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Virtual geographical environment (VGEs) by incorporation of unmanned aerial vehicle (UAV) imagery and acoustic profile for Pond Borabey

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Abstract

The Virtual Geographic Environment (VGEs) is a framework in which real-world information is conveyed and converted into the digital world. It contributes to a better understanding of geographic knowledge by human beings and helps decision-makers by giving them a profound view of geographic concerns like three-dimensional (3D) models. The production of 3D models is essential for the characterization, monitoring, and management of water areas. This study aims to expose the 3D model of the pond in the presence of Unmanned Aerial Vehicle (UAV) and Acoustic Doppler Profile (ACDP) bathymetry to precisely determine the actual amount of water in the pond for possible water problems in the future. Moreover, determine how the sediments carried by the mainstream and side tributaries feeding the pond affect the pond's water volume and in which parts of the pond their accumulation is concentrated. This study will contribute to the literature by using an ACDP device for the bathymetry measurement process which is rare in the literature. In this approach, the pond's underwater topography of the pond contributed to the sustainable management of the pond by producing Digital Elevation Models (DEM), which is a sensitive indicator of climate change and man-made effects.

1. Introduction

A fairly small part of the water resources in our world, called the blue planet, are suitable for living use, so it is necessary to protect and ensure sustainable management of existing water resources [1]. An understanding of underwater topography is necessary for maintaining the current state of water resources and ensuring resource management in water bodies. For example, it is necessary to determine the effect of the amount and level of sedimentation affecting the water quality of lakes on the volume and depth of lakes [2–4]. Additionally, it is also necessary to determine the level of water, volume, and surface area of the lake to observe the temporal changes in human activities and lakes [5].

Bathymetry, which constitutes an essential element of hydrological modeling, flooding estimation, and degrading or sediment removal and water depth data, is vital for sustainable management [6, 7]. Bathymetric maps in lakes are used to determine the effects of morphological change on water quality [8] and link physicochemical properties with bathymeter for the effective use of resources [9]. In this context, the obtaining of bathymetric maps of the lakes are essential data for these studies.

For the last fifteen years, river discharge measurements have been implemented by Acoustic Doppler Current Profiler (ADCP) in many countries worldwide. Ultrasonic signals emitted by ADCP in the water body and backscattered echoes from suspended particles have been listened to by using ADCP. The Doppler frequency shift measures immediate water velocity profiles, then total discharge through a cross-section. The particle properties like concentration and size have been reflected by the intensity of the backscattered signal [10]. Although the primary purpose of the ADCP device is to extract current profiles in a body of water, the device's ability to measure depth during the profiling process shows that the device can also be used to create bathymetry data [11, 12].

Nowadays, monitoring technologies (remote sensing) and geographic information systems (GIS) are widely used in the bathymetry analysis of water structures [13]. Also in recent years, remote sensing technologies that use Unmanned Aerial Vehicles (UAVs) instead of on-site measurement processes and other platforms have become a more costly and practical alternative [14, 15]. UAV equipped with Global Positioning Systems (GPS) and special thermal and multispectral sensors is collecting high-resolution and georeferenced spatial images. The use of these images provides an excellent advantage for fieldwork in Earth Sciences [16]. In this context, images obtained from UAV surveys are used in studies such as water resource management [17], river geomorphological change detection [18], water quality management [19], and shallow stream bathymetry [20]. Also, by creating 2D and 3D spatial information using high-resolution images obtained, it is possible to get an advantage for field research by obtaining detailed information about the workspace [21–23].

The virtual geographic environment (VGE) shows the spatial side of the bond between man and his surroundings relevant to the evolution of specific sciences such as climatology, hydrology, geology, and how human interacts with the environment [24, 25]. A VGE with cartography, remote sensing, and GIS assesses human activities' impact on the environment [26]. Virtual geographic environments consist of the relationship between the geographic environment and the digital world. VGEs enable identifying and interpreting datasets as spatial datasets or time-series data heterogeneous data [27]. VGE has a significant advantage over traditional GIS as it enables multi-source data integration, sharing, and information mining [28]. In contrast to conventional GIS, the goal of VGE is to express the real world, support complex geographic analysis models, and support cooperation interactivity between the natural world and the digital world [29]. The application of a VGE provides an opportunity to build a view, which can visualize geospatial data or geographic processes in a realistic 3D virtual environment [30]. Thereby, the VGE can "put up a human understanding of the geographic world and assist in solving geographic problems at a high level" [31].

The recent developments in multimedia and virtual reality technologies allow more information about water bodies bathymetry. A new generation of geographic analysis tools can be created by combining bathymetry maps and various data sets obtained using monitoring technologies and GIS systems with VGEs [32]. The proposed virtual water ponds bathymetric map relies upon the realistic representation in three dimensions and considers graphically based water models. Virtual water quality management approaches should combine realistic representations of water basins, simulation models' capabilities, and the options of manipulation and visualization provided by VR is just one system [33]. VGEs have been frequently used to model water pollution models [34], simulations of shallow water [35], hydrological cycles in large catchments [36], and simulation analyses of the dam-break floods [37]. In recent studies, data from UAV measurements, Geographic Information Systems (GIS), and area measurements are used to generate 3D digital elevation models effective in managing water structures. For example, studies have been carried out to study the hydrological and geomorphological structures of water reservoirs [38], to study the geomorphological structures of water reservoirs in difficult-to-reach areas such as mountains [39], to create virtual realities of water areas [40], and management of national parks [41].

This study aims to develop an innovative 3D model to accurately determine the water volume in small wetlands, such as ponds, in response to potential future water scarcity issues by combining UAV data with bathymetric measurements. In the literature, there are a limited number of studies that explore the detailed 3D modeling of wetlands through the integration of ACDP and UAV technologies. Most studies tend to use ACDP or UAV technologies in isolation, whereas this study seeks to achieve higher accuracy and resolution in water volume estimations by integrating both technologies. Specifically, this model, created by combining high-resolution bathymetric data obtained from ACDP with UAV data, offers a novel perspective on depth profiling and volume calculations of water bodies, differentiating itself from traditional methods found in the literature. Consequently, this model serves as both a scientific and practical guide for wetland management, providing a strategic information source for the academic community and decision-makers in water management.

2. Method

2.1. Study area

The study was carried out in Borabey pond, located in Emirce village of Eskişehir-Türkiye (Figure 1). The Borabey pond is in the coordinates 39° 52' 44'' N to 30° 27' 27'' E and covers an area of 166.559 m^2 at 924 above sea level. The Borabey pond was built between 1991-1992 by the Provincial Directorate of Rural Services to benefit 115 farmers in the 2480 decare area. In 1999, the pond had allocated to use as a water sports center of Anadolu University. Then it was planned to be used to contribute to the Eskişehir drinking water network. However, in 2011 this purpose was renounced [42].

2.2. Methods

Highly accurate volume and area calculations can be made using remote sensing and UAV data [43, 44, 45]. This study carried out depth measurement with the Acoustic Doppler Profiler device in Borabey Pond in Eskişehir - Türkiye. The depth points obtained from the measures were transformed into the bathymetric map using GIS methods. Besides, the acquired bathymetric map was combined with Digital Elevation Models (DEM). In addition to the DEM obtained, the 3D model of the Borabey Pond was created by combining the UAV surveying data and bathymetry surveying data. A more detailed Borabey pond model has been created using high resolution and georeferenced spatial images in the 3D model.

Additionally, in the process of UAV measurements, information about the pond's environment was obtained, and the process of interpretation of the changes in the pond's floor was contributed. We create a 3D-DEM of the Borabey pond and near environment for all of the measurement results. Preparing a 3D DEM of the Borabey pond is a process that includes many data sets and consists of sub-processes. The methods applied in creating a 3D DEM detail of the Borabey pond are shown in the flowchart diagram in Figure 2.

2.2.1. UAV mapping

A UAV named eBee, which was produced by Sensefly, and a Canon IXUS 127 HS camera were used to obtain the arial images of the Borabey pond area (Figure 3).

Technical information about the UAV and Canon IXUS 127 HS camera is given in Table 1. In a 34-minute flight with the UAV system, a total of 297 images were obtained from an area of 1,897 km2 with a ground sampling level of 6 cm (GSD). While making the flight plan with the UAV, 75% lateral and 70% longitudinal overlap ratios were used. Flight configuration is parallel strips, flight altitude is 100 m, Speed of flight 36-57 km/h but the speed varies with the wind. After that, images were recorded on a memory card in the camera. Pix4D photogrammetry software was used to generate DEM and orthomosaic from the images.

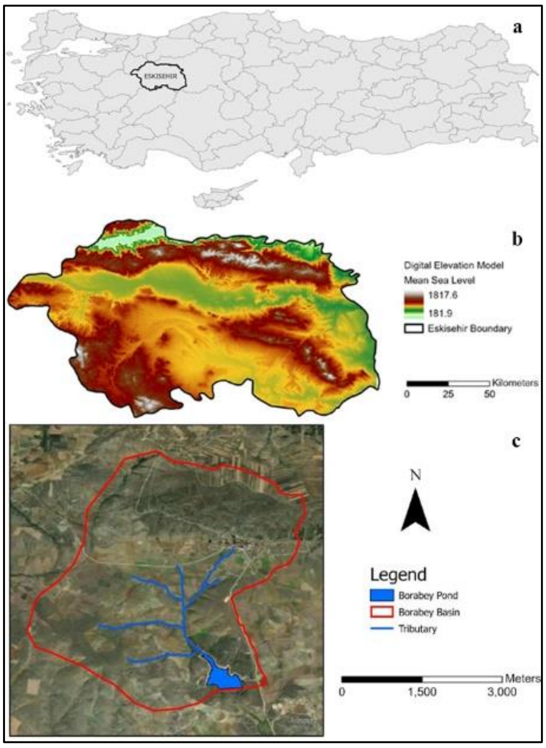

Figure 1. Study area a) Türkiye boundary; b) Eskişehir boundary; c) Borabey Basin boundary

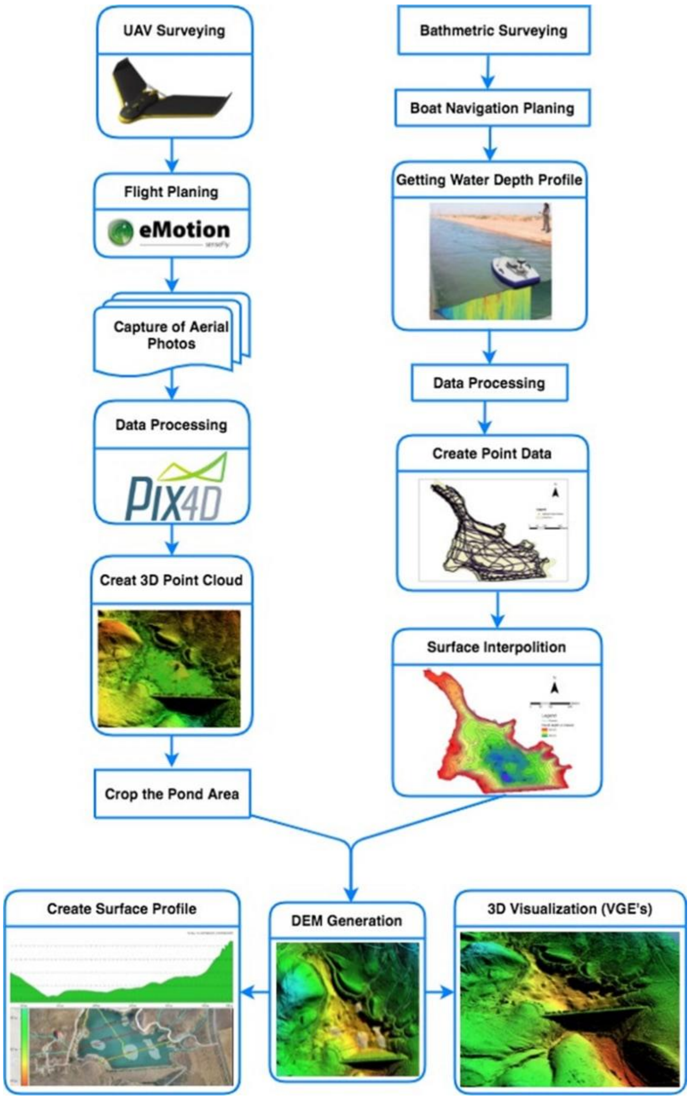

Figure 2. Flowchart diagram of UAV, bathymetric data acquisition, and processing

Figure 3. UAV, SODA camera, and generated DSM from UAV mapping

Table 1. UAV and Canon IXUS 127 HS camera device technical properties

UAV device technical properties	
Wingspan	0.96 cm
Weight (incl. supplied camera & battery)	0.7 kg
Radio link range	3 km nominal
Cruise speed	36-57 km/h
Max. flight time	45 minutes
Absolute horizontal/vertical accuracy (with GCPs)	Down to 3 cm / 5 cm
Canon IXUS 127 HS Camera device technical properties	
Sensor size	6.16 x 4.62 mm
Sensor type	RGB (16.1 megapixel)
Ground resolution (~100 m)	5 cm/px

Fourteen ground control points (GCPs) were used to georeferencing the images (RMS error: 0.049 m). Javad TRIUMPH Geodetic GNNS receiver was used to measure ground control points (Figure 4). According to the RTK (Real-Time Kinematic) method, measurements were carried out with a GNSS receiver. The coordinates of the ground control points were determined by making 120 epoch measurements according to the WGS-84 UTM Zone 36-N coordinate system.

Figure 4. The ground control points in the study area

2.2.2. Acoustic doppler profiler device

In the bathymetric mapping, the Sontek M9 Acoustic Doppler Current Profiler device was used. This device can make high-speed and precise measurements, especially in the pond for water velocities and flow measurements. This device has a total of 9 transducers, including one piece of 0.5 MHz Vertical Profile Ultrasonic transducer, four pieces of 1 MHz, and four pieces of 3 MHz 250 angular profile ultrasonic transducers. The device can take a profile of 0.06-40 m while measuring the depth of 0.2-80 m. Using the DGPS unit within the device, the measuring points are recorded with location information with approximately 10 cm precision [47]. The boat movement trajectory was not automatically provided in the study. Full linear trajectories could not be followed due to manual control of the boat engine, the drag effect of the wind, the presence of tree branches on the shores of the lake. Gap entire coastline of the lake has been completely crossed, and in areas where the slope has changed rapidly, transitions have been made at intervals of less than 5 m, while in areas where the slope has changed little, transitions have been made a gap of 10 - 15 m and more. The boat speed has the lowest possible speeds that have been selected for the ADCP device to make accurate measurements. The main parameters of the Acoustic Doppler Current Profile device are displayed in Table 2.

Table 2. Acoustic doppler profiler device mechanical properties

Depth	0.2-80 m
Temperature range	-5 ºC to 50 ºC
Salinity	0 ppt to 60 ppt
Acoustic Frequency	3 MHz, 1 MHz, 1.5 MHz, 250 MHz, and 500 MHz
Battery	30 days
Coordinate System	ENU
Accuracy	±1.0%

This device can measure water velocities and depth by sound waves. The primary design purpose of the device is for flow measurement in rivers. The salinity changes and temperature of the water within the stream do not show much variation in the depth. Due to the ponds' stratification event, parameters such as water temperature and salinity level in the pond vary depending on the depth. This causes the device's sound waves to move at different density water layers depending on the different temperatures and salinity. These changes are not taken into account when calculating the transmission and return time of the sound wave, leading to inaccurate depth results.

For this reason, Sontek, the manufacturer of the device, has developed another type of equipment called the hand-held conductivity, temperature, and depth (CDT) measuring device (CastAway CDT). This device records the temperature and salinity levels depending on the depth and provides the necessary corrections in the Sontek M9 device's measurements. More precise bathymetric mapping of the Sontek M9 ADCP device has been provided (Figure 5).

Figure 5. ADPD – a) device conceptual view; b) CastAway CDT device usage [47]; c) device usage on site

The data obtained from the device was exported with Matlab software. The depth values measured by the transducers measured by the vertical transducer measured by the device and the depth values measured by the transducers, and the measurement results in each transducer against the problems that can be experienced during the measurement were verified, and the depth data were obtained. The measurement works were carried out by splitting it into three different parts and accomplished within the same day due to the long distance covered in the pond and the difficulties caused by the terrain conditions. Before the measurements were made with the Sontek ADCP device, compass calibration of the device, battery power level checks were performed to ensure that the measurements were made continuously and accurately. Also, magnetic declination value used for correction of measurement direction errors affected by compass deviation between magnetic north and geographic north. The SOLINST Water Level Meter Model 101, which is used to measure the depth of water in underground water wells, was used to check whether the ADCP device gives the correct depth data during field measurements. According to the measurement study conducted at 10 random points in the lake, an RMSE value of 4.8 cm was obtained between the depth measurements performed with ADCP and the measurement results performed with Water Level Meter. It is seen that this obtained value is consistent with the literature [48].

The routes followed in the measurement study carried out with the Sontek M9 ADCP device are shown in Figure 6. At each point, the latitude and longitude coordinate values, the depth measured by the vertical transducer, and the depth values measured by the transducers built into the angular were recorded.

The data obtained from 3973 points on the pond area were modeled using ArcGIS software. The generated raster data should be cut according to the lake boundary. The lake boundary was obtained by digitizing the orthophoto data obtained from the UAV. UAV data is 6 cm resolution data. At the end of the study, A 2-dimensional bathymetric map was created (Figure 6).

3. Results and Discussion

This study is desired to determine how the sediments carried by the mainstream and side tributaries feeding the pond affect the pond's water volume and in which parts of the pond their accumulation is concentrated. And, to expose the 3D model of the pond in the presence of UAV and Acoustic Doppler Profile bathymetry to precisely determine the actual amount of water in the pond. Water topography can be obtained very clearly from the data obtained from the UAV. However, a similar accuracy cannot be obtained from the water surface. Therefore, the water area has been removed from the UAV data. Bathymetry DEM data defined in the same coordinate system is added to the extracted area and combined with the UAV data (Figure 7). The resulting map helps us to learn about the current and subsequently dried tributaries of the Borabey pond and changes in its surroundings.

When the resulting map is examined in detail, it was determined that there are sediment accumulation areas (Zone 1- 4) at certain places on the bottom of the pond, and it was recorded on the map. To determine this sediment accumulation, cross-sections (Sections 1 - 4) were placed in specific regions, and the results were interpreted. Since the stream that feeds the pond contains seasonally different flow regimes, and sediment accumulated by wind and wave effects in this relatively shallow region accumulates in other sections (Figure 8).

The mainstream tributary that feeds the Borabey pond flows during the year's pluvial, while it dries out in the summer season and does not contain surface runoff. Cross-section 1 located at the input side of the stream to the pond is examined, and it is observed that sediments arising from the flow of the stream accumulate at the entrance point. When we examine cross-section 1 shown in Figure 9 examine closely, it is seen that the accumulated sediments are generally concentrated in the area up to 75 m from the beginning of the pond.

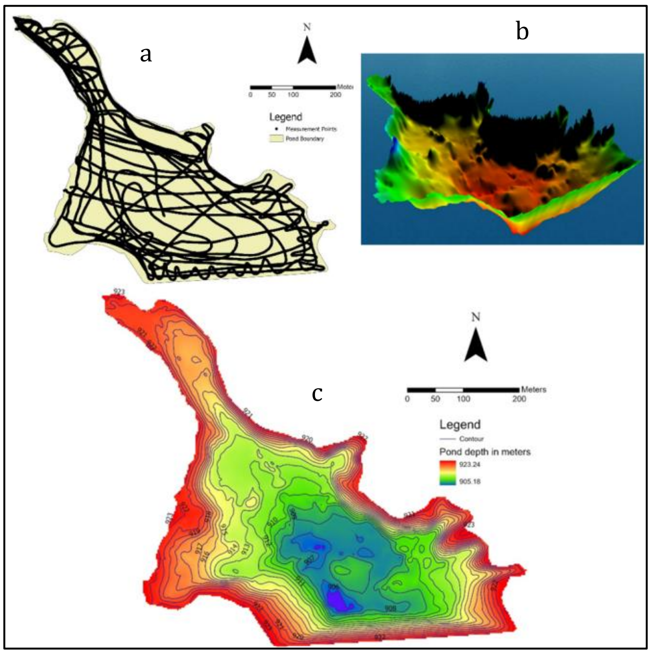

Figure 6. Pond ADCP a) measurement point; b) 3D bathymetry DEM; c) 2D bathymetry map

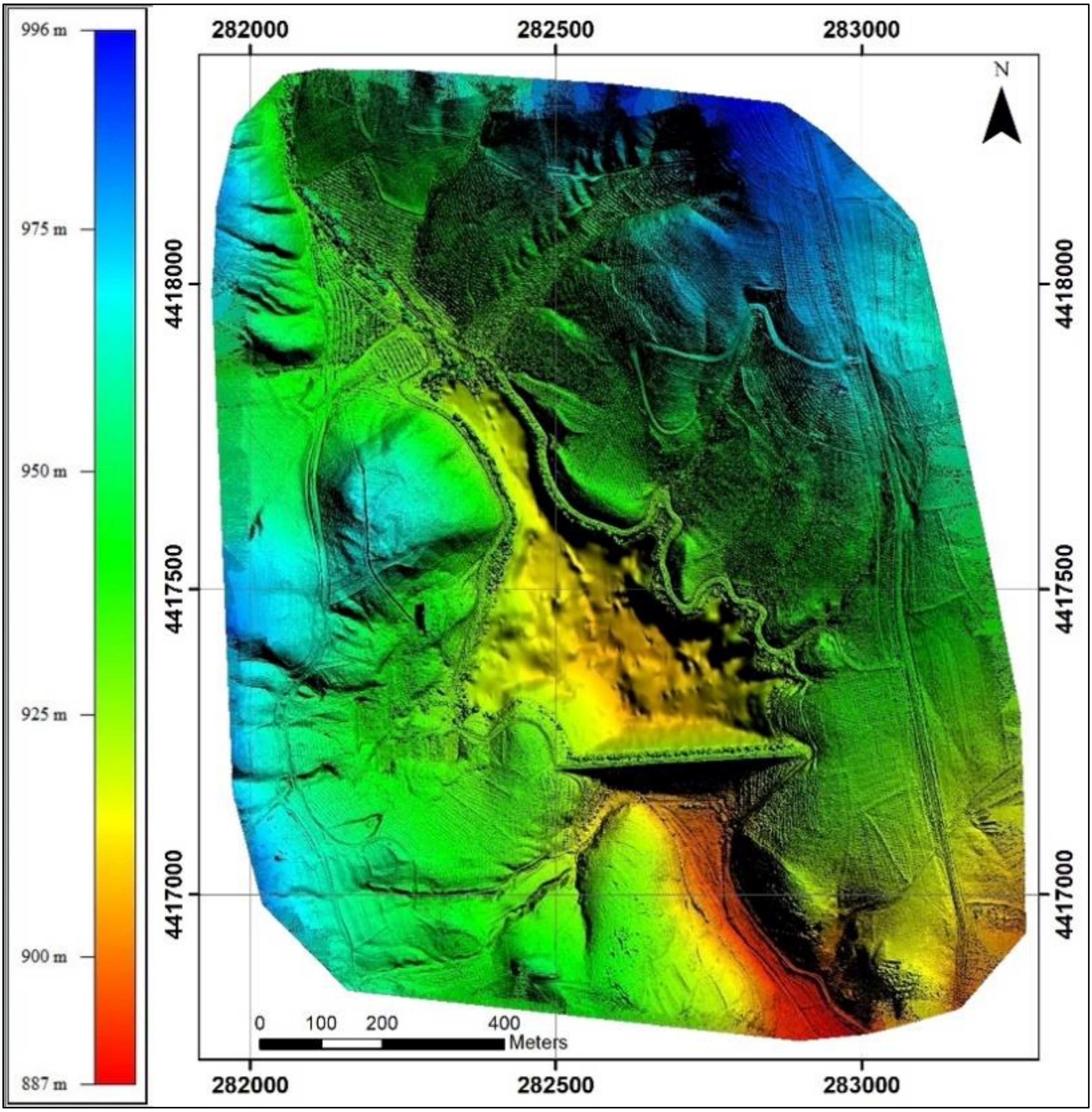

Figure 7. Combination of DEM bathymetry and UAV data

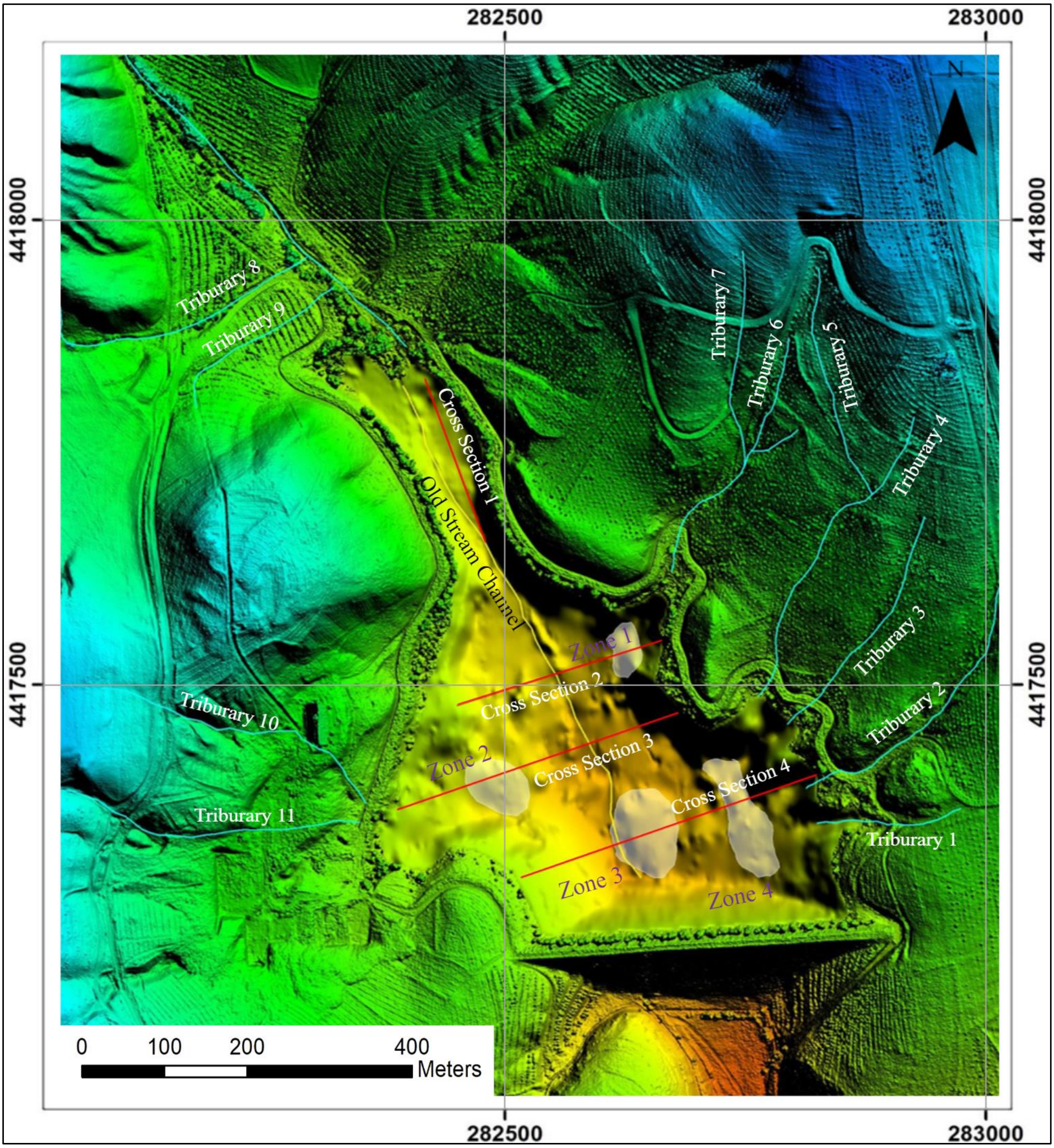

Figure 8. Combination of bathymetry DEM and UAV DEM

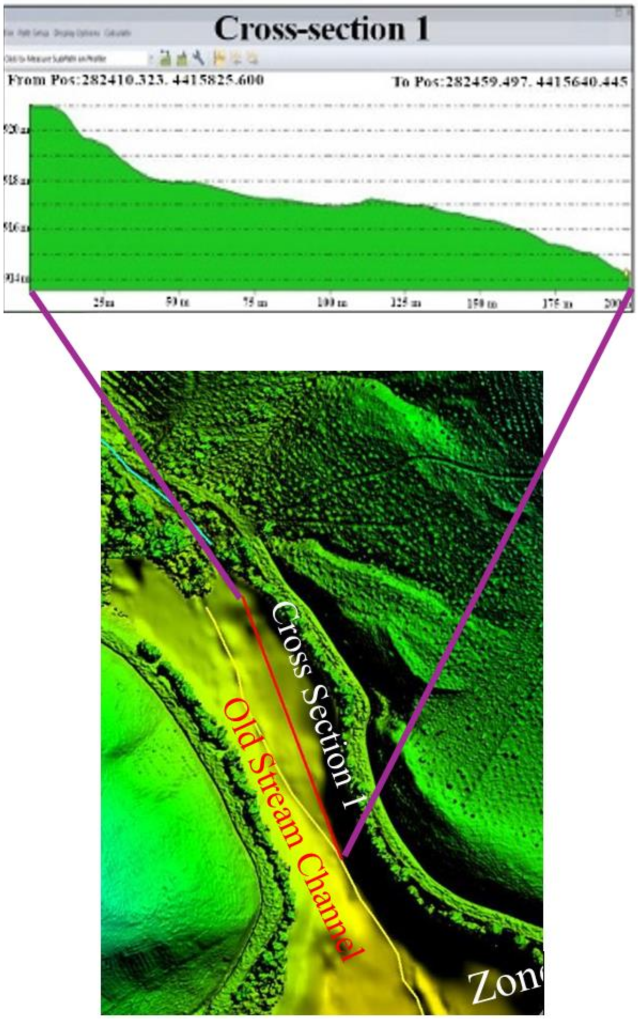

Figure 9. Cross-section of Borabey pond; the section located in the entrance area of the river is cross-section 1

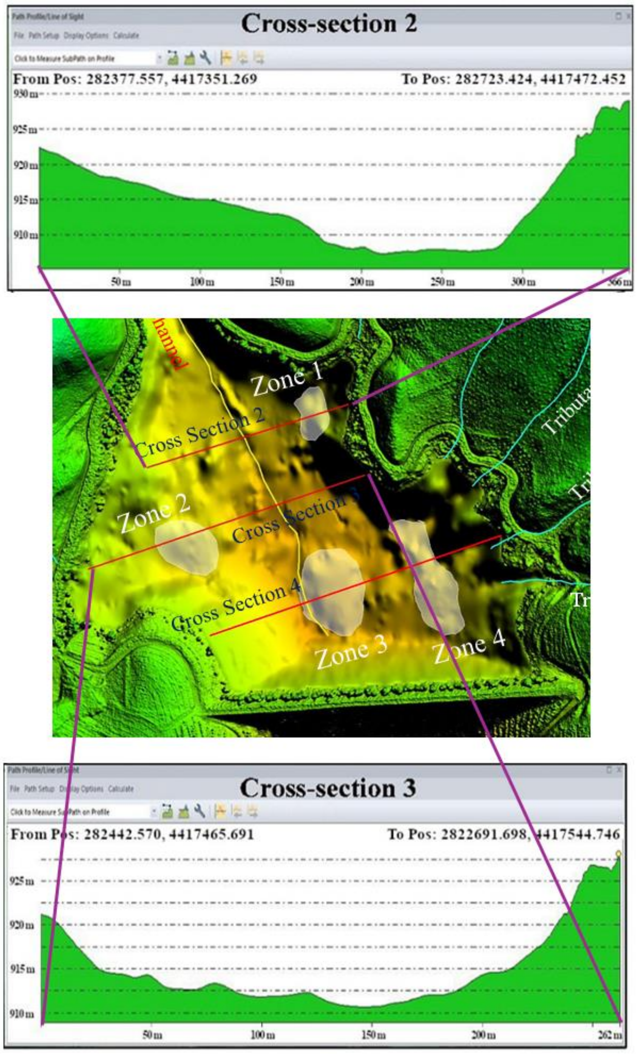

Figure 10. Cross-section of Borabey pond; cross-section 2 and 3 situated in the middle part of the pond

As shown in Figures 8 and 10, it is possible to say that the sediment accumulation in section 2 was caused by the sediment transport of tributaries 6 and 7. When cross-section 2 is examined in detail, it is seen that the sediment accumulation is intense approximately 280 m after the left of the cross-section due to the sediments carried by tributaries 6 and 7. Additionally, it is observed that a zone (Zone-1) is formed due to the accumulation of this sediment formed in cross-section 2. Cross-section 3 is examined, and it is observed that sediment deposition occurs in the right part of the pond approximately 25 – 150 m from the left part of the pond with sediment transport processes arising from tributaries 10 and 11. Besides, it is observed that a zone (Zone-2) was formed in cross-section 3 due to the accumulation of sediment from tributaries and the remains on the pond bed observed in field studies (Figure 10).

In cross-section 4, it is observed that the sediment input arising from the tributaries (tributaries 1, 2, 3, 4, and 5) located in the right part of the pond form 2 separate sediment accumulation zones in the pond. When we examine closely cross-section 4, it is observed that there is sediment accumulation in the region located approximately between 190-350 m (Figure 11). Also, when examining each cross-section, it is observed that the pond has undergone sediment accumulations due to sediment transport caused by the old water channel (thalweg). Besides, in UAV measurement data and field observations, it was observed that areas with trees remained underwater before turning the pond into a dam, and tree parts were moved to the pond floor by the new regime of flow in the pond.

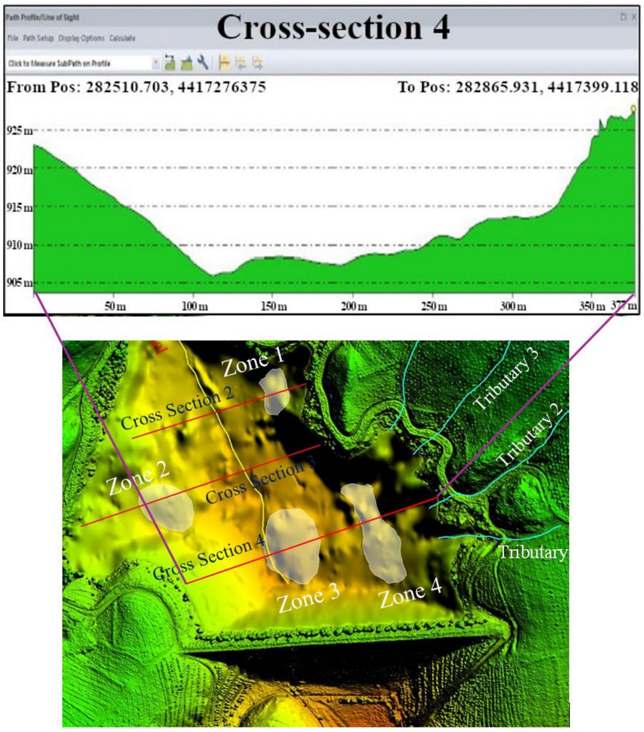

Figure 11. Cross-section of Borabey pond; cross-section 4 located in the lower part of the pond

The sediments carried by tributaries 10 and 11, located on the right coast of Borabey pond, were not very influential on the pond due to the land's lower slope, construction work in the area where it was located (Figure 8). However, the pond's old drainage structure and the sediment input from the old flow channel cause the formation of sediment zone in this area. For Zone 1, it is observed that the sediment transport caused by tributary 6, consisting of a combination of 3 separate tributaries, creates sediment accumulation in such a way as to take the form of a triangle (Figure 10). It is observed that the sediment accumulation of, the so-called Zone 2, forms a hill like a triangle and its peak is about 26 m away from the left part of the zone (Figure 10). The area is shown in Zone 3, is where the pond has the largest water body and is one of the regions where the most cross-section of the pond is wider. It is estimated that some of the sediments that came to the pond from the pond's construction date to the present day were transported to this area and deposited here. It is observed that the sediment accumulation formed a hillock with the load caused by the old flow channel of the pond (Figure 11). It has been observed that sediment accumulation in the region shown as Zone 4 accumulates in the form of a hillock, feeding on sediment from the erosion channels of tributaries 1-5 (Figure 8, Figure 11).

This study shows that Acoustic Doppler surveying systems, a fast and accurate measurement technique, can be used as an alternative to the bathymetric measurement studies performed in ponds. It can be seen that the Acoustic Doppler Current measuring device, which is used in this study and whose main function is a current measurement in rivers, can be used in such measurements without extra equipment cost. The conversion of bathymetric maps into 3D maps with VGE provides better management and protection of ponds in addition to scientific research. The 3D maps obtained in the scientific and administrative process can also increase public awareness and information about ponds. In this context, making such 3D maps can significantly protect sensitive areas and promote protected areas and national parks of great tourist importance.

4. Conclusion

Freshwater resources are vital in terms of the survival of living components. However, some freshwater resources are located in underground aquifers that are not suitable for human use. For this reason, it is of great importance to protect and manage surface water sources such as ponds, rivers, and streams that are suitable for humans. In this study, a bathymetric map was obtained, which will guide the changing structure of the Borabey pond from the past to the future. Bathymetry maps are generally built with sonar devices used in high-cost and large bodies of water and devices such as airborne LIDAR. However, this study used an Acoustic Doppler Profiler device, which has a low cost and offers advantages in small water bodies. The Acoustic Doppler Profile device provides a high advantage in determining the elevation-area-volume expressions of ponds. However, the presence of layers unconsolidated in shallow water bodies, such as rivers and lakes, can lead to variations in the use of the ACDP device. Additionally, the presence of unconsolidated bed layers in these water structures may create challenges in collecting field measurements in shallow areas. To mitigate these issues, it is crucial to establish station points for georeferencing images that will accurately represent the terrain topography [38].

The use of high-resolution and georeferenced spatial images of UAV, another data source used in creating a 3D model of Borabey pond, significantly increases the quality of the 3D model. Also, UAV systems are rapid, high-accuracy and inexpensive systems for producing high resolution DEM and orthomosaic around ponds compared to aircraft-based photogrammetric systems and conventional terrestrial surveys. Besides, management of remote data acquired through UAV allows us to learn about areas that are difficult to reach. However, the integrated use of UAV and ACDP technologies also brings certain limitations. The sensitivity of UAVs to weather conditions can limit the data collection process and reduce the quality of the captured images. Similarly, the use of ACDP may vary due to underwater conditions, affecting data accuracy. To overcome these challenges, it is recommended that fixed station points be established for the accurate georeferencing of UAV images and that advanced calibration techniques be used for collecting ACDP data. Future research should focus on optimizing the use of these technologies and improving data integration by employing precise positioning systems, such as Real-Time Kinematic (RTK) GPS, and advanced sensors. Furthermore, the limited resolution and accuracy of UAV and ACDP sensors may lead to an inadequate representation of real-world features, particularly in areas with complex or variable topography. To address these limitations, it is recommended to employ advanced algorithms and software in data integration processes, utilize higher-resolution sensors, and adopt cloud-based data processing and storage solutions. Future research should focus on optimizing the application of these technologies and enhancing data integration by incorporating machine learning and artificial intelligence techniques.

By integrating cartography's functionalities and then GIS in a virtual world, a better space for research is born: Virtual Geographic Environmental (VGE). A VGE is a new tool used in geography that has revolutionized the way we see the Earth. Virtual Geographic Environment is a three-dimension environment that multi-agents can use. Inside that computer-based environment, complex geographical datasets can be released to simulate processes or phenomena for various purposes, such as solving a problem or predicting a problem. This study enabled the determination and interpretation of the change of the Borabey pond. It is also of great importance in obtaining information for both academics and management by examining the change in 3D.

The visualization of the data produced by the Acustic Doppler and UAV used in this study in VGE provides important outputs in terms of determining the sediment accumulation areas of the pond, accurately identifying the branches feeding these deposits and predicting the future accumulation areas in smart water management. Adopting VGE can improve the quality of research in environmental sciences and solve environmental problems with more accuracy. Besides, it reduces costs by analyzing and solving possible issues by simulating the study area from a computer without fieldwork. Moreover, visualization in 3D or more through a Virtual Geographic Environment can be of good help in decision making. VGE helps us see beyond what eyes can see. It is imperative as the environment faces critical problems nowadays, and humans want to understand them better and find efficient solutions. Virtual Geographic Environment can be considered as a good helper in environmental assessment. A detailed visual resource has been created for researchers and decision-makers with the 3D model and virtual reality of Borabey pond. Besides, this study is critical in creating 3D models of water areas that are important for Türkiye, contributing to tourism, creating a resource for researchers, and creating visual data for decision-makers.

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Author contributions

Zehra Yiğit Avdan: Conceptualization, methodology, supervision, validation of results, writing – review and editing. **Ece Tuğba Mızık:** Data interpretation and writing original draft – review and editing. **Serdar Göncü:** Fieldwork, data interpretation – review and editing. **Resul Çömert:** Fieldwork, review, and editing. **Uğur Avdan:** Fieldwork, data generation, writing – review, and editing.

Conflicts of interest

The authors declare no conflicts of interest.

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