetnog jezera

Kapacitet umjetnog jezera neprestano se mijenja zbog različitih procesa koji utječu na njegovo dno. Erozija u slivu dovodi do zagađenja muljem jezera (Halaj i dr., 2013). Procjenjuje se da zagađenje muljem svake godine smanjuje kapacitet umjetnih jezera za 0,5–1,0% (White, 2010). Erozija i prijenos čestica ovise o tipu zemlje i na njih uvelike djeluje režim vode u tlu (Igaz i dr., 2012). Erozija nasipa uzrokovana valovima zbog vjetera dovodi do erozije obale jezera (Pelikán i Šlezinger, 2015). Prema Páneku i dr. (2007), važnu ulogu igraju i nanosi tla uzrokovani klizištima. Ti procesi i nagomilavanje sedimenta imaju različite negativne učinke, od kojih je najvažniji gubitak upotrebljivog volumena i kapaciteta, postupno zagađenje muljem i oštećenje struktura (izljeva ili cjevovoda) te posljedice na biote i ekološku kvalitetu vode (Ahmed i Sanchez 2011, Pradhan i dr. 2011). Međutim, za okoliš je daleko opasnije zagađenje uzrokovano ljudskim djelatnostima (Policht– Latawiec i dr., 2015) jer sedimenti naposljetku zagađuju jezero mnogim potencijalnim kemijskim i biološkim tvarima iz gradskog, poljoprivrednog i industrijskog zemljišta (Apitz i dr., 2005). Takve promjene mogu ostaviti velike



**Fig. 2** Vectorised old contour map in ArcMAP 10.2

**Slika 2.** Vektorizirane izohipse sa stare karte u programu ArcMAP 10.2

GCPs surveyed with the Global Navigation Satellite System (GNSS) Leica GS12 receiver in RTK kinematic mode. The achievable accuracy of the receiver in this mode is 10 mm + 1 ppm (rms) horizontally, and 20 mm + 1 ppm (rms) vertically (Leica Viva GNSS GS12 receiver Datasheet).

Further analysis showed that the old map contour data were incorrect, as the maximum water level elevation on the map was 686.7 m above sea level (ASL), but the true water level elevation surveyed as the elevation of the safety spillway was 688.4 m ASL. The elevation of the spillway crest is the same as at the time of the reservoir construction (Tirscher and Tezényi, 1887) so we presume that the old contours elevation contains an overall error. It was corrected by subtracting the water level elevation difference (1.70 m) from each contour elevation. Then, the contour vertices were extracted to obtain the point data. The old shoreline was reconstructed from the contour plan. This kind of error and means of dealing with it were similar to the research performed at the water reservoir in Golianovo, Slovak Republic (Fuska et al., 2014).

#### 2.4 Input Data for the Current State

The data collection (Figure 2) for Vindšachta's current bottom morphology was completed by the authors on 3 September 2014 according to the methodology for analysing and evaluating Ružín water reservoir (Pauk et al., 1997) and Klenovec water reservoir (Kočícký et al., 2002). This methodology was replicated for other reservoirs in the Banská Štiavnica region – Halčiansky reservoir (Weis and Kubinský, 2014), the Large Kolpášsky reservoir (Kubinský et al., 2014b), the Large and Small

Richňavská reservoirs (Kubinský et al., 2013 and Kubinský et al., 2014a), and reservoirs in other parts of the world (Ceylan et al., 2011). This survey meets international standards for hydrographic surveying (Manual of Hydrography, 2005).

Collection of bottom points coordinates was performed by a GNSS receiver and echo sounder mounted to the boat and fixed with a set of ropes to ensure the echo sounder and GNSS pole were perpendicular to the water level (Manual of Hydrography, 2005). Position data were obtained using a Leica GS12 receiver in RTK kinematic mode. Depth measurement was done using a Garmin echo sounder GPSmap 421s with a 200 kHz dual beam probe; the sonar probe was mounted on the GNSS receiver pole with a distance of 150 mm between the GNSS pole tip and the sonar probe. Sonar data was sent via cable as an NMEA sentence and stored in "Annotation" column for each point.

The boat traversed the reservoir in a set of parallel routes with 10 m between the routes. Position data were captured automatically every 2 m (3149 points were collected during surveying). The water level elevation on the day of sonar surveying was measured using GNSS at 688.368 m ASL.

The survey work was imported to Leica Geo Office where the survey data was loaded in MS Excel to process it to XYZ-coordinates of points on the reservoir bottom. From the full set of points, we removed those that had an estimated 3D accuracy less than 50 mm, and those with missing depth data (errors in communication between the GNSS receiver and sonar) were also removed, to ensure that only high quality data would be used for further processing.



Fig. 3 Data collection in boat (photo: Kubinský)

Slika 3. Prikupljanje podataka u čamcu (fotografija: Kubinský)

negativne posljedice na upotrebu umjetnog jezera (Marková and Hubačiková, 2015).

## 2.2. Područje istraživanja

Umjetno jezero Vindšachta nalazi se u selu Štiavnic-ké Bane u okrugu Banská Štiavnica u Slovačkoj (Slika 1). To i ostala umjetna jezera na tom području dio su svjetske baštine UNESCO-a kao tehnički spomenici u rudarskom području (Povijesni grad Banská Štiavnica i tehnički spomenici u njegovoj blizini). Izgradnja tog jezera počela je 21. srpnja 1712. Kruna brane dugačka je 237 m, visoka 15,2 m i široka 13,5 m, pri čemu površina vode iznosi 46 800 m<sup>2</sup> (Hydroconsult, 1991). Vindšachta je najveće jezero u kaskadnom sustavu jezera (Bakomi – Vindšachta – Evička). Trenutačno se upotrebljava za razonodu i pecanje šarana, a služi i Slovačkom ribolovnom savezu (Hydroconsult, 1991).

## 2.3. Ulazni podaci iz 1887.

Podaci iz 1887. zabilježeni su na karti “Računanje volumena vode jezera Vindšachta” što ju je izradio János Tezényi pod nadzorom rudarskog inženjera Józsefa Tizsheza na terenskoj izmjeri 1887. (Tirscher i Tezényi, 1887). Ta je karta u mjerilu 1:1000 skenirana u razlučivosti od 600 točaka po inču. Izohipse/izobate su vektorizirane poluautomatski upotrebom programa R2V (R2V User’s Manual, 2008), a visine su dodane kao atribut svakoj izohipsi. Bilo je potrebno obaviti konverziju visina iz Jadranskog u Baltički sustav visina,  $H_{\text{Balt.}} = H_{\text{Adriat.}} - 0,41$  m. U Slovačkoj je ta razlika visina između -0,40 i -0,42 m zbog razlika između stare i suvremene izmjere (Pravda i

Kusendová, 2007). Kasnije su ti vektorski podaci georeferencirani u koordinatni sustav S-JTSK u programu ArcMAP 10.2 (slika 2) upotrebom identičnih točaka iz ortofotokarata koje je izradio Eurosense 2006. i kontrolnih točaka izmjerenih upotrebom prijmnika Global Navigation Satellite System (GNSS) Leica GS12 u načinu rada RTK. U tom načinu rada točnost prijmnika doseže 10 mm + 1 ppm (rms) horizontalno i 20 mm + 1 ppm (rms) vertikalno (Leica Viva GNSS GS12 receiver Datasheet).

Daljnja analiza je pokazala da su podaci o izohipsama sa stare karte netočni zato što je najviša razina vode na karti bila 686,7 m nadmorske visine, a izmjerena razina vode sigurnosnog preljeva na brani bila je 688,4 m nadmorske visine. Razina krune preljeva na brani bila je jednaka onoj u vrijeme kad je jezero izgrađeno (Tirscher and Tezényi, 1887), pa pretpostavljamo da stare visine izohipsi sadrže pogrešku. Ta je pogreška ispravljena oduzimanjem razlike razine vode (1,70 m) od svake visine izohipse. Tada su točke linija koje prikazuju izohipse izdvojene kako bi se dobili točkasti podaci. Povijesna obalna linija rekonstruirana je iz izohipsi. Opisana pogreška i način njezina ispravljanja slični su onima u istraživanju na jezeru u Golianovom u Slovačkoj (Fuska i dr., 2014).

## 2.4. Ulazni podaci za 2014.

Autori su prikupili podatke (slika 2) o trenutnoj morfologiji dna jezera Vindšachta 3. rujna 2014. u skladu s metodologijom analiziranja i procjene jezera Ružín (Pauk i dr., 1997) i Klenovec (Kočícký i dr., 2002). Ta je metodologija primijenjena i na druga jezera u regiji

All points were then loaded in ArcMAP and later, the number of points was manually reduced to keep only those in a grid approximately  $10 \times 10$  m, to maintain the regularity of the network and eliminate erroneous points, creating a relevant and spatially homogeneous dataset with density comparable in both directions. We collected points automatically every 2 metres during sailing, to make sure there would be enough points to formulate the approximate regular distribution  $10 \times 10$  m in both directions (10 m between sailing routes and 10 m of points in one sailing line). The current shoreline was outlined from the orthophotomap with the elevation of the safety spillway surveyed during fieldwork.

## 2.5 Calculation of Reservoir Volume

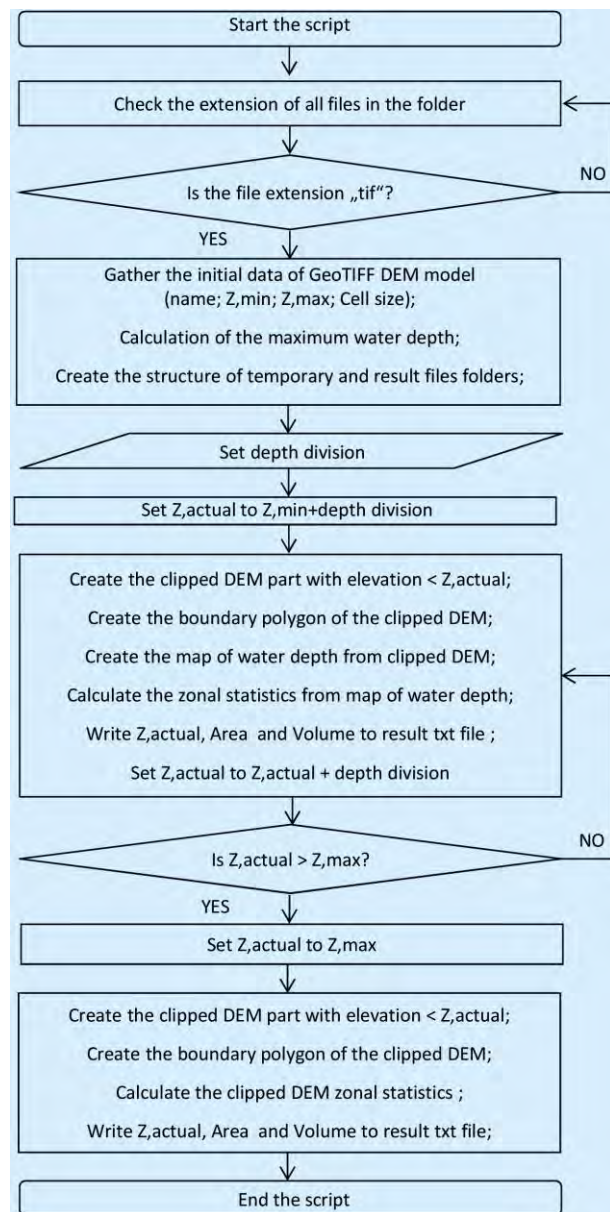
The 1887 and 2014 reservoir bottom raster digital elevation models (DEM) were created using the “*Topo to raster*” tool and both models were generated with a cell size of  $1 \times 1$  m, while polygons of the shoreline for both years were used as the DEM boundary. This interpolation method creates hydrologically correct, very smooth models of the terrain, which is important for valley reservoirs such as Vindšachta that were created by damming a natural valley. Even the reservoir bottom can be affected by siltation, while the emptying of this reservoir has created a network of channels and ridges that can usually be seen in elevation models (Fuska, Kubinský and Lenárt, 2014). Users of digital elevation models must be aware of their main characteristics in order to assess their suitability for a specific application (Varga and Bašić, 2013).

Calculation of the reservoir volume was executed by a new method using the Python script developed by the authors with the ArcPy site-package, which creates a water depth map for each water level elevation examined and calculates the water volume and water surface area automatically using a zonal statistics tool. The script gathers the metadata (min. and max. elevation) from the GeoTIFF DEM of the reservoir bottom and allows the user to input the required division of total water depth.

This method uses calculation of the water volume and water surface area for any required range of water depth division from the water depth map derived from the reservoir bottom DEM. This is a new approach to calculating the area-storage capacity curve, as it is not bound to the creation of a contour map to produce a calculation using the prismatic method {1 and 2}, but automatically processes the input DEM of the water reservoir bottom with the required water depth division interval.

The script has been built as stand-alone script that must be stored in the same folder as the GeoTIFF DEM of the reservoir bottom, and can be run from the basic

Python IDLE window. The process starts with an analysis of the files in the working folder where the script file is stored. After the script finds the GeoTIFF file of the reservoir bottom DEM, it gathers the name of the file, maximum and minimum elevation and cell size. Then it calculates the maximum water depth by subtracting minimum elevation from maximum elevation and prompts the user to set the depth division interval. The calculation process is used to calculate the parameters for the depths that are increased for the depth division interval. For example, if the water depth is 3.4 m and the water depth interval is set to 1 m, the script calculates the parameters for depths of 1 m, 2 m, 3 m and ends with 3.4



**Fig. 4** Calculating the area-storage capacity curve from the DEM of the water reservoir bottom

**Slika 4.** Računanje krivulje kapaciteta u odnosu na površinu iz digitalnog modela dna jezera

Banská Štiavnica – umjetno jezero Halčiansky (Weis and Kubinský, 2014), veliko umjetno jezero Kolpášsky (Kubinský i dr., 2014b), veliko i malo jezero Richňavská (Kubinský i dr., 2013, Kubinský i dr., 2014a) te na jezera u drugim dijelovima svijeta (Ceylan i dr., 2011). Izmjera je provedena u skladu s međunarodnim standardima hidrografske izmjere (Manual of Hydrography, 2005).

Koordinate točaka dna prikupljene su prijamnikom GNSS i dubinomjerom postavljenim na čamac i učvršćenima s pomoću užadi kako bi sonar i motka GNSS-a bili okomiti na površinu vode (Manual of Hydrography, 2005). Podaci o položaju dobiveni su prijamnikom Leica GS12 u načinu rada RTK. Dubina je izmjerena s pomoću sonara Garmin GPSmap 421s sa sondom s dvostrukim snopom i frekvencijom 200 kHz; sonda sonara postavljena je na prijamnik GNSS na udaljenosti od 150 mm između vrha motke GNSS-a i sonde sonara. Podaci sonara poslani su kablom u obliku poruke NMEA i zapisane u stupac „Bilješka“ za svaku točku.

Čamac je prošao po jezeru u paralelnim smjerovima koji su bili udaljeni jedan od drugoga 10 m. Podaci o položaju automatski su bilježeni svaka 2 m (izmjereno je 3149 točaka). Na dan izmjere sonarom izmjerena je razina vode upotrebom GNSS-a i dobivena je vrijednost 688,368 m nadmorske visine.

Podaci izmjere učitani su u Leica Geo Office, potom spremljeni u MS Excel kako bi ih se pretvorilo u koordinate XYZ dna jezera. Iz skupa svih točaka uklonili smo one čija je procijenjena 3D točnost bila manja od 50 mm te one kojima su nedostajali podaci o dubini (greške u komunikaciji između GNSS-prijamnika i sonara) kako bi se osiguralo da će u daljnju obradu ući samo podaci visoke kvalitete.

Potom su sve točke učitane u program ArcMAP, nakon čega je broj točaka ručno smanjen kako bi se zadržale samo one u pravilnoj mreži veličine otprilike  $10 \times 10$  m i dobio relevantan i prostorno homogen skup podataka s podjednakom gustoćom u oba smjera. Točke smo snimili automatski svakih 2 metra tijekom plovidbe kako bismo osigurali dovoljan broj točaka i oblikovala približno pravilna raspodjela od  $10 \times 10$  m u oba smjera (10 m između smjerova plovidbe i 10 m točaka u jednom plovidbenom smjeru). Trenutačna obalna linija izvučena je iz ortofotokarte s visinom preljeva na brani koji je izmjeren na terenu.

## 2.5. Računanje volumena umjetnog jezera

Digitalni modeli visina starog i trenutnog stanja dna jezera izrađeni su upotrebom alata “Topo to raster” i s veličinom ćelije obaju modela od  $1 \times 1$  m, dok su poligoni obalne linije iz obiju godina upotrebjeni kao granica

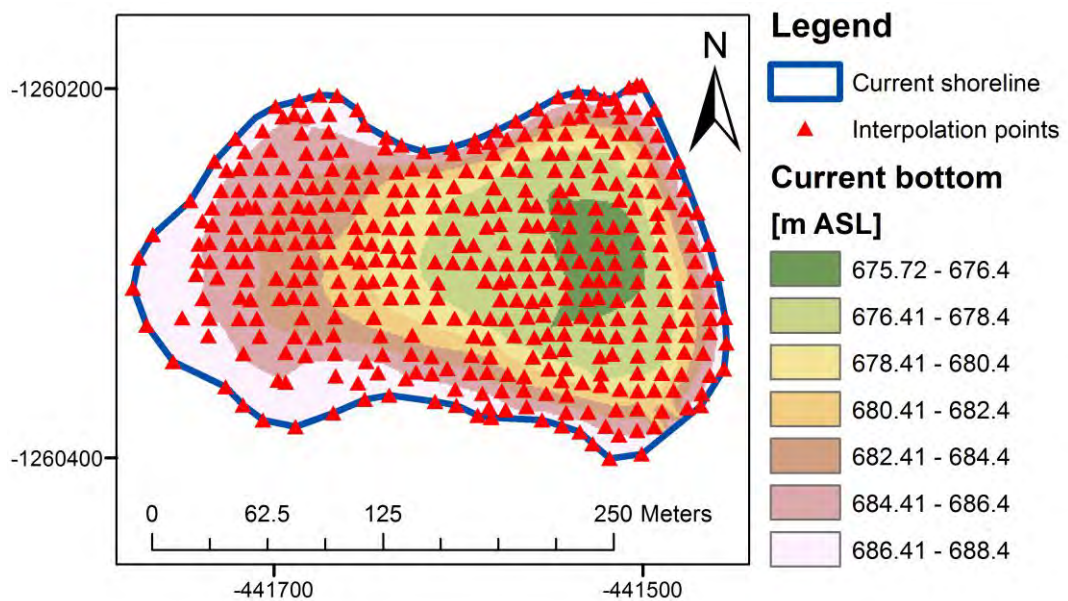
digitalnog modela visina. Takvom interpolacijskom metodom dobivaju se hidrološki točni, vrlo glatki modela zemljišta, što je važno za umjetna jezera u dolini kao što je Vindšachta, izgrađeni postavljanjem brane u prirodnoj dolini. Čak i dno umjetnog jezera može biti (i obično je) zagađeno muljem, dok pražnjenjem jezera nastaje mreža kanala i grebena koje se mogu vidjeti u digitalnim modelima (Fuska, Kubinský i Lenárt, 2014). Korisnici digitalnih modela visina trebaju biti svjesni njihovih glavnih svojstava kako bi mogli procijeniti jesu li prikladni za određenu primjenu (Varga i Bašić, 2013).

Volumen jezera izračunan je s pomoću nove metode, primjenom skripte u programu Python koju su razvili autori ovoga rada, te paketa ArcPy, kojim se dobiva karta dubine vode za svaku razinu vode i račun volumena i površine vode automatski upotrebom alata za statistiku zone. Skripta uzima podatke (najmanju i najveću visinu) iz digitalnog modela dna u formatu GeoTIFF i omogućuje korisniku unošenje podjele ukupne dubine vode.

Ta metoda računa volumen i površinu vode za bilo koji raspon podjele dubine vode iz digitalnog modela dna. To je novi pristup računanju krivulje kapaciteta u odnosu na površinu jer nije ograničen na izradu karte izohipsi kako bi se računanje provelo s pomoću prizmi {1 i 2}, već automatski obrađuje ulazni digitalni model dna s potrebnim intervalom podjele dubine vode.

Skripta je izrađena kao samostalna skripta koja treba biti spremljena u istoj mapi na disku kao digitalni model dna u formatu GeoTIFF i može ju se pokrenuti iz osnovnog prozora programa Python IDLE. Postupak počinje analizom datoteka u radnoj mapi u kojoj se nalazi datoteka skripte. Nakon što skripta nađe datoteku GeoTIFF digitalnog modela dna, uzima ime datoteke, najmanju i najveću visinu i veličinu ćelije. Potom računa najveću dubinu vode oduzimanjem najmanje visine od najveće i traži od korisnika da unese interval podjele dubine. Postupak računanja upotrebljava se za računanje parametara dubine koji se povećavaju za interval podjele dubine. Na primjer, ako je dubina vode 3,4 m, a interval dubine vode 1 m, skripta će izračunati parametre za dubine 1 m, 2 m, 3 m i zaključiti s 3,4 m. Računanje se provodi u petlji kako bi se automatski izračunali svi parametri do najveće dubine vode. Kako bi to postigla, skripta izrađuje kartu dubine vode za najveću dubinu vode uzimanjem isječka digitalnog modela kako bi se dobile samo ćelije s onom visinom, gdje je dubina vode manja ili jednaka dubini vode koja se proučava – dubina vode izračunava se kao razlika između visine dna i dubine vode koja se proučava {3}. Kad se izradi karta dubine vode, skripta stvara granice područja i računa zbroj dubina voda za sve ćelije i broji ćelije za statistiku zone –





**Fig. 5** DEM of the bottom of Vindšachta water reservoir in 1887  
**Slika 5.** Digitalni model dna umjetnog jezera Vindšachta, stanje 1887.

m. The calculation runs in a loop to provide automatized calculation until it reaches the maximum water depth. To do so, the script creates a water depth map for the maximum water depth examined by clipping the DEM to get only the cells with the bottom elevation, where the water depth is less or equal to the water depth examined – water depth is calculated as the difference between the bottom elevation and the water level examined {3}. When the map of the water depth examined is created, the script creates the map boundary and calculates the sum of the water depth for all cells and count of these cells with zonal statistics – the water depth map is set as the input data raster and the boundary polygon is set as the zone dataset. The sum of the water depths is used to calculate the water volume by multiplying it by the cell area {4}, and the count of the cells is used to calculate the water surface area by multiplying it by the cell area {5}. All data (water level elevation, water depth, water surface area, water volume) for the water level elevation examined are stored in a text file and a loop continues to calculate until the maximum water depth is calculated, when the script ends.

$$\text{Raster}_{\text{water depth}} = \text{Elevation}_{\text{water level}} - \text{Raster}_{\text{DEM}} \quad \{3\}$$

$$V_{\text{water}} = \sum_{i=1}^n \text{Depth}_{\text{water},i} \times \text{Area}_{\text{cell}} \quad \{4\}$$

$$S_{\text{water}} = \text{Count}_{\text{cell}} \times \text{Area}_{\text{cell}} \quad \{5\}$$

After the script was executed, data was loaded in MS Excel to produce a graphic representation of the area-storage capacity curves for each year.

### 2.6 Cross-Sections of the Bottom

To visualize the changes to the reservoir bottom elevation over time, we created cross-sections of the

bottom in identical positions for each year. This was achieved using TIN models of the bottom, which were subsequently loaded in AutoCAD 2012, where the construction of cross-sections was performed. ArcGIS offers a “Create Profile Graph” tool that is useful for creating informative profile views with a variety of settings, but importing the TIN model to AutoCAD and creating profiles expands the variety of further engineering applications, such as reservoir profiles for technical blueprints with the necessary labels and notes; input for excavation and maintenance planning, etc.

### 3 Results

Altogether, 2542 out of 3149 points were loaded in ArcMAP, then reduced to 342 points in a grid approximately 10 × 10 m, ranging from 675.711 m to 688.281 m ASL. The old map of the reservoir consisted of 16 contours ranging from 674.4 m to 690.4 m ASL after elevation error correction. Models (Figures 5 and 6) for both years were created using “Topo to raster” interpolation with drainage enforcement to remove possible sinks, and shoreline polygons were used as the interpolation boundaries.

Both DEMs were exported to GeoTIFF, because the Python script is built to process this file type. The script calculates the surface area and water volume at the given water level elevation in accordance with the water depth division interval set by the script operator during its execution. In the case of Vindšachta, where the water depths were 14.1 m (old status) and 12.7 m (current status), we used a depth division of 1 metre.

There is also the option to use the “Surface volume” tool to calculate partial volumes, but our newly developed script tool also automatically creates a water depth

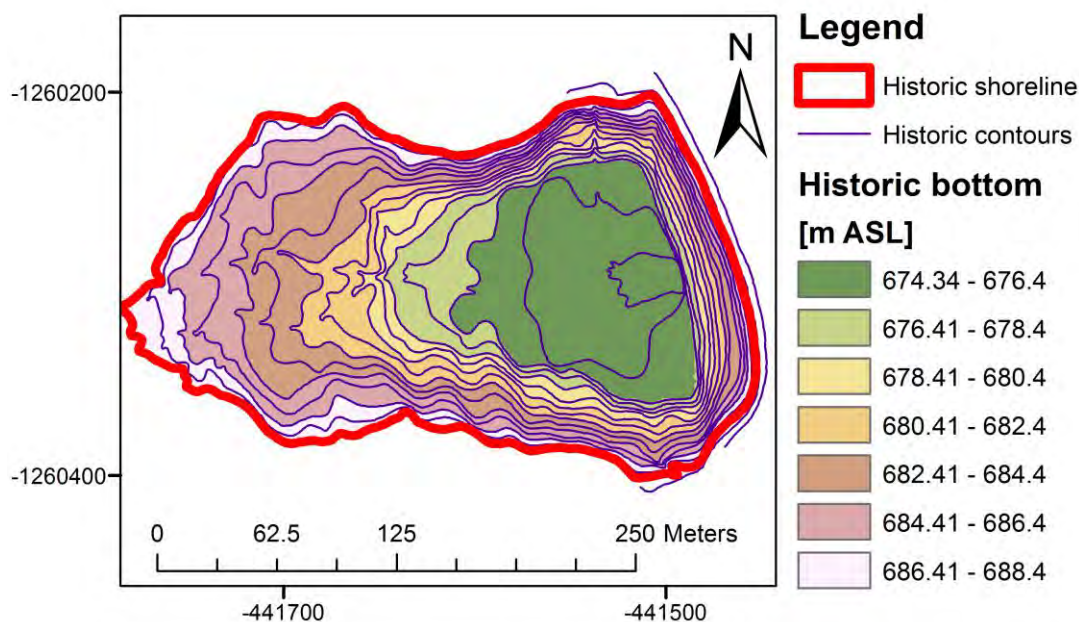


Figure 6. DEM of the bottom of Vindšachta water reservoir in 2014

Slika 6. Digitalni model dna spremnika za vodu Vindšachta, stanje 2014. godina

rasterska karta dubine vode je ulazni podatak, a poligon je granica područja za skup podataka o zoni. Volumen vode se računa kao zbroj dubina vode pomnožen s površinom ćelije {4}, a površina vode računa se kao broj ćelija pomnožen s površinom ćelije {5}.

Svi podaci (razina vode, dubina vode, površina vode, volumen vode) spremaju se u tekstualnoj datoteci i skripta nastavlja računanje dok ne stigne do najveće dubine vode.

$$Raster_{water\ depth} = Elevation_{water\ level} - Raster_{DEM} \quad \{3\}$$

$$V_{water} = \sum_{n=1}^i Depth_{water,i} \times Area_{cell} \quad \{4\}$$

$$S_{water} = Count_{cell} \times Area_{cell} \quad \{5\}$$

Nakon što se skripta izvrši, podaci se učitaju u MS Excel kako bi se dobio grafički prikaz krivulja kapaciteta u odnosu na površinu za svaku godinu.

### 2.6. Poprečni presjeci dna

Kako bismo prikazali promjene u visinama dna jezera s vremenom, izradili smo poprečne presjeka dna u identičnim položajima za svaku godinu. To smo postigli upotrebom modela nepravilne mreže trokuta koje smo učitali u AutoCAD 2012, gdje smo izradili presjeke. ArcGIS nudi alat "Create Profile Graph" koji je pogodan za izradu informativnih profila s različitim postavkama, no učitavanje modela nepravilne mreže trokuta u AutoCAD i izrada profila proširuje daljnje inženjerske primjene, poput profila dna za tehničke nacрте s potrebnim oznakama i bilješkama; planiranje iskopavanja i održavanja, itd.

### 3. Rezultati

U ArcMap učitano je ukupno 2542 od 3149 točaka, što je potom smanjeno na 342 točke u mreži veličine otprilike 10 × 10 m, od 675,711 m do 688,281 m nadmorske visine. Stara karta jezera sastojala se od 16 izohipsi u rasponu od 674,4 m do 690,4 m nadmorske visine nakon korekcije visina. Modeli (slike 5 i 6) za obje godine izrađeni su s pomoću funkcije za interpolaciju "Topo to raster", a poligoni obalne linije upotrebjeni su kao granice interpolacije.

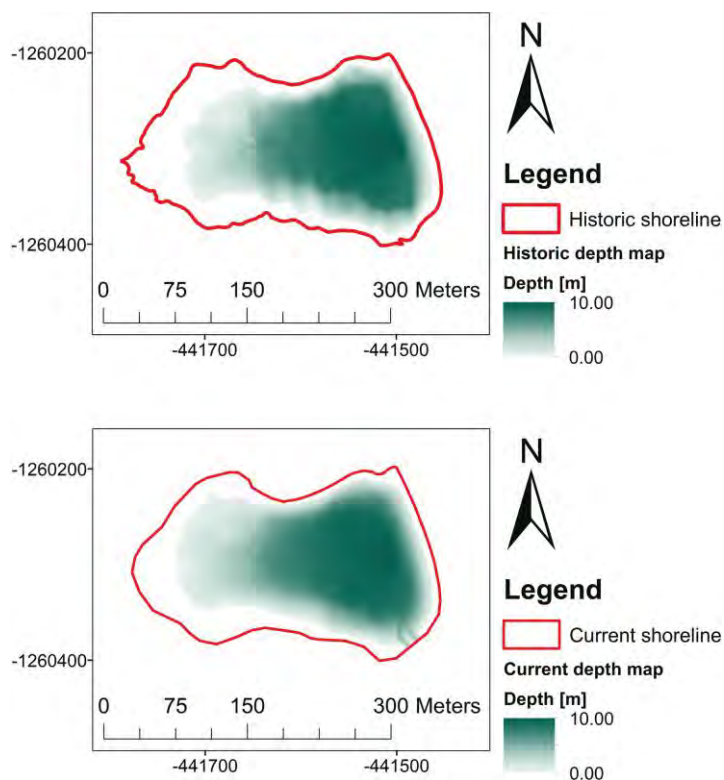
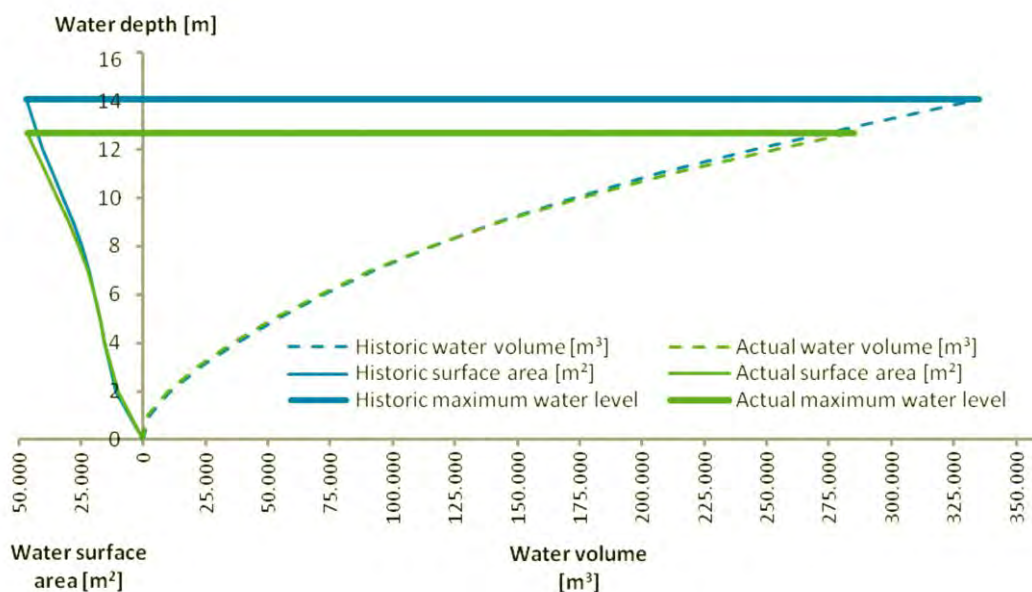


Fig. 7 Examples of water depth maps created

Slika 7. Primjeri izrađenih karata dubine vode



**Graph 1** Area-storage capacity curves of Vindšachta water reservoir (old data – 1887; current data – 2014)

**Graf 1.** Krivulje kapaciteta u odnosu na površinu umjetnog jezera Vindšachta (podaci iz 1887., podaci iz 2014.)

map for each water level elevation analysed, and this can be accessed and used if necessary (see Figure 7) – a typical application for assessing the needs of calculation and visualization in irrigation reservoirs, where the water level elevation drops significantly to the specified elevation after pumping irrigation water.

The data for water volume and water surface area at each water depth division surveyed were stored in a text file and then used in MS Excel to create graphs of the area-storage capacity curves for both years (Graph 1), where the y-axis displays the water depth, the left part of the x-axis shows the water surface area, and the right part of the x-axis shows the water volume. To provide positive values and the increment of water surface area from right to left, the data were converted to negative values and displayed on a secondary x-axis, modifying the display of negative values by omitting the minus sign.

The maximum water volume (Table 1) in the reservoir is at the water level elevation of 688.40 m ASL; in 1887 it was 335,000 m<sup>3</sup>, and in 2014 it was 285,000 m<sup>3</sup>.

The creation of the reservoir bottom cross-sections required the creation of TIN models for both years with a specific workflow (Figure 8).

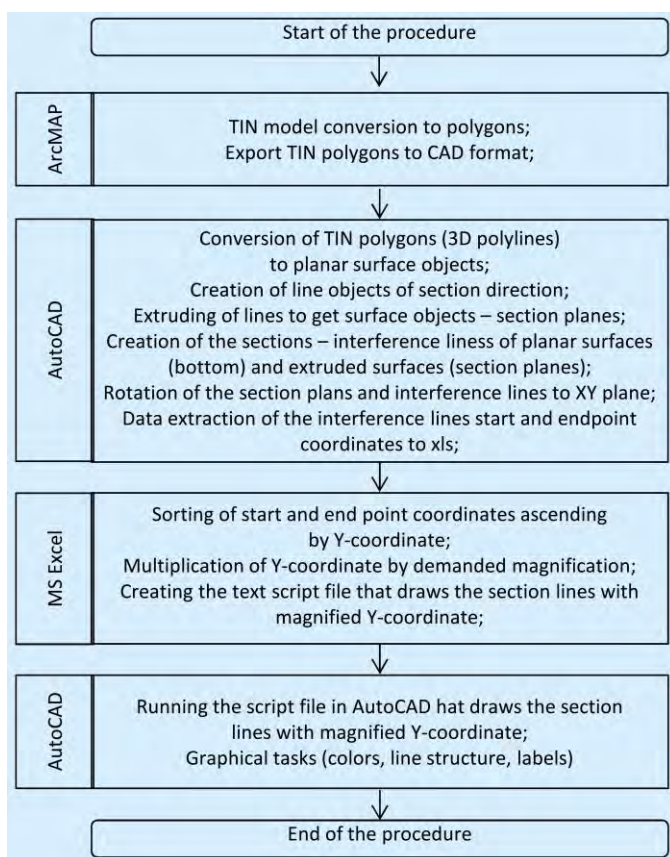
**Table 1.** Comparison of the water volume and water surface area

	Water volume at maximum water level		Water surface area at maximum water level	
	[m <sup>3</sup> ]	[%]	[m <sup>2</sup> ]	[%]
1887	335 000	100	47 000	100
2014	285 000	85	46 500	99

TIN models were exported to AutoCAD file format and processed in AutoCAD 2012, where 3D Polylines of TIN models were converted to planar surfaces. Sections were constructed as the interferences of the planar surfaces and extruded cross-section planes. Cross-sections were created in three parts parallel to the direction of the earth dam endpoints, and in one longitudinal line across the reservoir from the inflow to the earth dam. For better visualization, we used 10x magnification of the vertical size; this was done as the extraction of the interference line coordinates to an MS Excel file, where the elevation data was multiplied. Modified coordinates of these lines were used in AutoCAD script to re-draw the interference lines in a magnified vertical size (Fig. 9).

#### 4 Discussion

Vindšachta water reservoir is a technical monument inscribed in the UNESCO World Heritage List, and with other reservoirs in the region, provides the only source of surface water that fulfils quality criteria for bathing (some others are used as drinking water reservoirs). So it is necessary to ascertain its current status, document development trends, and implement management measures to maintain its long-term function as a reservoir of water. Results have shown the negative effects of erosion and siltation processes on overall morphological changes to the reservoir bottom. Lost storage capacity can be re-established mainly through expending a great deal of human effort, but this is obviously an expensive process (excavation, transport, storage or disposal of excavated sediments). Gradual siltation may lead to the disappearance of



**Fig. 8** Flowchart for the bottom profiles creation  
**Slika 8.** Dijagram toka za izradu profila dna

Oba su modela prenjeta u format GeoTIFF jer skripta u programu Python obrađuje taj tip datoteka. Skripta računa površinu i volumen vode na određenoj razini vode u skladu s intervalom podjele dubine koji je odredio korisnik. U slučaju Vindšachte, gdje dubina vode iznosi 14,1 m (stanje 1887. godine) i 12,7 m (stanje 2014. godine), uzeli smo podjelu dubine od 1 metra.

Također postoji mogućnost primjene alata “Surface volume” za računanje djelomičnih volumena, no naša nova skripta automatski izrađuje kartu dubine vode za svaku razinu vode (vidi sliku 7), što može biti korisno, npr. u tipičnoj primjeni kao što je potreba računanja i vizualizacije spremnika za navodnjavanje, gdje se nakon ispumpavanja vode za navodnjavanje razina vode značajno smanjuje na određenu razinu.

Podaci o volumenu i površini vode za svaku dubinu vode spremljeni su u tekstualnoj datoteci i upotrebljeni u programu MS Excel za izradu krivulja kapaciteta u odnosu na površinu za obje godine (graf 1), pri čemu os y predstavlja dubinu vode, lijevi dio osi x predstavlja površinu vode, a desni dio osi x predstavlja volumen vode. Kako bi se dobile pozitivne vrijednosti i prikazalo povećanje površine vode s desna ulijevo, podaci su pretvoreni u negativne vrijednosti i prikazani na osi x, izostavljanjem negativnog predznaka.

Najveći volumen vode (tablica 1) u jezeru je na razini vode od 688,40 m nadmorske visine; 1887. bio je 335 000 m<sup>3</sup>, a 2014. bio je 285 000 m<sup>3</sup>.

**Tablica 1.** Usporedba volumena i površine vode

	Volumen vode na najvećoj razini vode		Površina vode na najvećoj razini vode	
	[m <sup>3</sup> ]	[%]	[m <sup>2</sup> ]	[%]
1887	335 000	100	47 000	100
2014	285 000	85	46 500	99

Izrada poprečnih presjeka dna jezera zahtjevala je izradu modela nepravilne mreže trokuta za obje godine sa specifičnim tokom rada (slika 8).

Modeli nepravilnih mreža trokuta obrađeni su u programu AutoCAD 2012, gdje su 3D polilinije u nepravilnoj mreži trokuta pretvorene u ravnine. Presjeci su izrađeni kao interferencije (interference checking, naredba u AutoCAD-u) ravnina u modelu i ravnine presjeka. Presjeci izrađeni su za tri poprečna smjera paralelna sa smjerom vrha brane te u jednom smjeru uzduž jezera od utjecanja do brane. Zbog bolje vizualizacije upotrijebljeni su deseterostruko povećanje visine; to smo izveli tako da smo koordinate linija interferencije spremili u datoteku MS Excel, gdje su podaci o visinama pomnoženi. Modificirane koordinate tih linija učitane su u skriptu programa AutoCAD kako bi se nacrtali konačni presjeci (slika 9).

#### 4. Rasprava

Umjetno jezero Vindšachte je tehnički spomenik koji pripada Svjetskoj baštini UNESCO-a zajedno s drugim umjetnim jezerima u tom području. Ti su spremnici jedini izvori površinske vode koji zadovoljavaju kriterije kvalitete za kupanje (neki druge se upotrebljavaju kao izvor vode za piće). Prema tome, neophodno je utvrditi njegovo trenutno stanje, zabilježiti razvojne trendove i provesti mjere upravljanja kako bi se održala njegova dugotrajna funkcija spremnika za vodu. Rezultati istraživanja pokazuju negativne utjecaje erozije i zagađenja muljem na morfološke promjene dna jezera. Izgubljeni kapacitet može se ponovno uspostaviti ulaganjem velikog truda, predma je to očito skup postupak (iskopavanje, prijevoz, skladištenje ili odstranjivanje iskopanog sedimenta). Postupno zagađenje muljem moglo bi dovesti do nestanka jezera Vindšachte, važnog dijela kulturne baštine UNESCO-a i mjesta koje lokalno stanovništvo i turisti često upotrebljavaju za kupanje, pećanje i uživanje u ljepoti krajobraza. U razdoblju od

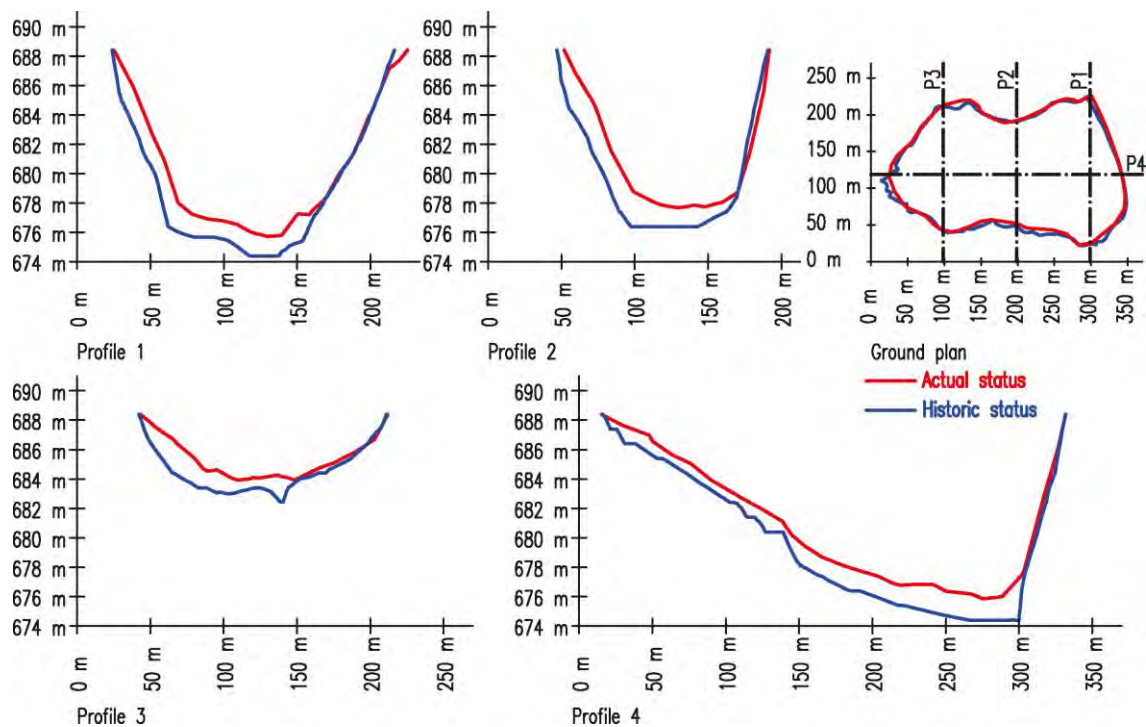


Figure 9. Reservoir bottom cross-sections

Slika 9. Presjeci dna umjetnog jezera

Vindšachta water reservoir, an important part of UNESCO cultural heritage, and a place frequently used for leisure activities by local citizens and tourists (swimming, fishing, and its aesthetic and landscape elements). Over a period of 127 years (1887–2014), the water reservoir volume has decreased by approximately 50 000 m<sup>3</sup>. However, in this fairly long period, a decrease of 15% of the original storage capacity means the siltation is not extreme. In comparison, Altınapa reservoir in Turkey shows a decrease of 33.4% for the period 1967–2009 (Ceylan et al., 2011). A negative situation has been detected and described in Poland, where research has shown that 25 surveyed lakes have lost 9.9% of their storage capacity over the past 50 years (Choiński and Ptak, 2009). Sediment accumulations reaching several metres near withdrawal objects (Kubinský and Weis, 2012) may lead to disfunction in the reservoir purposes. Unfavourable situations have also been noted for other reservoirs, such as Dąbie reservoir in Poland, where the sediment layer thickness reached 2 metres during the period 1962–1996 (Wiśniewski and Wolski, 2005).

Expanding construction and building activities have been extremely relevant in the last few decades (Newman et al., 2009). Construction activities, such as the expansion of urban areas, are approaching or encroaching on the water surface, and frequently do not adhere to erosion control measures (Jurík and Kaletová, 2014; Lenárt et al., 2013). In meadow areas, new buildings have emerged accompanied by slope modifications and entry roads. For the further mapping of current land use

surrounding water reservoirs, “low cost” data collection is suitable (Kliment, M. et al., 2012), or data from the INSPIRE Geoportal at the European level or the EnviroGeoPortál (environmental infrastructure geoportal for spatial information) at the Slovak level, for the environmental domain (Kliment, T. et al., 2012). The usefulness of a GIS project would be significantly increased if a larger number of users were given simple access to data in GIS, which could be linked with data from other systems, then analysed and presented (Fraňčula et al., 2002) in a generally accessible and intuitive way (Leitmanová et al., 2013). Establishing a digital spatial data infrastructure means improving the existing one, and can be defined as a number of activities aiming at providing easier access to and wider dissemination of existing spatial data, and their easier, more efficient use (Cetl et al., 2009).

According to the geology map (SGÚDŠ, 2013) it is evident that the larger part of the Vindšachta watershed is located on diluvial sediments, mostly clay and rock (or sandy rock) in sloped areas that are unstable in terms of erosion. The material erodes quickly after exposure, so sand and clay are transported by surface runoff. On a large scale, these factors contribute to reservoir siltation. The reservoir was reconstructed between 2000 and 2002, but the sediment was not removed from the bottom. As can be seen in cross-section (Fig. 9), the distribution of sediment is quite regular on the bottom. This is result of the gradual, slow accumulation of sandy material from the watershed.

127 godina (1887–2014), volumen vode smanjio se za oko 50 000 m<sup>3</sup>. Međutim, s obzirom na dugo razdoblje, smanjenje od 15% znači da zagađenje muljem nije ekstremno. Za usporedbu, umjetno jezero Altinapa u Turskoj smanjilo se za 33,4% od 1967. do 2009. godine (Ceylan i dr., 2011). Negativno stanje također je otkriveno i opisano u Poljskoj, gdje su istraživanja pokazala da je 25 jezera izgubilo 9,9% svojih kapaciteta u razdoblju od 50 godina (Choiński i Ptak, 2009). Gomilanje sedimenta od nekoliko metara blizu mjesta povlačenja ili preusmjerenja vode (Kubinský i Weis, 2012) može dovesti do disfunkcije umjetnog jezera. Nepovoljna situacija utvrđena je i u drugim umjetnim jezerima, npr. u jezeru Dąbie u Poljskoj, gdje je sloj sedimenta dosegao debljinu od 2 metra od 1962. do 1996. (Wiśniewski i Wolski, 2005).

Širenje izgradnje veoma je važno tijekom posljednjih nekoliko desetljeća (Newman i dr., 2009). Širenje gradskih područja počinje povređivati vodene površine i često se ne drži mjera zaštite od erozije (Jurík i Kálová, 2014; Lenárt i dr., 2013). Na livadama se pojavljuju nove zgrade koje mijenjaju padine i ulazne ceste. Za daljnje kartiranje upotrebe zemljišta koje okružuje umjetna jezera pogodno je jeftino prikupljanje prostornih podataka (Kliment, M. i dr., 2012) ili podaci s Geoportala INSPIRE na europskoj razini ili EnviroGeoPortál (Environmental infrastructure geoportal for spatial information) u Slovačkoj (Kliment, T. i dr., 2012). Korisnost projekta GIS-a bila bi znatno veća kad bi više korisnika imalo jednostavan pristup GIS-u, koji bi se mogao povezati s podacima iz drugih sustava i potom analizirati i predstaviti (Frančula i dr., 2002) na pristupačan i intuitivan način (Leitmanová i dr., 2013). Uspostavljanje infrastrukture prostornih podataka znači poboljšanje postojećeg pristupa i može se odrediti kao aktivnosti koje ciljaju na jednostavniji pristup i veću distribuciju postojećih prostornih podataka te njihovu lakšu i učinkovitiju upotrebu (Cetl i dr., 2009).

Prema geološkoj karti (SGÚDŠ, 2013), očito je da se veći dio sliva Vindšachte nalazi na diluvijalnim sedimentima, uglavnom glini i kamenu (ili pješčanom kamenu) na kosim područjima koja su nestabilna u smislu erozije.

Nakon kiše brzo dolazi do erozije, pa se pjesak i glina prenose površinskim otjecanjem. Ti čimbenici naposljetku dovode do zagađenja jezera muljem. Jezero je rekonstruirano između 2000. i 2002., no sediment s dna nije uklonjen. Kao što se vidi na poprečnom presjeku (slika 9), sediment je prilično ravnomjerno raspoređen na dnu. To je rezultat postepenog i sporog nagomilavanja pješčanog materijala iz sliva.

Upotreba novog alata za računanje parametara krivulje kapaciteta u odnosu na površinu spremnika za vodu inovativno je iz dvaju glavnih razloga – nije potrebna dugotrajna izrada karata izohipsi za daljnju upotrebu pri metodi računanja s pomoću prizmi jer skripta računa parametre automatski, a dobivaju se karte dubine vode za neku buduću upotrebu.

## 5. Zaključak

U ovom je istraživanju upotrebljena dijakronička analiza starih batimetrijskih podataka za 1887. te podaci izmjere GNSS-om i sonarom za 2014. Za vrijeme tog razdoblja od 127 godina umjetno jezero smanjilo se za 50 000 m<sup>3</sup> (u prosjeku 396 m<sup>3</sup>/god.). Prema tome, potrebno je kartirati i pratiti stanje i uvjete, bilježiti razvojne trendove i provesti mjere osiguranja dugotrajnih funkcija ovog umjetnog jezera.

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The implementation of the newly developed script tool for calculating the parameters of the water reservoir area-storage capacity curves is innovative in two main ways – it eliminates the time-consuming creation of contour maps for further use in the prismatic calculation method of calculation, as the script calculates the parameters automatically for the required depth division, and it also produces water depth maps for further use.

## 5 Conclusion

This study used diachronic analyses of old bathymetric data for 1887 and current data from non-contact GNSS and sonar surveying for 2014. During this period of 127 years, the water reservoir storage capacity decreased by 50 000 m<sup>3</sup> (396 m<sup>3</sup>/year on average). So it is necessary to map and monitor the status and conditions, document development trends and implement measures to secure the long-term functions of the water reservoir.

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