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Quantifying the Reliability of Volumetric and Areal Calculation with UAV-Generated DEMs: A Comparative Study with Ground Truth Data

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Keywords:
UAV; DEM; Volume Calculation; Negative Volume; Flight Parameters.

Highlights:

- *UAVs provide more detailed data than traditional surveying for small depressions.*
- *Comprehensive analysis done by comparing GNSS RTK, and UAV DEM for volume estimation.*
- *UAV-DEMs accurately quantify negative volumes with 97% accuracy.*

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Abstract: For performing an assessment of the volume estimation accuracy using Digital Elevation Models (DEMs) generated by Unmanned Aerial Vehicles (UAVs), an evaluation of suitability has been made. The study was operated at Tikrit University, on a man-made topographic depression in the form of fishponds. The generated DEM by using the images of the UAV followed by accuracy assessment using Ground Control Points (GCPs), the points distributed evenly throughout the pond. The results showed that the Root Mean Square Error (RMSE) calculated for the DEM at the optimum flight plane ranged between 0.14 to 0.45. Comparing the pond's predicted volume utilizing UAV DEMs to the ground truth volume obtained using GNSS RTK surveying, it was discovered that the UAV DEM calculation was 97% accurate. The study came to the conclusion that the UAV Structure from Motion (SFM) method and the generated DEMs are appropriate for precisely surveying the volumes utilizing the appropriate range of flying parameters based on prior knowledge.

قياس موثوقية الحسابات الحجمية والمساحية باستخدام نماذج الارتفاع الرقمية المنشأة بواسطة الطائرات بدون طيار: دراسة مقارنة مع البيانات الأرضية الحقيقية

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قسم علوم الارض التطبيقية / كلية العلوم / جامعة تكريت / تكريت – العراق.

الخلاصة
لضمان التقدير الدقيق للحجوم باستخدام نماذج الارتفاع الرقمية (DEMs) التي تم إنشاؤها بواسطة الطائرات بدون طيار أو الدرون (UAVs)، يجب إجراء تقييم لمدى ملاءمتها لهذا الغرض. تم إجراء الدراسة في جامعة تكريت حيث تم تحديد حوض اصطناعي للأسماك. تم استخدام صور الطائرة بدون طيار وبمعاملات طيران مختلفة لإنشاء DEM وأجري تقييم للدقة باستخدام نقاط سيطرة أرضية دقيقة وموزعة بالتساوي في الحوض. أظهرت النتائج أن الـ(RMSE) لـ DEM الذي ولد باستخدام معاملات الطيران الأمثل تراوح بين ٠,١٤ إلى ٠,٤٥. تم حساب حجم البحيرة باستخدام DEM المولدة بواسطة الطائرة بدون طيار، وتبين أنه دقة القياس تصل الى نسبة ٩٧٪ مقارنةً بحجم الحقيقي الذي تم استخراجه بواسطة GNSS RTK استنادًا إلى هذه النتائج، استنتج البحث أن خوارزمية (SFM) مناسبة لرصد الحجوم بدقة باستخدام نطاق مناسب من معلمات الطيران.

الكلمات الدالة: طائرة بدون طيار، نماذج الارتفاع الرقمي، حساب الحجوم، الحجم السالب، معاملات الطيران.

1.INTRODUCTION

The UAVs used for measuring volumes in recent years have been obtaining momentum in growth term Stalin and Gnanaprakasam [1], tested the utilization of UAV imagery in measuring the stockpiles volumes. Accurate determining of stockpile volumes is important for effective planning and resources management. the decision of the study that drone imagery can efficiently calculate stockpile volume with reduced cost and time consumption is particularly significant. The study suggested that the technology can potentially optimize resource management processes. The use of DEM based volume calculation for accurate volume computation was studied by Cho et al. [2], and the DEM data obtained from the drone survey has reported the accuracy. The findings revealed that the new DEM method can be applied to Building Information Modeling (BIM) design and construction instead of the cross-section method. Kim et al. [3] focused on improving the accuracy and efficiency of calculating earthwork volume, especially for irregularly curved terrains like mountains, reservoirs, and coasts, using UAVs. The authors propose a method that automates the on-site calculation of construction errors and supports the on-site monitoring using BIM using a chain method with a planned plane map based on the average end-area method. They also applied the digital surface model method to optimize the earthwork volume calculation using UAV. The study provided specialized construction management information for excavation work. Overall, the proposed earthwork analysis using UAV can intuitively review earthwork progress in 3D by linking the current site with the planned plane. Furlan et al. [4] utilized high-resolution images taken by UAVs to monitor changes in wetlands' dynamics and landscape. In a wetland in São Paulo's Paulista Peripheral Depression, the research simulated flooding and water flow and validated the simulations. Data obtained by UAV was used to validate the seasonal water storage volume of wetlands and the flooding simulations. By Using simulated submerging analysis and UAV photogrammetry a novel technique for estimating sediment silted by check dams in China's Loess Hilly region was put forth [5]. The study uses regression analysis to create five different models for estimating the sediment volume and residual capacity of check dams. the area-volume model, is one of these models which showed a high level of accuracy and had the potential to evaluate sediment retention capacity across the entire region. Previous research in volume calculation has focused on DEM's to calculates volume, with accuracy assessed using RMSE based on ground control points at specific locations. However, this study recognized the limitations of this approach and aimed to calculate the volume of a regularly shaped, manly made depression using both leveling instrument and global navigation satellite system (GNSS) real-time kinematic (RTK) techniques. Furthermore, the study compared the volume estimate obtained through these methods with the volume derived from a UAV DEM's, this will provide a comprehensive analysis of the different approaches.

1.1. Study Site

The study site is Tikrit University in Tikrit city, Salah Al-din governorate. The area is defined by coordinates between two latitudes (34°40'54" N) (34°40'41" N) and between two longitudes (43°38'3" E) (43°39'51" E). The study area encompasses a topographic depression and a fishpond. The total captured area of interest is (26,200 m²). It must be larger than the pond because some uncertain edges were removed during the DEM generation process. These edges were captured by only a few images, leading to lower confidence values along those boundaries., which serve as the primary focal points of investigation and as a control for the analysis. Fig. 1. shows a map of the study area in satellite images. Digital Terrain Model (DTM) and Digital Surface Model (DSM) are DEM types that represent a certain area topography. They are different regarding the information they represent. A DTM represents the bare earth surface without any vegetation cover, buildings, or other objects. It only includes the ground surface elevation and is often used for terrain analysis, hydrological modeling, and civil engineering design applications. DTM is also called as Digital Elevation Model (DEM). On the other hand, DSM represents the earth's surface, including all objects above it, such as buildings, trees, and other structures. It is used for various applications, such as 3D modeling, urban planning, and aerial imagery analysis (Krauss et al., 2011). The difference between the two models is shown in Fig. 2.

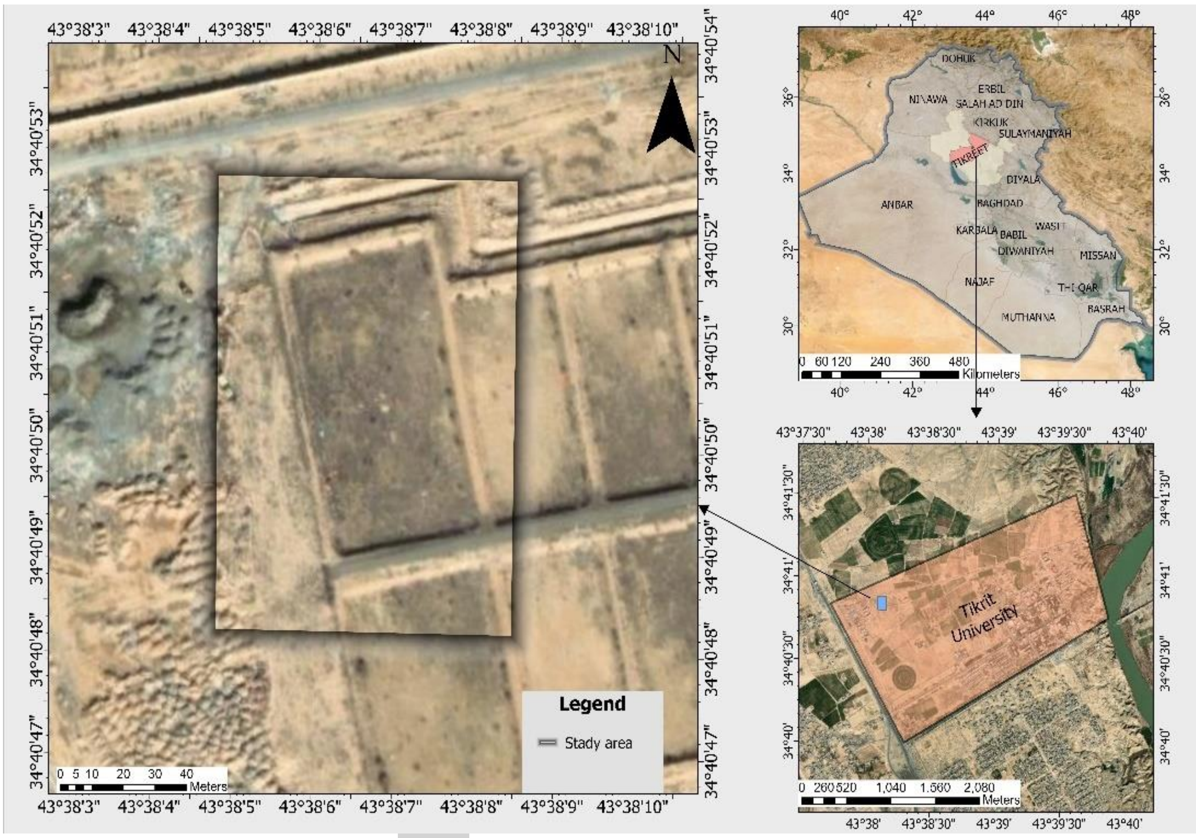

Fig. 1 The Area of Interest in Iraq.

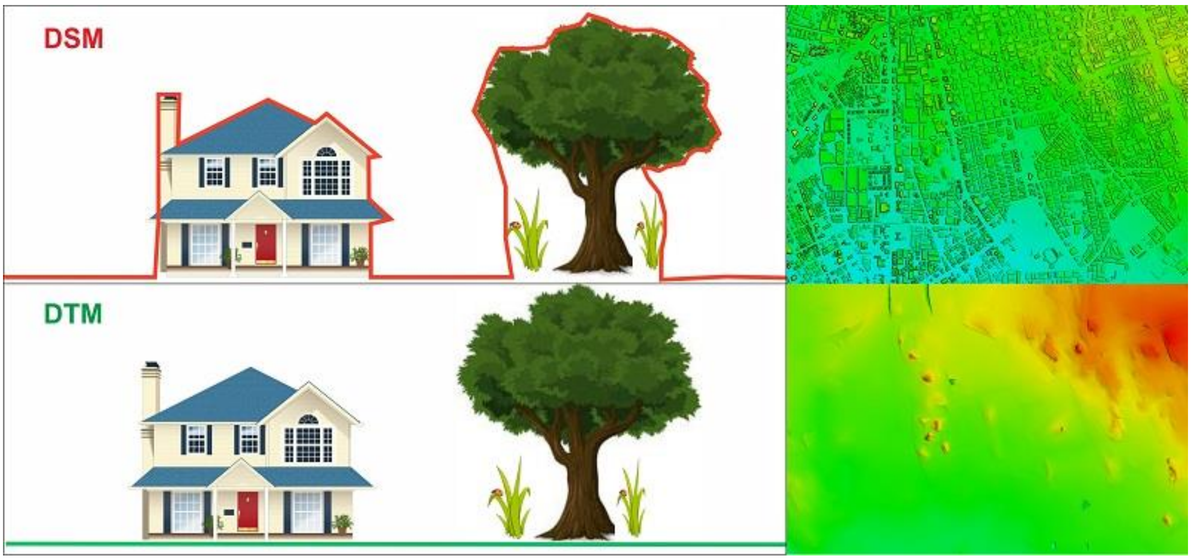

Fig. 2 Deference between DSM and DTM.

2.METHODOLOGY

2.1.Devices Specifications

DJI Mavic 2 Zoom used in field work surveying purposes. This UAV can classified under multicopters category. The multicopters yielded excellent outcomes for the ground features in areas with steeper slopes [6]. This UAV has the following specifications: sensor with 20 million effective pixels, a camera lens with a 35 mm format equivalent to 28 mm, and an aperture can range between f/2.8-f/11. The electronic shutter speed ranges from 8 to 1/8000 seconds,and dimensions of the still images are 5472x3648 pixels. The drone maximum speed is about 5 meters per second and maximum flying duration is 31 minutes under calm wind conditions. The GNSS technology used is a combination of GPS and GLONASS, with a maximum broadcast range of 10000 meters [7]. An additional multicopter was used. The DJI Mavic Air 2S gained a reputation for its small size and impressive performance. The UAV is equipped with a sensor that has 20 million effective pixels, camera lens with a 35mm format equivalent to 22mm, and an aperture between f/2.8 to f/11. The shutter speed range 8 to 1/8000 seconds, and dimensions of the still images are 5472×3648 pixels. The gadget's maximum vertical speed is 6 meters per second and the maximum duration of flight is 31 minutes in calm weather conditions. The GNSS-RTK was used. The E600-N model can reach horizontal measurement precision between 8mm+1ppm RMS, and a vertical measurement accuracy between 15mm+1ppm RMS. The survey points' precision was linked to the use of RTK mode, because all data points were gathered using this technique. It is possible to verify the accuracy and reliability of each UAV by comparing the volume estimated using RTK technology to the volume estimated using UAV DEM. Utilizing this comparison may also aid in identifying disparities or contradictions between the two approaches.

2.1.1.Flight Parameters

Flight planning is a crucial stage in UAV photogrammetry because it controls the selecting of the optimal flight path for the UAV operation to achieve the desired coverage and capture the necessary pictures. The flight plan aims to provide excellent images while reducing the duration of the flight and prevent any risks to both the UAV and those in the vicinity [8]. Drone Harmony and Drone Deploy, two mobile apps were used in the fieldworks. The choice to use two distinct mobile apps, for the fieldwork was motivated by the specific compatibility requirements of the UAVs. The Drone Harmony application was found to be entirely compatible with the Mavic Air 2s drone. The Drone Deploy application was found to be more compatible with the Mavic 2 Zoom drone. The first step in UAV flight planning is to select the appropriate area based on project requirements and mission goals. After selecting the area of interest, determining the optimal flight altitude is crucial to achieving the desired image resolution and scale. A higher altitude results in lower resolution but broader coverage. Additionally, the overlap percentage between images is essential for accurate image matching and 3D modeling. The parameters of the flight mission are illustrated in Fig. 3. Altitude is one of the most essential factors in a UAV flight. The flight time, area covered, the number of photos per unit area, and the spatial resolution of images captured are affected by altitude. The point cloud's clarity was significantly influenced by aircraft height. The lower altitude of the UAV, the more precise the texture of the point cloud. The clarity increases with the drop in height. The altitude of an aircraft significantly affects the timescale for fieldwork. The time required for field operation decreases as the altitude rises; at this point, less power is required to run the UAV [9]. The altitude indicated by the resolution is referred to as the "GSD" (ground sample distance). The formula of the GSD Eq. (1).

$$GSD=\frac{SW*FH}{f*IW}\times 100 \quad (1)$$

Where SW is the sensor width in mm, FH is the flight height in m, F is the focal length in mm, and IW is the image width in mm. Image overlap is a method that ensures that the UAV sequential images can satisfy the needs of surveying and mapping and that there are enough comparable feature points to finish image mosaicking or mapping [10]. Front and side overlaps are the ratio of overlapping images can be explained in Fig. 4. The fight operation duration will extend due to the increase in overlap, which will also improve data accuracy. Each software or author advised a minimum limit for the overlap ratios. For example, the Pix4D software manual advises that UAV photos require at least 75% front overlap and 60% side overlap [11]. To reduce gaps caused by changes in flight height, tilt, and terrain variation, it is suggested that the overlap in surveying operations must be greater than 50%. 3D formations with low overlap percentages are unclearly adequate [12]. The UAV speed is one of the user-defined characteristics that can be chosen in the flight plane. The speed of a UAV during a survey is determined by multiple factors, including the UAV model, its payload, flight altitude, and wind conditions. Depending on its features and specifications, a UAV can travel from a few knots to several hundred knots. UAVs are often flown at slower speeds for surveying purposes to allow accurate data collection and mapping. This can be accomplished by flying the UAV at a lower altitude or a slower airspeed. The exact speed will be determined by the survey requirements and the capability of the UAV. The UAV's speed must be chosen according to the shutter speed because if it moves while the shutter is open, more light will be captured from a wider area, resulting in blurry images. Also, flight speed directly affects power consumption [13].

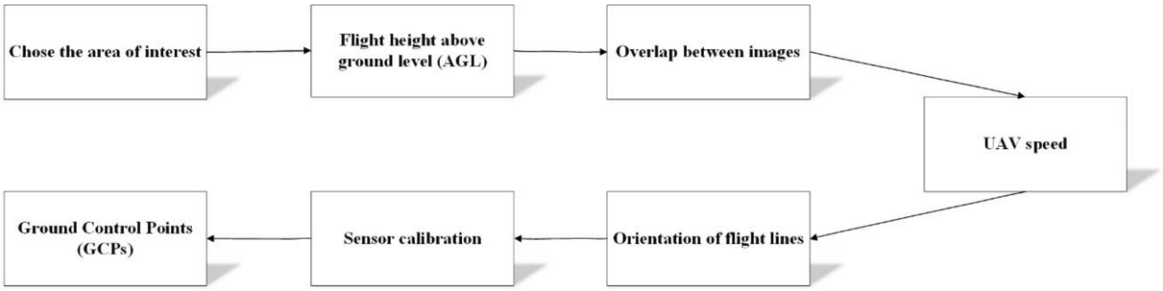

Fig. 3 Flow Chart of the Flight Plan.

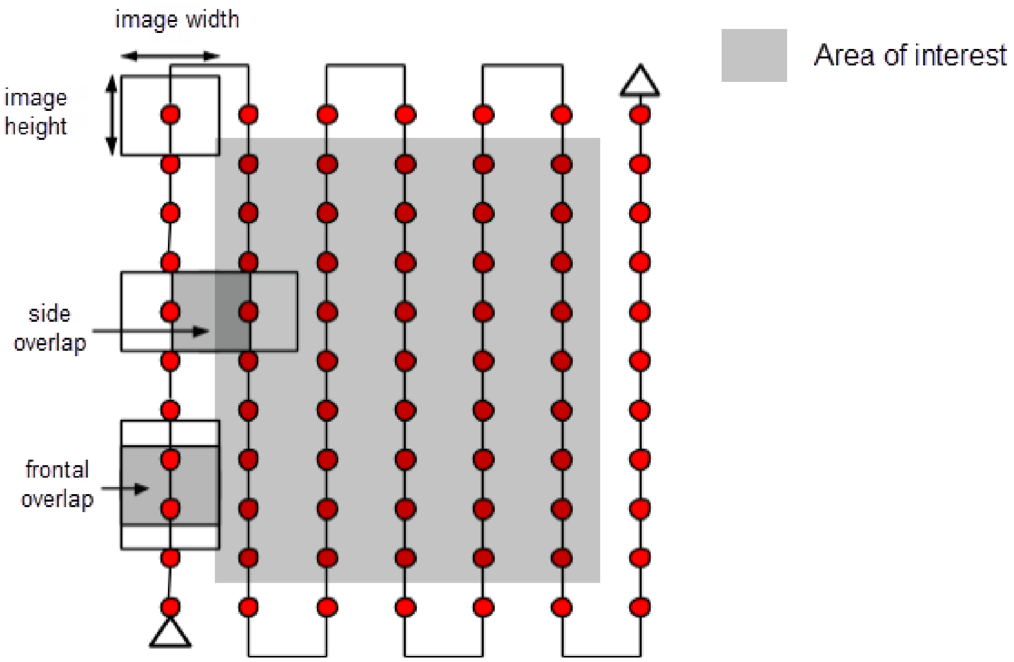

Fig. 4 The Front and Side Overlap.

In flight planning, the gridding scenario is an essential factor that can impact the final product's accuracy for topographic mapping projects. To cover the study region, there are two basic scenarios: single gridding and double gridding. Using double gridding for mapping purposes can result in more precise outcomes, particularly in regions with intricate topography or considerable variability in elevation. However, it typically requires more time and resources than single gridding. The selection between single and double-gridding approaches hinges on various factors, such as the required precision level, the available resources, and the time and cost constraints of the project [14]. Fig. 5 illustrates the differences between single and double gridding. The camera configuration is divided into the nadir (vertical) and the oblique images. For steep terrain, two types of camera configuration can be used, one is the vertical axis, and the other is oblique when capturing the slope images, the oblique images are more suitable in overhangs and steep topography; however, there are some problems, such as the objects rise above the ground, the images captured from the side of the object may cause these issues; moreover, there is a problem with orthomosaic generation. On the other hand, large-scale variation in the single image of the vertical images is the major problem; also, the processing time is longer. The optimum survey in steep terrain combines vertical and oblique images [15]. It is generally true that nadir (vertical) images are well-suited for producing DEMs of areas with gentle elevation changes. Because nadir images are taken directly above the ground, they can be utilized to build highly detailed and precise topographic maps. The vertical perspective of nadir photos can provide a clear and unobstructed view of the ground surface in places with mild elevation changes, making it easier to measure the elevations of different spots on the ground correctly.

Fig. 5 (A) Single Gridding and (B) Double Gridding.

The number and spatial distribution of GCP's highly influence the accuracy of produced DEM. GCPs defined as physical points on the ground with known coordinates used to georeference the images that will be used in the creation process of the DEM. The use of GCPs makes it possible to align the images accurately with the real world and create accurate DEM with the ground. This is often accomplished using geospatial software to turn raw survey data into a representation survey of the region. The size of the pattern of GCPs attached to the terrain is determined by the UAV's height. This feature makes it easier for the software user to identify the pattern in the images that were taken [16]. Homogeneous distribution of GCPs refers to the pattern of GCPs that are evenly spaced and cover the entire survey area. It can aid in high precision and accuracy in the survey [17]. Fig. 6 shows the collection of GCPs by GNSS RTK and the GCPs distribution in the site.

Fig. 6 (A) The Distribution of the GCPs in the Site and (B) Collect GCPs by GNSS RTK.

2.2.UAV Configurations in the Fieldwork

The fieldwork was conducted via multiple separate flights. Each flight has its distinct configuration, as listed in Table 1.

2.3.Images Processing

Triangulation photogrammetry is a technique that determines the three-dimensional coordinates of points in space based on the triangulation principle. It involves using overlapping images of an object or scene from different perspectives. The parallax between the photos can be used to derive the 3D coordinates of points. Photogrammetric software is a form of computer software that can process photos and generate DEMs and maps from them using photogrammetric techniques. Agisoft Metashape (previously known as Agisoft PhotoScan) is photogrammetry software that is used to create digital 3D models from pictures. Users can use Agisoft Metashape to produce high-resolution 3D models, orthomosaics, and digital elevation models (DEMs) from aerial and ground-based photographs [18]. The DEM creating process using Agisoft Metashape was involves the following steps:

- Import images into the software and align them to create the sparse point cloud. This phase determines the position and orientation of each camera and generates the model that can be refined for accuracy.
- Generate the dense point cloud using the aligned images. To handle outliers and improve the density of the point cloud, quality and depth filtering modes are available to changed.
- Utilize the point cloud or dense point cloud data to create polygonal models (meshes).
- Generate a DEM from various data sources, such as dense point clouds, sparse point clouds, or meshes. Adjust parameters are projection type, data source, interpolation, and point classes.
- Customize the DEM generation process to produce the DTMs by classify ground points from the dense cloud or produce DSM without any customize.
- Export the resulting DEM in GeoTIFF, Arc/Info ASCII Grid, Band Interleaved File Format (BIL), or XYZ file format.

This article outlines the process of building DEMs using Agisoft Metashape. It covers the procedures from picture alignment to the final export of the model for future applications. The process of image processing is shown in Fig. 7. To support the precision of the UAV-DEMs, Different methods can be employed. These methods include the utilizing of GCPs with established coordinates and elevations, using checkpoints with known elevations at various locations, comparing the DEM with pre-existing high-resolution DEMs, and visually inspecting the model to detect any evident errors or inconsistencies. The Root Mean Square Error (RMSE) is a statistic commonly used to assessing the accuracy of the DEM obtained by an UAVs. The RMSE quantifies the different between the anticipated and actual values for the (X, Y, and Z) variables. It is calculated by taking the square root of the average of the squared errors. The RMSE is calculated by comparing the coordinates and elevations of GCPs in the DEM to their known values. GCPs with known heights are utilized for this comparison [19]. Low RMSE number signifies high level of precision, while high RMSE value indicates poor level of accuracy. The RMSE value can be influenced by both the picture quality and the quantity of used GCPs. Enhancing the quantity of GCPs and using better quality pictures may enhance precision and reduce the RMSE value [20]. Eq. (1) represents the RMSE formula.

$$\mathrm{RMSE}=\sqrt{\frac{\sum_{i=1}^{n}\left(z_{obs,i}-z_{model,i}\right)^{2}}{n}} \qquad \textbf{(2)}$$

where Obs are the GNSS RTK values for x, y, or z, and model is the DEM values for x, y, or z.

Table 1 UAV Configurations.

Date	Site	Platform	Altitude (m)	Area (m2)	GSD (cm/pix)	Overlap	UAV speed (m/s)	Total Captured Images	GCPs	Weather	Duration (min)
4/10/2022	Fishpond	DJI Mavic 2 Zoom	40	26,200	0.73	80%	3	268	8	sunny	16
4/10/2022	Fishpond	DJI Mavic 2 Zoom	40	26,200	0.73	70%	3	111	8	Sunny	14
15/3/2023	Fishpond	DJI Mavic Air 2S	40	26,200	0.62	75%	6	90	8	Cloudy, windy	10
15/3/2023	Fishpond	DJI Mavic Air 2S	40	26,200	0.62	85%	6	203	8	Cloudy, windy	14

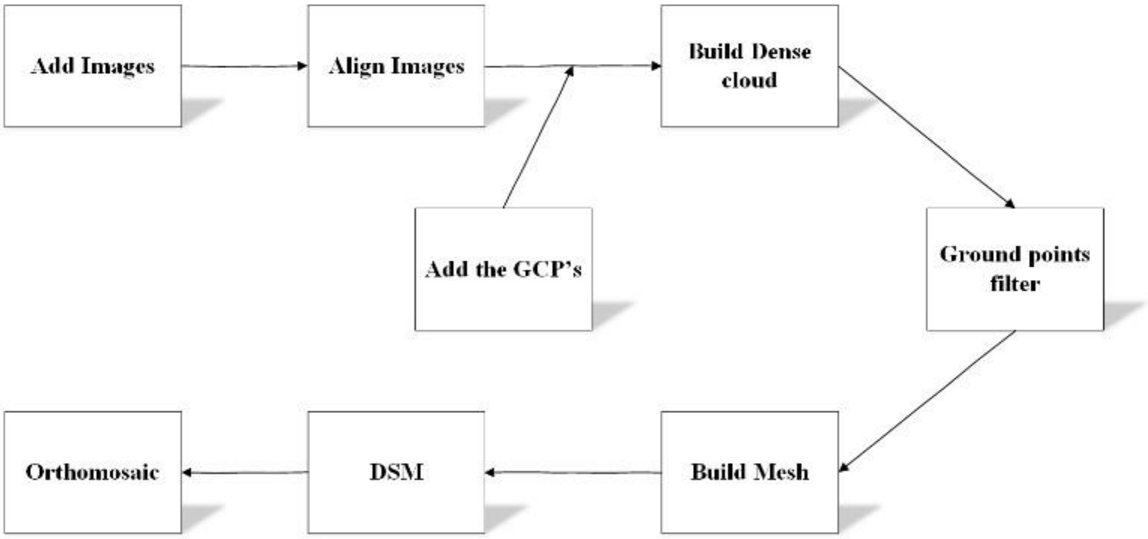

Fig. 7 Agisoft Workflow to Generate DSM and DTM.

3.RESULTS AND DISCUSSION

The DEMs generated from the selected field site were very accurate and high-resolution due to careful and thorough procedure. The method was tested by comparing results from a survey of a fishpond to reliable techniques such as level and GNSS RTK, Fig. 8, With volumetric measurements taken at maximum capacity. The resulting DEMs were compared visually and through volume measurement. The maximum capacity of the fishpond was determined by the highest contour line encompassing it. This closed contour approach is preferable for volume comparison with the DEM generated by the UAV, as it ensures that there is no inclusion of any additional area resulting from the surrounding pixels in the calculation. The objective is to compare the DEMs generated for the same site (fishpond) using different configurations to assess the accuracy of the DEM generated by a UAV. Specifically, the highest enclosed contour volume in each DEM was calculated to compare volume calculations. The visual representation of these configurations is depicted in Fig. 9. The optimal method for illustrating disparities among the DEMs is to generate contour lines with uniform intervals, Fig. 10. Therefore, it was focused on variations in the z values throughout the model. This method provides a clear visualization of the variations in elevation across the terrain and allows for a more accurate comparison of the DEMs. Additionally, contour lines identify errors or artifacts in the DEMs, as abrupt changes in elevation, which do not correspond with natural topographic features, may indicate inaccuracies in the data.

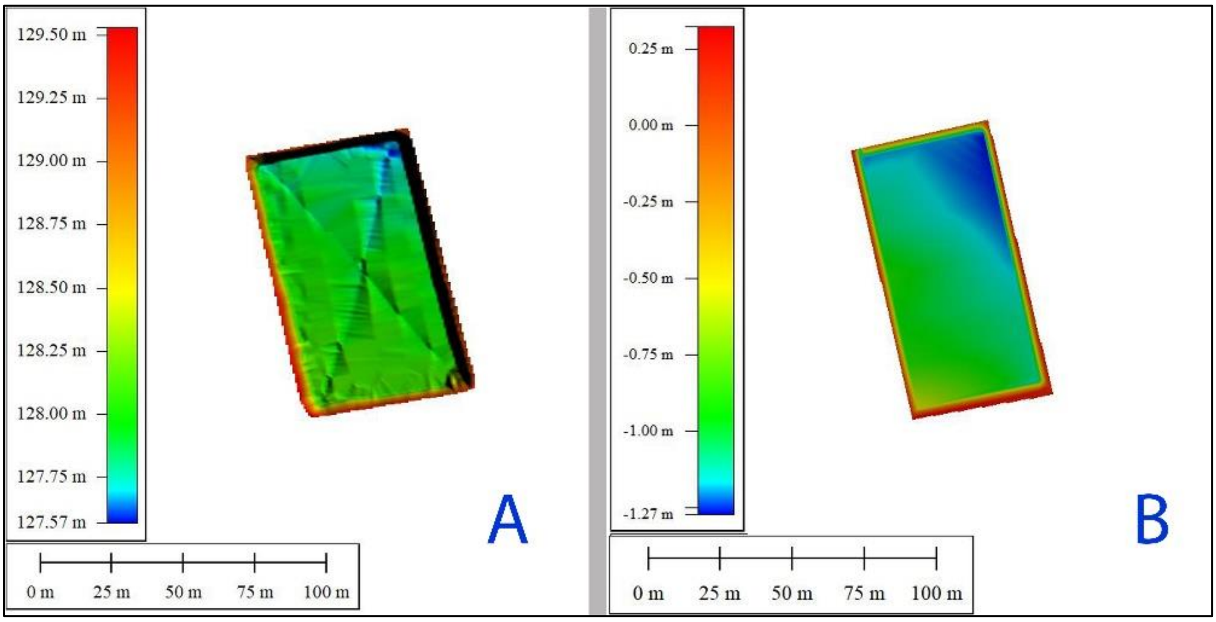

Fig. 8 (A) DEM Generated by GNSS RTK with 1200 Survey Points and (B) DEM Generated by Level.

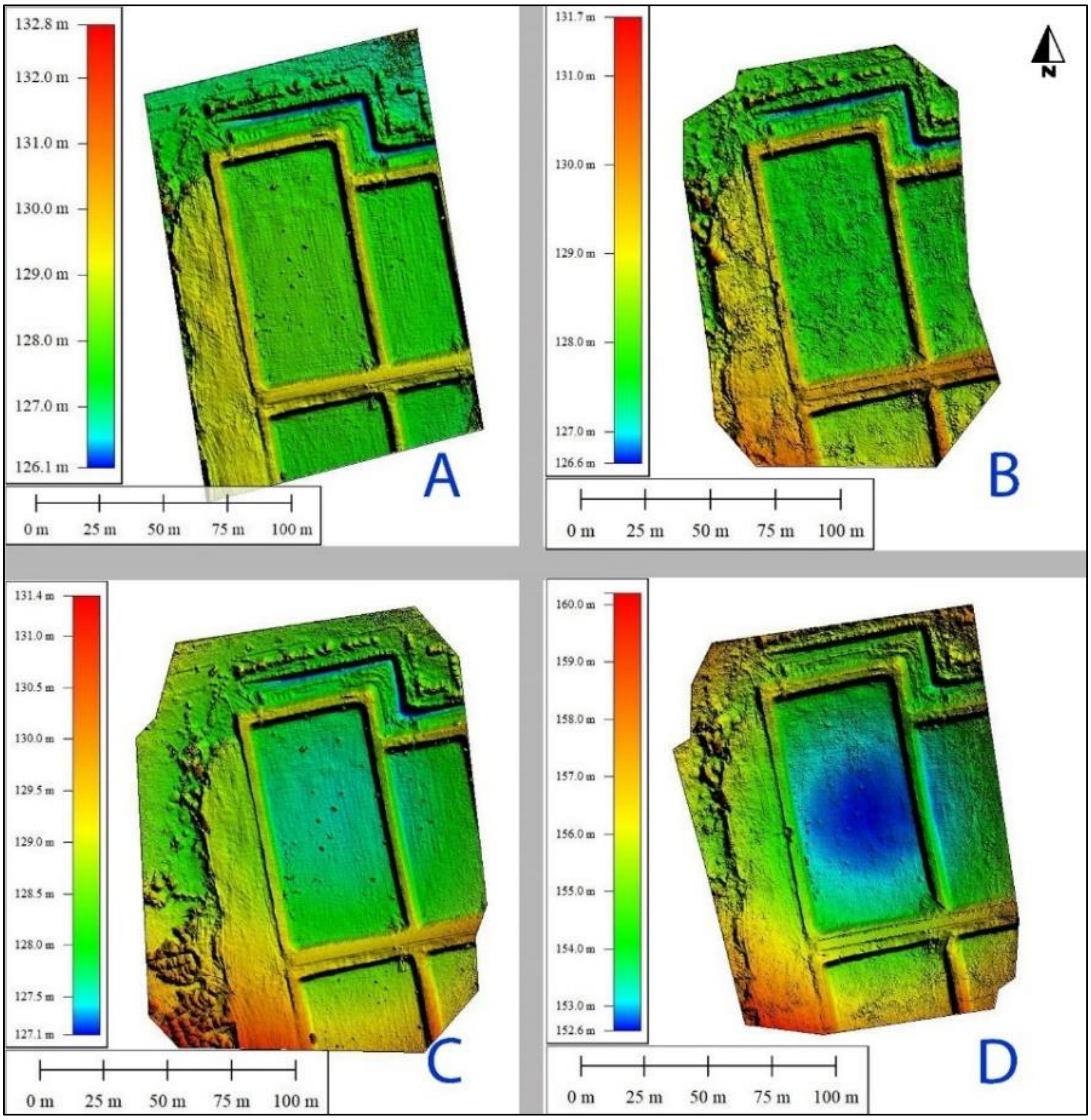

Fig. 9 (A) DEM Generated by UAV with Altitudes of 40% and 70% Overlap for Both Front and Side.
(B) DEM Generated by UAV with Altitudes of 40% and 75% Overlap for Both Front and Side.
(C) DEM Generated by UAV with Altitudes of 40% and 80% Overlap for Both Front and Side.
(D) DEM Generated by UAV with Altitudes of 40% and 85% Overlap for Both Front and Side.

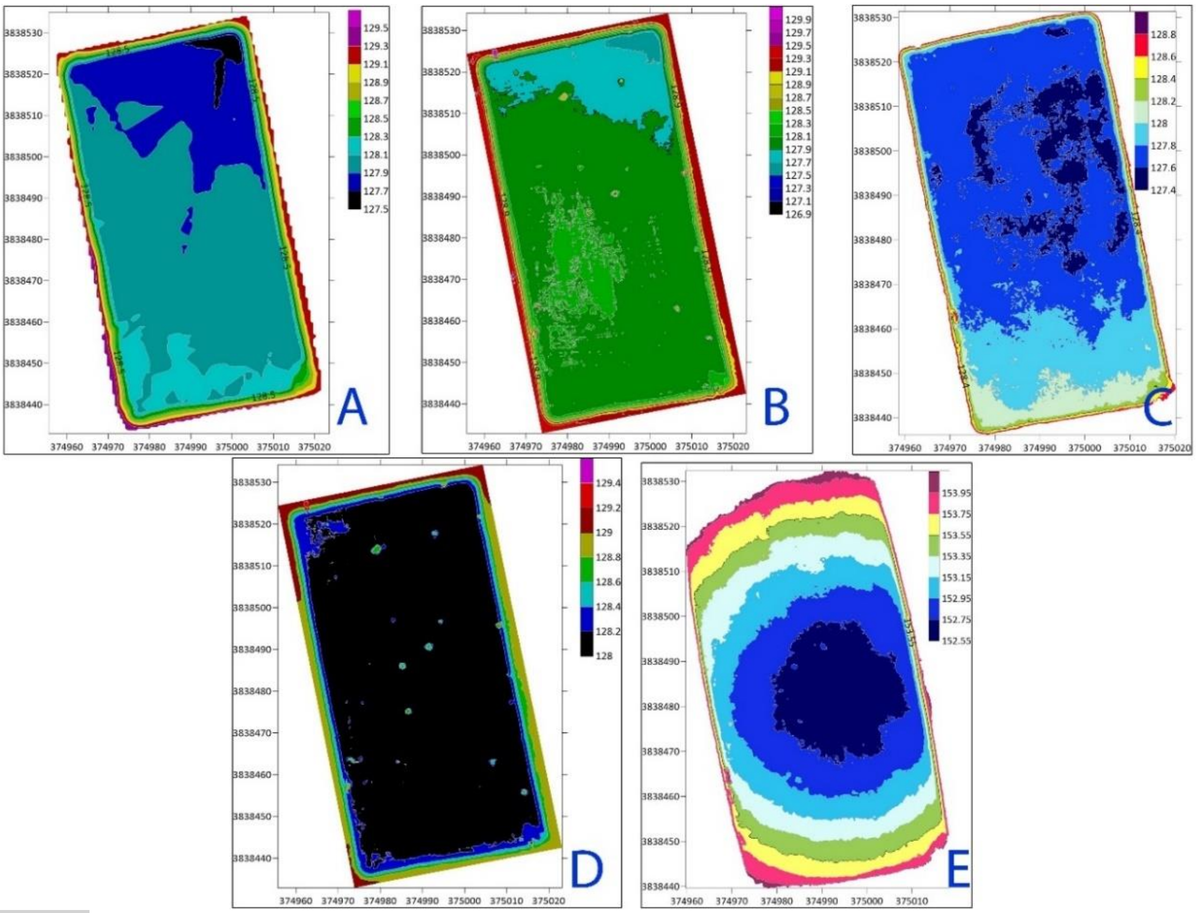

Fig. 10 Filled Contour Map by an Interval of 0.2-Meter, (A) DEM Generated by RTK GNSS, (B) DEM Generated with 70% for Both Side and Front Overlap, (C) DEM Generated with 75% for Both Front and Side Overlap. (D): DEM Generated with 80% for Both Front and Side Overlap. (E): DEM Generated with 85% for Both Front and Side Overlap.

As the degree of overlap surpasses 80%, the contours' configuration begins to deviate from the correct form. Specifically, the contour values of the E-shape (85% overlap) significantly exceed the ground truth. Root Mean Square Error is a commonly used statistical measure of the difference between two sets of values. In the context of DEM accuracy assessment, RMSE is often used to evaluate the accuracy of a DEM generated from UAV data by comparing it with a ground truth dataset. Table 2 shows the RMSE for GCPs in the surveyed site.

Table 2 RMSE Values (in Meters) for GCPs.

The site	Configurations	GCPs	RMSEx	RMSEy	RMSEz
Fishpond	70% overlap,40m	8	0.45	0.14	0.038
	75% overlap,40m	8	0.05	0.05	0.1
	80% overlap,40m	8	0.52	0.16	0.078
	85% overlap,40m	8	2.30	3.69	21.47

Comparative analysis was conducted between the DEM derived from a UAV and the DEM produced by GNSS RTK surveying. To ensure the accuracy of the comparison, the GNSS RTK DEM was utilized as the reference standard due to its high level of accuracy. A geographic information system (GIS) was used to generate an error map using "raster calculation." The formula used in this analysis involved subtracting the values of the UAV DEM (the model data) from those of the GNSS RTK DEM (the ground truth), resulting in comprehensive control of all pixel values. The results of this analysis are depicted in Fig. 11. Also, the resulting frequency distribution of the error values was illustrated graphically. After verifying the DEM accuracy with a 70% overlap, a volume calculation check was conducted to ensure that the calculated volume matched the ground truth for all produced DEMs. The results were tabulated in Table 3 and graphically illustrated in Fig. 12. This step was important to ensure the accuracy and reliability of the DEM. The check was done at the highest enclosed contour, and it was observed that the highest contour value in both DEMs (RTK and 70% overlap) was 129.1, indicating consistency and reliability in capturing terrain features, which improved the accuracy and reliability of the DEMs for volume calculations.

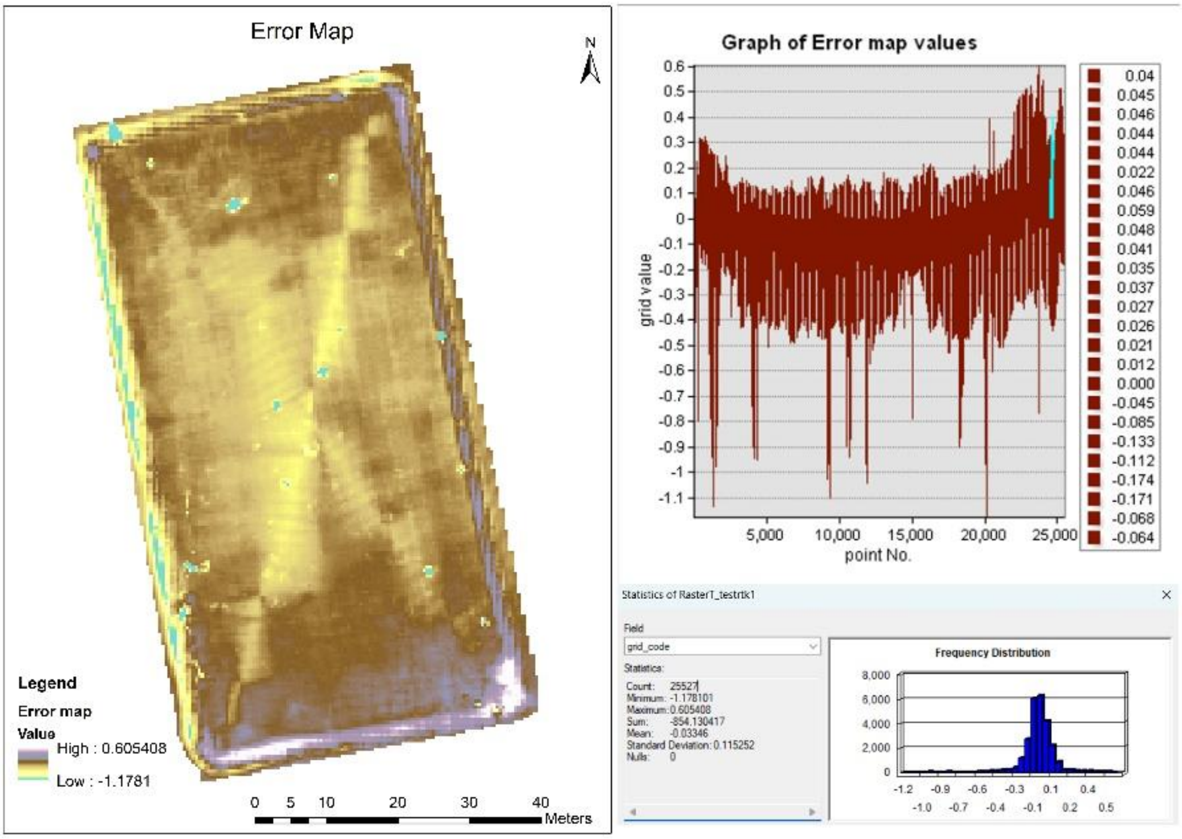

Fig. 11 Error Map of 40m and 70%Overlap DEM.

Table 3 The Resulting Volumetric and Areal Elements for the Produced DEMs.

DEM	Level	Fill Volume (m³)	Cut Volume (m³)	Enclosed Area (m²)	Fill Volume Error (m³)
GNSS RTK	129.10	4486.99	0.21	4343.00	0.00
Level	Local	3677.74	0.037	4,110	810
UAV 70%overlap	129.10	4351.80	0.18	4236.00	135.19
UAV 75%overlap	128.85 m	4324.08	0.00	4130.00	162.91
UAV 80%overlap	128.8 m	2628.99	0.20	4216.00	1861
UAV 85%overlap	154 m	3424.37	0.01	4074.00	1062.62

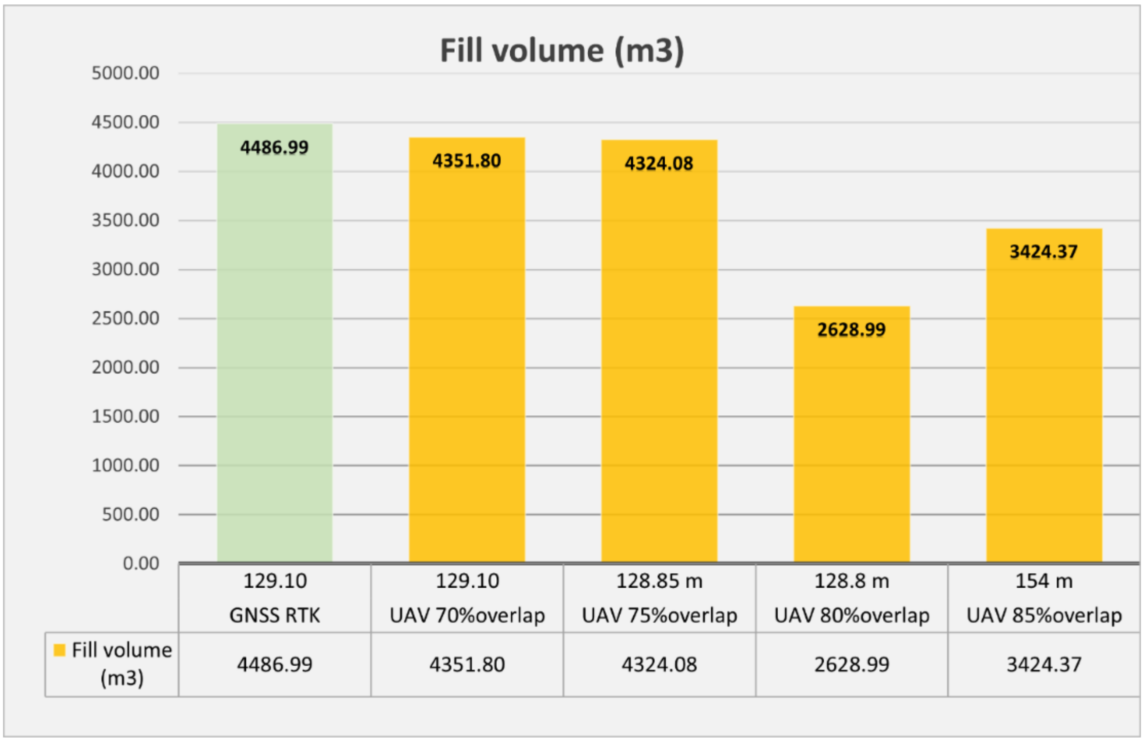

Fig. 12 The Fill Volume Different between the Generated DEMs.

4.CONCLUSIONS

Based on the data provided, it is concluded that using UAVs for generating DEMs is a highly effective technique for surveying small topographic depressions and providing more detailed data than traditional surveying methods. However, it is worth mentioning that the RMSE values for the (X, Y, and Z) dimensions ranged from 0.05 to 0.45m in both 70% and 75% overlap. It is also important to consider the optimum overlap for volumetric calculation, which was 70% for both front and side overlap with a flight altitude of 40 m in the fishpond. The resulting negative volume was 97% of the ground truth negative volume. The resolution of orthomosaics for the Mavic Air 2S drone ranged from 1.19 for 75% overlap to 1.23 for 85% overlap, while the Mavic 2 Zoom drone resolution ranged from 1.19 for 70% overlap to 3.02 for 80% overlap. A decline in resolution occurred above 80% overlap for the same altitude. It is also important to note that the RMSE values started to fluctuate significantly once the overlap reached 80% or higher, with the range touching 21m even with GCP. It is imperative to visually inspect the volume calculated from the UAV-derived Digital Elevation Model (DEM), as with the volume computed from the DEMs with 80% and 85% overlap. Although the DEM generated with 85% overlap exhibited a closer approximation to the true volume, a thorough visual inspection of the DEM revealed a concavity in the middle, which caused an inflated negative volume measurement inconsistent with the expected outcome. Consequently, the DEM created with 80% overlap was deemed more reliable, reflecting a more reasonable representation of the negative volume. Multiple UAV platforms, such as multispectral and thermal sensors, can enhance the surveying results. Further research should be conducted to determine the optimal flight parameters, especially for specific types of water bodies and topographic features. These recommendations can improve the quality and reliability of UAV-based surveying, hydrological assessments, inform water management, and conservation decisions.

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