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Enhancing Aerial Image Texture for Better 3D Reconstruction: A Comparison of Histogram Equalization and Contrast Limited Adaptive Histogram Equalization Techniques

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Abstract: The quality of aerial imagery is often degraded due to factors such as adverse weather conditions, atmospheric interference, or camera limitation. These factors significantly impact the effectiveness of the three-dimensional reconstruction process, particularly during the feature extraction and point cloud formation stages. The problem becomes more pronounced when reconstructing relatively homogenous surfaces, where a lack of texture leads to poor feature matching, resulting in incomplete or inaccurate models in the Structure from Motion (SfM) workflow. This study aims to evaluate the effectiveness of two methods of improving image quality, Histogram Equalisation (HE) and Contrast Limited Adaptive Histogram Equalisation (CLAHE), in improving texture quality and consequently enhancing the accuracy and completeness of 3D reconstruction in homogeneous areas. The evaluation was conducted through visual analysis, point cloud density, and spatial comparison using a Cloud-to-Cloud (C2C) approach. The HE and CLAHE processed point clouds were compared against those derived from the original, unenhanced imagery. The results indicated that the CLAHE method provides a more controlled contrast increase and produces point clouds with improved density and distribution compared to HE and the original image. Furthermore, the C2C analysis revealed lower spatial deviations in the reconstructions generated using CLAHE. These findings suggest that CLAHE is more effective in enhancing visual quality, especially in low-textured areas, to support the reconstruction of photogrammetry-based mapping.

Keywords : Image Enhancement; Feature Extraction; Aerial Photos; Point Cloud

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Introduction

The rapid growth of aerial photogrammetry is driven by the increasing demand for accurate and real-time spatial data across industries (Apriyanto et al., 2023). This encourages aerial photography to be done faster and with a wider area coverage. However, in reality, the quality of aerial photos is often degraded due to many factors (Iglhaut et al., 2019; Xiao, 2023), including poor weather conditions, atmospheric disturbances, and limitations of the camera used (Ernida, 2020). The need for faster data acquisitions further increases this risk, leading to reduced accuracy in the 3D reconstruction process, particularly during feature extraction and point cloud generation (Budiharto et al., 2021; B. L. Putra, 2020). This can affect the quality of the matching and reconstruction results of 3D models using the Structure from Motion (SfM) and Multi-View Stereo (MVS) approaches (Dai et al., 2022; Maharani et al., 2025). This degradation can inhibit the process of feature extraction, resulting in the resulting spatial model becoming less representative (Dai et al., 2022). This condition is a real challenge in the use of UAVs for various industrial needs, which demand high accuracy in a short time and varied operational conditions.

Image matching is an important process in image processing, especially in photogrammetry and 3D reconstruction applications, which require matching feature points between image pairs to form precise spatial representations (Agrafiotis et al., 2017; Maharani et al., 2020). The performance of the image-matching algorithm is greatly influenced by the quality of the input image, especially related to the aspect of contrast and pixel intensity distribution (Xiao, 2023). Low-contrast imagery or unevenly distributed intensity

histograms generally result in a limited number of features and low stability, which directly impacts decreased feature matching accuracy and, overall, the quality of the reconstruction results (Refianti & Rokhmana, 2021). This is even more complex when images are taken on visually homogeneous objects, such as waters, which lack texture and contrast, making it difficult for algorithms to detect and match features.

To overcome the problem of low image quality, various image enhancement techniques have been applied as a preprocessing stage before image matching. Among them, the Histogram Equalization (HE) and Contrast Limited Adaptive Histogram Equalization (CLAHE) methods are commonly used approaches to improve the visual quality of images (Lionnie & Alaydrus, 2024). HE is a classic technique that aims to evenly distribute the pixel intensity across the histogram range, thereby improving image contrast globally (Rao, 2020). Although effective, this approach often leads to artifacts such as over-enhancement and loss of detail in certain areas (Arif & Maharani, 2025; Subramani & Veluchamy, 2020). CLAHE was developed as a solution to the limitations of HE by dividing the image into small blocks and applying local histogram equalization to each block. In addition, this technique limits the level of contrast amplification to prevent excessive noise enhancement (Sholihin & Purwoto, 2014). These two methods are often applied as the initial stage in UAV image processing, especially to overcome the problem of uneven lighting and low contrast.

Although HE and CLAHE have been widely applied in improving image quality, there are still challenges in determining the most optimal method to improve image matching performance in aerial imagery generated by UAV (Majumdar & Kumar, 2014). Each technique has its own characteristics, advantages, and limitations that depend heavily on the conditions and attributes of the image, as well as the context of the desired application. The advantage of the HE method is that it is able to increase contrast in aerial photos that have too dark intensity or low contrast (Kenyta & Wonohadidjojo, 2020). Meanwhile, the CLAHE method has the advantage of increasing contrast locally by dividing the image into small blocks and applying equalization to each block by limiting the contrast in each of the local blocks, so that the CLAHE method can avoid the effect of over-enhancement (Saputra et al., 2021). In addition, comparative studies that specifically evaluate the influence of HE and CLAHE on image-matching performance in UAV imagery are still relatively limited, especially in the context of industry needs that increasingly prioritize image processing automation for increased operational efficiency and accuracy (Dai et al., 2022).

Along with the rapid development of UAV technology and the expansion of its applications, the need for accurate and reliable image-matching results in various sectors, such as digital mapping, precision agriculture, and environmental monitoring, has also increased. In this context, the study of the influence of image enhancement techniques on image-matching performance in UAV aerial imagery is very relevant and strategic in supporting technological advances and meeting industry demands. Unlike previous studies that applied HE and CLAHE for general image enhancement or medical imaging, this study explicitly evaluates their impact on UAV-based 3D reconstruction of homogeneous surfaces (water bodies), an area where feature extraction is particularly challenging. Through a comprehensive understanding of the advantages and limitations of each method, this study is expected to provide appropriate recommendations in the selection of image preprocessing techniques to improve the accuracy and efficiency of the image-matching process in real-world implementation.

Methodology

This research begins with the evaluation stage of data quality to ensure that the images used meet the feasibility criteria before entering the further processing process. The data used is aerial photos of the Embung Tambakboyo area, as shown in Figure 1. Aerial photo were taken using a 4864 × 3648 pixel resolution sensor with a focal length of 8.8 mm, resulting in 549 photographs representing the ground surface with a ground sampling distance of 3.08 cm/pixel. The dataset used in this study is in the form of aerial photographs obtained from the results of shooting the Tambakboyo Reservoir area, which in general has relatively homogeneous visual characteristics. This is because the surface of the water body does not have a striking color difference and does not have a stable texture or pattern, and is influenced by reflections, ripples, and changes in light that make its visual features inconsistent between images. Whether the water surface is stable will result in the detection and matching of points. This characteristic makes the area relevant as a test object to analyse the effectiveness of image enhancement methods, namely Histogram Equalization (HE) and Contrast Limited

Adaptive Histogram Equalization (CLAHE), in improving image matching performance in images with low heterogeneity.

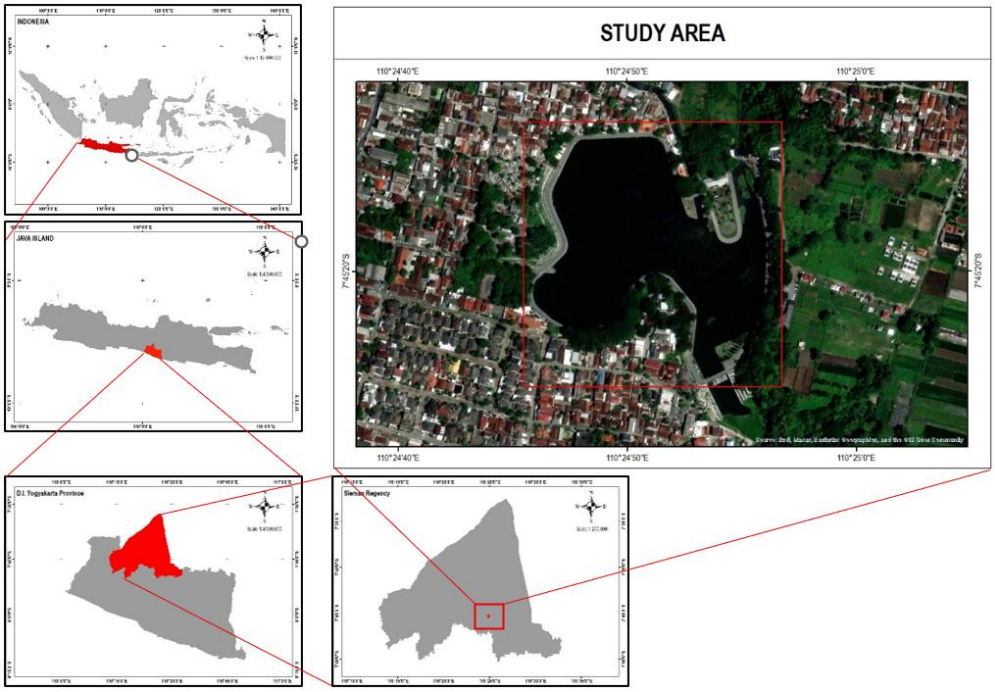


Figure 1. Study Area

Figure 2 shows the flow of research conducted in this study. The quality check process is carried out by sorting and excluding images with low visual quality, such as blurry, dark, or distorted due to uneven lighting. Once the filtering process is complete, the remaining data is processed using the Google Colaboratory (Colab) platform, using several Python programming libraries such as OpenCV, OS, and Python Imaging Library (PIL). These libraries are used to improve image quality through the HE and CLAHE algorithms in a systematic manner.

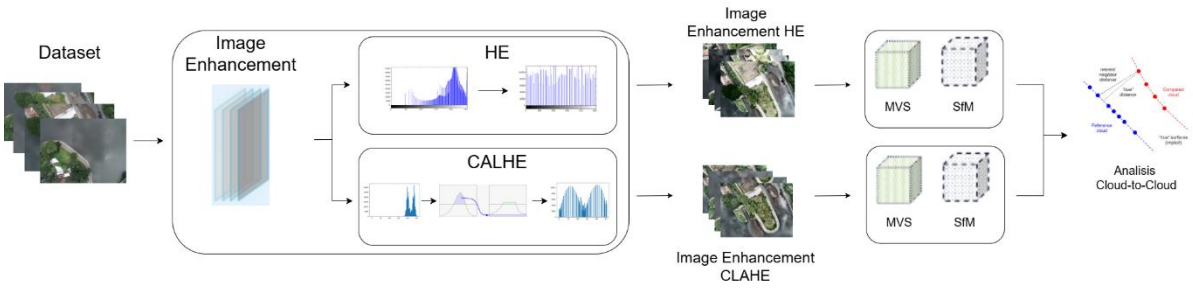


Figure 2. Research Flow

The results of preliminary observations of the data that have been prepared show that the reservoir area, especially the water body, does have a relatively uniform distribution of pixel intensity and minimal textural features. This reinforces the assumption that the image from this region is an appropriate representation to test the performance of the image enhancement method to improve the accuracy of image matching in homogeneous regions.

In Table 1, there is a parameter setting of the key point limit and tie point limit. This parameter helps to adjust the number of features that are recognized and matched between photos. In this process it will be categorized into three parameter settings based on variations in these parameters, both Original Image and Image enhancement. The difference in this setting is intended to assess the extent to which parameter changes affect the same number of dots on two or more different photos.

Table 1. Parameter setting

Parameter	Setting 1	Setting 2	Setting 3
Key point Limit	40,000	80,000	50,000
Tie point Limit	10,000	30,000	20,000

In the key point limit, this value specifies the maximum limit of the number of feature points to be taken from each image. Higher values allow for the detection of more features, which has the potential to improve matching accuracy, but also impacts longer processing times and greater memory usage. Meanwhile, the tie point limit sets a limit on the number of relationships between points that will be maintained in the cross-photo matching process. This setting is important to maintain efficiency while maintaining the structural quality of the result match points.

Histogram Equalization

Histogram Equalization (HE) is an image enhancement technique that works by spreading the pixel intensity distribution so that the image histogram becomes more even[20]. This process aims to increase the contrast of the image, especially in images that have too dark, too bright, or low contrast lighting[21]. In HE, the pixel intensity is changed based on the Cumulative Distribution Function (CDF) of the image's histogram, resulting in a more uniform grayness distribution. HE utilizes intensity transformations to reset the pixel values of grayscale images. The transformation formula is generally written as (Gonzalez & Woods, 2018):

$$s_k = T(r_k) = (L-1)\sum_{j=0}^{k} P_r(r_j) = \frac{(L-1)}{MN}\sum_{j=0}^{k} n_j \quad (1)$$

The advantage of this method is that it is able to increase contrast globally, is simple to implement, and is effectively used to clarify details in images. However, the downside is that HE does not consider local variations in the image, so it can lead to over-enhancement and loss of detail in certain areas if used in images with uneven lighting (Zhou et al., 2021).

The results of image processing using the Histogram Equalization (HE) method showed a significant increase in contrast. However, this improvement is accompanied by the appearance of dark areas that are more dominant in most of the image (Ikhsan et al., 2024). This is a consequence of the basic principle of HE that redistributes pixel intensity globally without considering the local characteristics of each image region (Kenyta & Wonohadidjojo, 2020). As a result, in areas with uneven lighting, some parts of the image, particularly in water bodies, become too dark or too bright. After the application of the HE method, there was a significant redistribution of pixel intensity, with the histogram being more evenly distributed across the entire range of pixel values.

Contrast Limited Adaptive Histogram Equalization

The CLAHE method is a development of HE, this method applies clipping to a smaller area so that the alignment of the histogram becomes smoother, in this method a limit is given to the leveling so that the details in the aerial photo remain controlled (Patil & Patil, 2020). The clip limit of the CLAHE histogram is calculated using the equation (2) (Saifullah, 2020; D. Putra, 2010):

$$\beta = \frac{M}{n}\left(1 + \frac{\alpha}{100}(s_{max} - 1)\right) \quad (2)$$

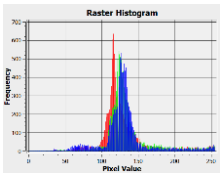
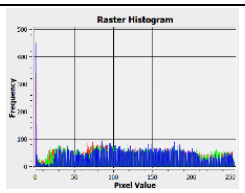
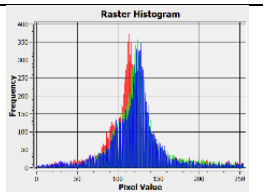
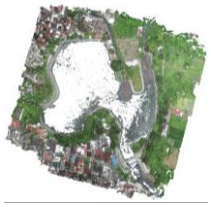
The results of image enhancement processing using the Contrast Limited Adaptive Histogram Equalization (CLAHE) method show more controlled results both in sharpness and contrast produced, because in the processing the histogram alignment is carried out on tiles that have been divided and uses cliplimits so that the resulting histogram becomes more controlled (Majumdar & Kumar, 2014). This affects the extraction of point cloud features that have increased compared to the original in relatively homogeneous areas. The appearance is produced from the distribution of the pixel range that is flattened using local distribution and using cliplimit so that the appearance of the image enhancement results becomes more controlled (Freyssenita Kanditami et al., 2014).

Results and Discussion

Overall Image Enhancement

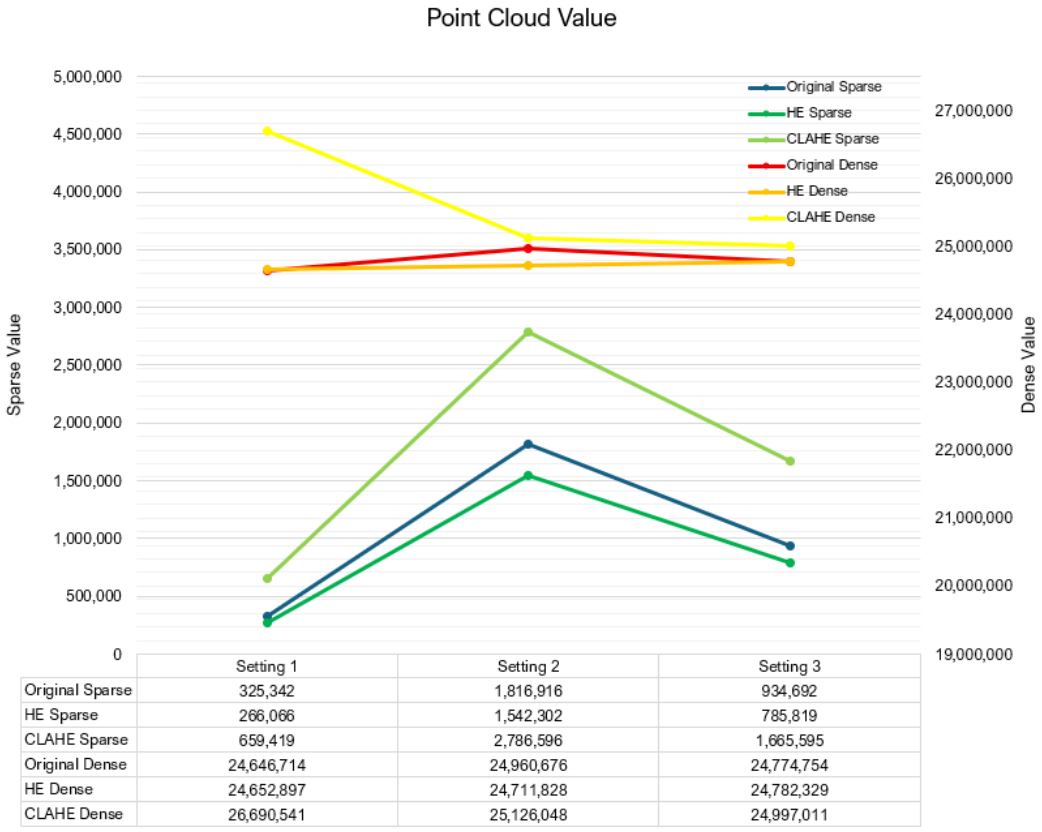
The results of the analysis showed that the point cloud of the CLAHE method had a greater distribution of points than HE, This method is able to effectively increase local contrast. Visually, the processed point cloud results show increased contrast and sharpness compared to the original. The HE method produces high contrast but tends to cause excessive dark shadows, while CLAHE provides a more balanced and visually natural result. The analyzed histograms show that CLAHE expands the pixel intensity distribution more evenly compared to HE and the original image, supporting improved visual quality and feature extraction potential.

Table 2. Visualization results

	ORIGINAL	HE	CLAHE
Orthophoto			
Histogram			
Point Cloud Setting 1			
Point Cloud Setting 2			
Point Cloud Setting 3			

The Histogram Equalization (HE) method works globally by spreading the pixel intensity values across the range of 0–255. This result can be seen from the histogram becoming flat without a dominant peak. This distribution that is too flat and does not pay attention to local variations results in the loss of textural information, especially in images with a certain intensity dominance. Whereas CLAHE produces a histogram that is not completely flat as in HE, but retains the local peak and natural distribution shape of the image.

The advantages of CLAHE are even more prominent in the dense cloud stage. In almost all parameters CLAHE produces the highest number of point cloud. Local distribution selectively enhanced by CLAHE increases the success of pixel matching between images, resulting in a denser and even point cloud, As can be seen in Figure 3 diagram.



	Setting 1	Setting 2	Setting 3
Original Sparse	325,342	1,816,916	934,692
HE Sparse	266,066	1,542,302	785,819
CLAHE Sparse	659,419	2,786,596	1,665,595
Original Dense	24,646,714	24,960,676	24,774,754
HE Dense	24,652,897	24,711,828	24,782,329
CLAHE Dense	26,690,541	25,126,048	24,997,011

Figure 3. Point cloud value

Table 3. Percentage distribution point cloud enhanced image: (HE and CLAHE) and ground truth data with three classes from 0 cm to 0.5 cm.

Percentage Distribution of Point Cloud			
	Class (cm)	HE	CLAHE
Point Cloud Setting 1	0.0-0.2	76%	76.63%
	0.2-0.4	18.34%	18.12%
	0.4-0.5	5.66%	4.77%
Point Cloud Setting 2	0.0-0.2	69.16%	78.23%
	0.2-0.4	24.18%	17.64%
	0.4-0.5	6.66%	3.47%
Point Cloud Setting 3	0.0-0.2	5.68%	73.17%
	0.2-0.4	20.12%	13.58%
	0.4-0.5	74.20%	5.59%

Water Body Image Enhancement Area

In areas of water bodies that are homogeneous and have minimal texture, the CLAHE method has been proven to provide significant advantages over other methods. This improvement is very important because in water bodies, visual features such as water ripples, light reflections, and differences in intensity are minimal. HE tends to exacerbate these conditions with an increase in non-selective global contrast, leading to the appearance of noise and decreased feature matching quality. CLAHE, with its local approach and contrast restriction, can

refine the intensity distribution adaptively, strengthen the uniformity of textures between images, and make it easier for the SfM algorithm to detect and match spatial features.

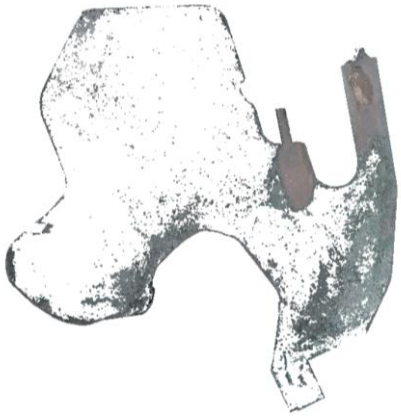


Figure 4. Segmentation original point cloud of water body

The results of segmentation which is done on the original point cloud as reference for segmentation setting other parameters and point cloud analysis in the water area showed that CLAHE produced the highest number of points compared to other methods. A comparison of the number of point clouds formed in water-specific areas is visualized in Figure 5, showing that CLAHE produces the highest number of points in water areas, followed by the original data, and finally HE.

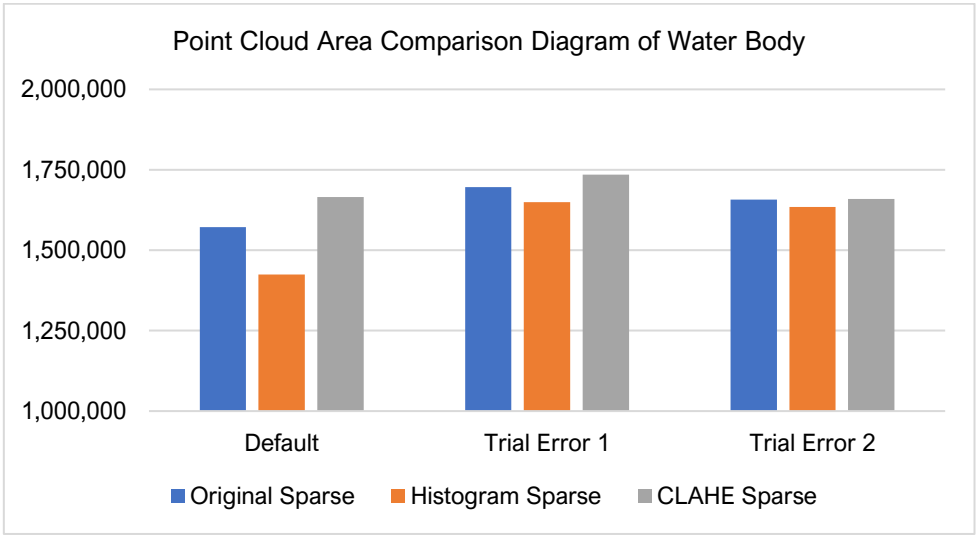


Figure 5. Point cloud area comparison diagram of water body

Table 4. Point cloud area comparison of water body

Parameter	ORIGINAL	HE	CLAHE
Setting 1	1,572,197	1,424,932	1,665,352
Setting 2	1,696,427	1,649,068	1,734,475
Setting 3	1,656,914	1,634,956	1,659,770

Cloud-to-Cloud (C2C) is used to compare the accuracy of the point cloud resulting from the image enhancement to the point cloud reference from the original image. In this process, the original point cloud is used as a reference, then each point on the point cloud resulting from the HE and CLAHE methods is calculated in distance to the nearest point in the reference. The results were visualized in colour gradation, where blue

showed a small distance difference, blue and green showed a relatively moderate distance difference, and red indicated a large spatial deviation. Through this visualization, it can be seen the increase in point cloud in water bodies, where the additional point cloud will be red.

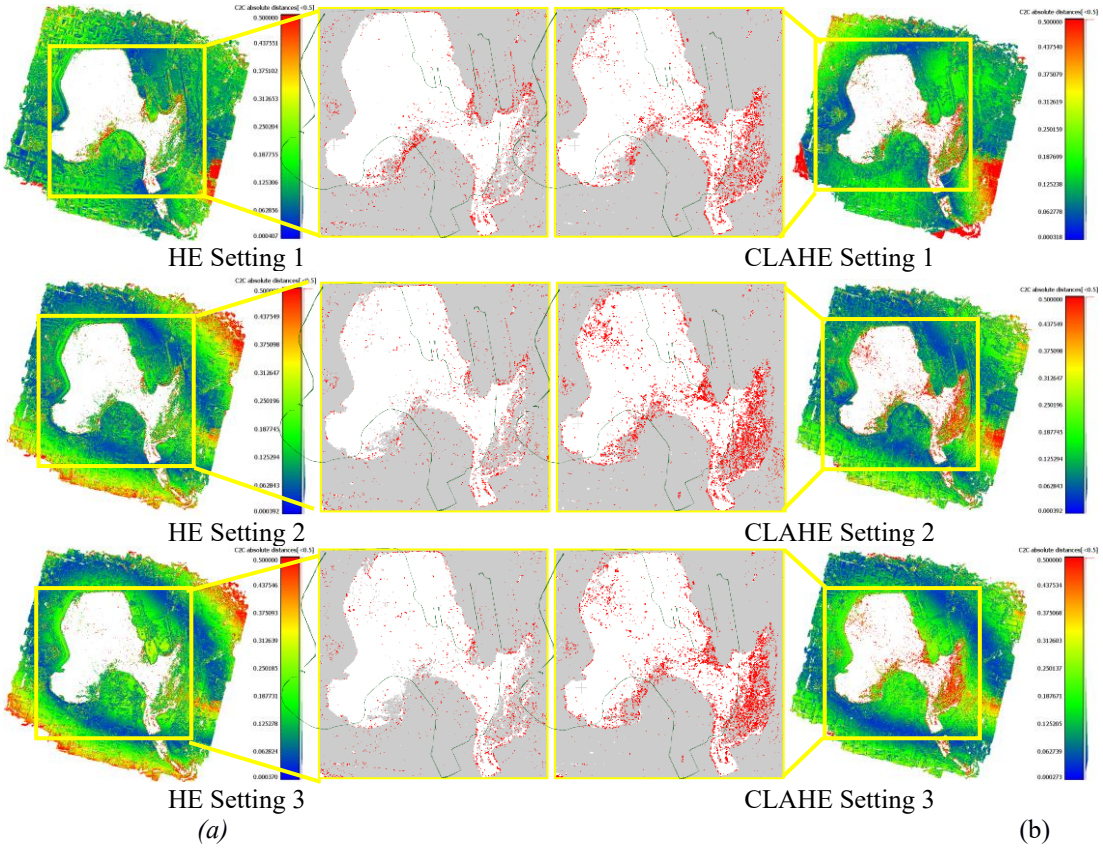


Figure 6. (a) C2C HE Water Area Against Original, (b) C2C CLAHE Water Area Against Original

These findings indicate that image enhancement using the CLAHE method is able to retain and extract spatial information more effectively in relatively homogeneous regions, such as the water surface, thus allowing the extraction of more points. Meanwhile, HE actually produced a smaller number of points than the original, indicating that the increase in global contrast through HE was less effective in retaining detail in certain areas, especially water, leading to information loss in the form of loss of points in the reconstruction results. Thus, CLAHE can be considered more effective in handling areas with low texture that are generally challenging in the photogrammetry reconstruction process.

Conclusions

The results of this study demonstrate a significant improvement in visual quality, characterized by better image sharpness and more balanced contrast compared to the original imagery. Based on point cloud analysis, the CLAHE method consistently showed more reliable performance in enhancing feature extraction in aerial photos, as indicated by the higher number and denser distribution of point clouds compared to both the original image and the HE-processed data. Improved visual quality such as increased contrast, sharpness, and more even histogram distribution facilitates feature detection and contributes directly to the accuracy of the 3D reconstruction process. This is particularly beneficial in homogeneous areas, such as water bodies, where conventional feature extraction is often challenging.

Beyond methodological validation, these findings suggest practical implications for UAV-based mapping in low-texture environments, such as water resource monitoring, environmental management, and infrastructure assessment in aquatic or homogeneous landscapes. By enabling denser and more accurate point clouds,

CLAHE provides a promising preprocessing step for improving the reliability of UAV photogrammetry in real-world applications. Nevertheless, this study is subject to certain limitations. The analysis was conducted using a single dataset from the Tambakboyo Reservoir and relied on one UAV sensor type, which may restrict the generalizability of the results. Future research should validate these findings across different UAV platforms, sensors, and environmental conditions, as well as explore advanced enhancement methods, including deep learning–based approaches, to further optimize image preprocessing for aerial photogrammetry.

Author Contributions

The authors were responsible for the conceptualization, methodology, data collection, data processing, formal analysis, visualization, and preparation of the original manuscript. The authors also performed the review and editing of the manuscript and approved the final version for publication. Conceptualization: ARP and MM; Methodology: ARP and MM; Data curation: ARP; Formal analysis: ARP and MM; Investigation: ARP; Visualization: ARP; Writing – original draft: ARP; Writing – review & editing: ARP and MM; Supervision: MM. All authors have read and agreed to the published version of the manuscript.

Declaration of Generative AI Usage

During the preparation of this manuscript, the author used AI-assisted to assist with language refinement, grammar checking, and improving the clarity of the manuscript. The author carefully reviewed and edited all AI-assisted content and takes full responsibility for the accuracy, originality, and integrity of the published work.

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