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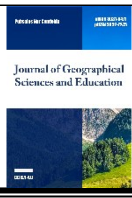

[Research Article]

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Comparative of Digital Terrain Model Quality Based on Cloth Simulation Filter and Simple Outlier Elimination in LiDAR Data

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Abstract

The quality of Digital Terrain Models (DTM) from LiDAR data is highly dependent on the effectiveness of the ground filtering process, especially in areas with complex mountainous topography and dense vegetation cover. This study aims to systematically analyze and compare the quality of DTMs generated from three different processing schemes, namely Raw DTM, Simple Outlier Elimination DTM (ELM), and Cloth Simulation Filter DTM (CSF), using LiDAR point cloud data on Mount Aso, Japan. The methods used involved ground filtering using CSF and ELM, followed by IDW interpolation, as well as descriptive statistical evaluation and Hillshade visualization with enhanced Z Factor. The ELM filter proved ineffective in producing statistics identical to the raw DTM, while CSF successfully reduced the average elevation from 130.73 m to 124.06 m and confirmed that vegetation noise was eliminated. In complex terrains, future LiDAR research should prioritize adaptive algorithms like CSF over simple statistical filters to ensure higher accuracy in digital terrain representation.

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Abstrak

Kualitas Digital Terrain Model (DTM) dari data LiDAR sangat bergantung pada efektivitas proses ground filtering, khususnya di wilayah dengan topografi pegunungan kompleks dan tutupan vegetasi padat. Penelitian ini bertujuan untuk menganalisis dan membandingkan secara sistematis kualitas DTM yang dihasilkan dari tiga skema pemrosesan berbeda yaitu DTM raw, DTM Eliminasi Outlier Sederhana (ELM), dan DTM Cloth Simulation Filter (CSF) menggunakan data point cloud LiDAR di Gunung Aso, Jepang. Metode yang digunakan melibatkan ground filtering menggunakan CSF dan ELM, diikuti oleh interpolasi IDW, serta evaluasi berbasis statistik deskriptif dan visualisasi Hillshade dengan Z Factor yang diperkuat. Filter ELM terbukti tidak efektif menghasilkan statistik yang identik dengan DTM raw, sementara CSF berhasil menurunkan elevasi rata-rata dari 130.73 m menjadi 124.06 m dan mengonfirmasikan bahwa noise vegetasi telah tereliminasi. Pada medan yang kompleks, penelitian LiDAR di masa depan harus memprioritaskan algoritma adaptif seperti CSF dibandingkan dengan filter statistik sederhana untuk memastikan akurasi yang lebih tinggi dalam representasi medan digital.

INTRODUCTION

High-fidelity topography and accurate digital surface models are fundamental elements in various geospatial analyses that require precise representation of the Earth's surface elevation. One key product widely utilized in this context is the Digital Terrain Model (DTM). A DTM is a model that represents the actual land surface spatial data after removing non-surface elements such as vegetation and artificial structures (Li et al., 2020). The accuracy of a DTM directly impacts the quality of the output from subsequent analyses, including hydrological modeling, slope stability analysis, and risk-based planning (Graf et al., 2018). However, generating accurate DTMs in forested and mountainous areas remains challenging because terrain complexity and vegetation density often lead to significant misclassification between ground and non-ground points.

Advances in Light Detection and Ranging (LiDAR) technology have provided superior solutions for acquiring elevation data through high-density point clouds with high vertical accuracy (Baltsavias, 1999; Elaksher et al., 2023). However, the resulting raw LiDAR data generally still includes all objects that reflect the laser beam, including vegetation and man-made objects, making it more representative of a Digital Surface Model (DSM) than a DTM. The presence of these non-surface objects generates significant noise that can interfere with land surface estimation, especially in areas with dense vegetation and complex relief (Meng et al., 2010). Therefore, effective ground filtering is a critical step to transform LiDAR-derived DSMs into reliable DTMs, especially in densely vegetated mountainous regions. Inadequate filtration often creates false topography from vegetation noise, which directly compromises the accuracy of slope stability and environmental models (Sithole & Vosselman, 2004; Zhao et al., 2018).

With the advancement of geospatial processing technology, filtering algorithms have evolved from basic statistical methods to adaptive classification approaches (Guan et al., 2025). However, conventional threshold-based methods such as Simple Outlier Elimination face significant limitations in complex terrains because they rely on rigid parameters that cannot adapt to abrupt topographical changes (Sithole & Vosselman, 2004). In densely forested mountainous regions, these methods frequently struggle to distinguish between low-lying shrubs and the actual ground surface, often resulting in an over-smoothed DTM or the accidental removal of critical features like sharp ridges (Meng et al., 2010; Zhao et al., 2018). Therefore, a more rigorous empirical evaluation of specialized algorithms, specifically Cloth Simulation Filtering (CSF) and Elevation Linear Method (ELM), is urgently needed (Cai & Yu, 2023). This evaluation is crucial to determine their effectiveness in overcoming the specific challenges of high canopy density and steep slopes characteristic of such challenging environments (Huang et al., 2020).

The CSF has been recognized as one of the most effective methods for environments with complex relief due to its ability to simulate a virtual cloth that dynamically follows the contours of the land surface (Zhou et al., 2023). Empirical studies have shown that CSF provides more stable performance than conventional filtration methods, especially in swampy, mountainous, and forested areas with sharp elevation variations (Li et al., 2021; Wang et al., 2025). Nevertheless, the performance of CSF may vary depending on terrain characteristics and vegetation structure, indicating the need for further empirical evaluation in specific geomorphological settings. In certain conditions, such as areas with extremely steep slopes or very dense low-lying shrubs, the cloth may not perfectly fit the ground surface, potentially leading to elevation bias (Zhang et al., 2016). This inconsistency represents a research gap that necessitates a more rigorous assessment to determine its robustness in high-density forested environments.

Comparative studies of ground filtering algorithms in forested areas with extreme relief remain limited, and existing methods often fail to produce comparable results between flat and mountainous terrains (Lu & Wong, 2008). Silva et al. (2018) further demonstrated that filtration performance in complex forested environments remains inconsistent, highlighting a critical gap in the literature. This deficiency forms the basis of the present research, which seeks to conduct a systematic empirical assessment of the CSF. Such evaluation is essential to determine the algorithm's effectiveness in mitigating vegetation noise and ensuring reliable land surface representation in complex geomorphological settings (Chen et al., 2021).

Based on this context, this study systematically evaluates the performance of CSF and ELM in generating accurate DTMs in the forested mountainous terrain of Mount Aso. Specifically, the objectives of this study are to assess the statistical distribution of elevation values, including the mean and standard deviation, generated by each algorithm, and to evaluate the visual and quantitative effectiveness of these methods in reducing vegetation noise through hillshade visualization and Z-factor analysis. This study serves as an empirical benchmark for optimizing DTM precision in complex geomorphological environments.

METHOD

Types and Methods of Research

This study uses a quantitative comparative research approach. Comparative research was chosen because it aims to systematically and objectively compare the output quality of three different LiDAR data processing schemes, Raw Data, Outlier Elimination, and CSF, against the same dataset. The DTM quality evaluation was conducted based on descriptive statistical analysis and qualitative visual analysis. This approach ensures that performance differences among the processing schemes can be clearly identified and measured under consistent evaluation criteria. Furthermore, the use of identical input data for all schemes minimizes external variability and enhances the reliability of the comparison. The results are expected to provide empirical evidence regarding the most effective processing strategy for complex volcanic terrains.

Study Area

This research focuses on the Mount Aso area in Kumamoto Prefecture, Japan. Geographically, the site is situated at approximately 32°23′37″N and 130°38′5″E. This location was selected due to its unique volcanic topography, characterized by complex mountainous terrain and varying vegetation cover. These conditions provide a rigorous environment for assessing the performance of ground filtering algorithms against extreme geomorphological challenges. Additionally, the area's active volcanic history further enhances its suitability as a representative site for testing terrain classification robustness. The study area and its topographical context are illustrated in Figure 1.

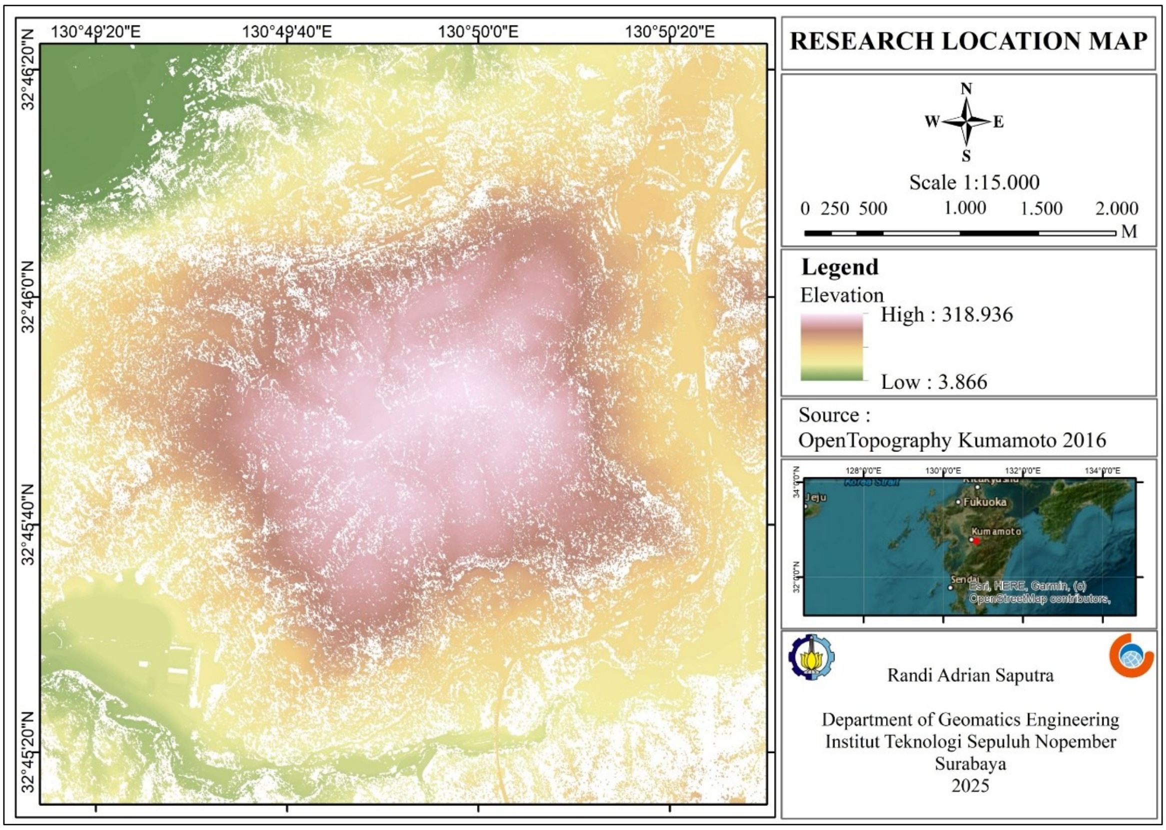

Figure 1. Research Location (OpenTopogrphy, 2016)

Data Materials

The main material used in this study is a high-density LiDAR point cloud dataset obtained as a secondary source from the OpenTopography facility. To ensure transparency and data clarity, the comprehensive characteristics of the dataset are detailed in Table 1. The data covers a total area of 95.85 km^2 around Mount Aso, with the acquisition (survey) carried out on April 23, 2016. The dataset provides a point density of 4.47 pts/m^2, which is considered sufficient for generating a high-resolution DTM in a complex forested environment. For geospatial consistency, the data refers to the Japan Plane Rectangular Coordinate System (System II) for horizontal positioning and the JGD2000 system for vertical elevation.

Table 1. Technical Specifications and Metadata of the LiDAR Dataset

Information	Description
Data type	LiDAR Point Cloud (Raw)
Data format	LAZ/LAS
Data source	OpenTopography Facility
Date of acquisition	2016
Data status	April 23, 2016
Point sensitivity	4,47 pts/m^2
Coordinate system	Horizontal: JPRCS System II (EPSG: 2444), Vertical: JGD2000 (EPSG: 6694)
Area coverage	95.85 km^2

Source: Data Processing Results, 2025.

Data Collection Technique

Data collection techniques were carried out through literature studies and data downloads. The literature study was conducted to identify relevant ground filtering algorithms (CSF), Outlier Elimination, and interpolation methods (IDW), and to determine optimal parameters. Data downloads were carried out to obtain LiDAR point cloud data downloaded directly from the OpenTopography repository, followed by pre-processing for initial noise cleaning and Area of Interest/AoI cropping.

Data Analysis Techniques

Data analysis techniques are divided into three main stages. First, DTM formation is generated and compared using the Pipelinedata Analysis Library (PDAL) for filtering and ArcGIS Desktop for interpolation. Raw DTM is interpolated directly from the point cloud to DTM. DTM Outlier Elimination is performed using a simple statistical filter to eliminate outliers, then interpolated using IDW. The DTM Cloth Simulation Filter is processed with a CSF filter to classify soil points, and then the classified points are interpolated using IDW. The IDW is used for all three DTM schemes, with uniform grid resolutions of 1.0 and 5.0 to ensure a fair comparison

A quantitative analysis process was carried out to measure the statistical differences in the DTM surface. Elevation statistics for each DTM model were calculated using ArcGIS Desktop based on parameter data with minimum, maximum, average, and standard deviation values. The Min and Max values were used to measure how effectively the CSF filter removed vegetation peaks, while Std. Dev. was used as an indicator of surface roughness.

Qualitative analysis is also needed to evaluate visual differences in noise and slope representation quality. This analysis was performed using Hillshade Visualization (shaded relief) for each DTM at two Z Factor intensity levels to maximize noise detection, namely 1.0 for realistic representation and 5.0 for enhanced representation to create smooth noise and make processing artifacts more dramatic and clearly visible.

RESULT AND DISCUSSION

DTM Statistical Comparison

The statistical comparison was performed by calculating descriptive elevation parameters, specifically the minimum, maximum, mean, and standard deviation for the three DTM schemes (raw, Outlier Elimination, and CSF). These parameters serve as quantitative indicators of how each method handles vegetation noise within the Mount Aso dataset (Table 2).

The statistical data provide strong evidence regarding the performance of each method. The Raw DTM and Outlier Elimination DTM produced identical statistical values, with a maximum elevation of 323.07 m and a mean of 130.73 m. This identical result demonstrates that the Simple Outlier Elimination method is ineffective in this specific environment. In densely vegetated and complex topography, non-ground points (canopy) are distributed as continuous surfaces rather than isolated statistical anomalies, causing this basic filter to fail in identifying them as outliers.

In contrast, the CSF algorithm successfully refined the terrain model. It reduced the maximum elevation from 323.07 m to 318.94 m (a decrease of 4.13 m) and lowered the mean elevation from 130.73 m to 124.06 m. Interestingly, the standard deviation showed a slight increase in the CSF result at 89.55 m compared to the Raw DTM at 84.86 m. This increase does not signify an error; rather, it indicates that the CSF algorithm successfully removed the dense vegetation layer that previously smoothed the terrain data. By eliminating this vegetation, the DTM more accurately captures the true topographic ruggedness and steep slopes of Mount Aso, which naturally results in a broader distribution of elevation values.

Table 2. Digital Terrain Model Statistical Comparison of Elevation Parameters

Statistics	Raw DTM	DTM Outlier Elimination	DTM Cloth Simulation Filter
Minimum	3.94 m	3.94 m	3.94 m
Maximum	323.07 m	323.07 m	318.94 m
Mean	130.73 m	130.73 m	124.06 m
Standard Deviation	84.86 m	84.86 m	89.55 m

Source: Data Processing Results, 2025.

The CSF visually produces a smoother surface as shown in Figure 2, with a Standard Deviation value of 89.55 m, which is higher than the Raw DTM or ELM of 84.86 m. This anomaly indicates that during the filtering and interpolation process, the CSF filter may have produced a variety of filtering artifacts on the otherwise smooth ground surface, or indicates that the distribution of the remaining ground points has a wider variation than the overall distribution of the DSM.

Hillshade Z Factor 1.0 Visualization

The DTM visualization results with Hillshade Z Factor 1.0 provide a realistic slope representation, but the differences are less clear and almost no difference. The Raw DTM and ELM DTM (Figure 2a) both show very rough surfaces (spiky and textured), which visually confirm the failure of Outlier Elimination in separating vegetation. In contrast, the Cloth Simulation Filter DTM shows a much smoother and more defined surface. This proves the success of CSF in removing vegetation noise.

The comparative results presented in Table 2 and the Z Factor 1.0 visualization clearly indicate that CSF is the most effective method for LiDAR ground filtering in the mountainous region of Mount Aso. The success of CSF is supported by a significant decrease in the maximum value from 323.07 m to 318.94 m and the average elevation from 130.73 m to 124.06 m. This decrease directly confirms the success of the CSF filter in eliminating high vegetation noise. This is in line with literature findings that confirm the superiority of CSF compared to other non-parametric methods in densely vegetated terrain (Zhang et al., 2016).

The ELM method failed to refine the DTM, as evidenced by its identical statistical values to the Raw DTM. In the Mount Aso environment, this failure occurred because vegetation noise is not distributed as isolated extreme outliers; instead, it forms a dense, continuous layer over the terrain. This condition makes the filter unable to distinguish treetops from actual hilltops, especially given the steep slopes where vegetation and ground points often share similar elevation ranges. These findings are consistent with the literature, which suggests that basic statistical filters are largely ineffective in forested mountainous areas. As noted by Meng et al. (2010), single-elevation threshold-based filters are prone to significant errors in dense forests because non-ground points become integrated into the primary elevation distribution rather than appearing as anomalies. Consequently, only simulation-based or adaptive classification methods, such as CSF, are capable of accurately separating these features in such complex geomorphological conditions.

Based on this, quantitative and qualitative analysis of the CSF results is the most effective method for LiDAR ground filtering in the complex topography of Mount Aso. Although the Outlier Elimination method is simpler and faster, it has proven to be invalid for densely vegetated areas, because vegetation noise does not fit the definition of extreme statistical outliers. The effectiveness of CSF is supported by a substantial decrease in the Max and Mean elevation values.

The statistical method of Outlier Elimination is not relevant for LiDAR ground filtering in complex vegetated areas. The CSF Standard Deviation highlights that DTM quality evaluation should be performed with a combination of quantitative and qualitative metrics with high Z Factors, as a single statistical metric can be distorted by subtle processing artifacts. Therefore, more careful optimization of CSF parameters is needed in the future to mitigate this issue.

Hillshade Z Factor 5.0 Visualization

The visualization results with a hillshade Z factor of 5.0 were used to visually enhance the differences in surface textures. The analysis at Z factor 5.0 was still conducted comparatively between methods, but focused on the geomorphological stability and visual consistency of the DTM results with increasing vertical exaggeration. This approach is consistent with common practice in digital geomorphological analysis. Pike et al. (2009) explained that vertical exaggeration is used to highlight subtle relief variations and identify surface artifacts that are not visible at normal visual scales.

At the vertical exaggeration level, the surface roughness in the raw DTM and ELM DTM becomes obvious (Figure 2b), indicating high levels of noise spread across the surface that can be interpreted as unfiltered vegetation peaks. This phenomenon is consistent with previous findings that in forested terrain and steep slopes, vegetation points tend to form surface textures that resemble natural relief when visualized with high vertical exaggeration (Meng et al., 2010). In contrast, the CSF DTM retains relatively minimal surface roughness, which visually supports the effectiveness of this filter.

Several studies have shown that CSF is able to maintain the continuity of the land surface geomorphology visually, even when the elevation model is visualized with a high degree of vertical exaggeration (Zhang et al., 2016; Cai et al., 2023; Yarroudh et al., 2023). However, in the CSF DTM, artificial artifacts in the form of fine tiling patterns are still identified, which explains the higher standard deviation value due to local elevation variations that do not represent the ideal land surface.

As a complement to the quantitative analysis at Z factor 1.0, visualization with Z factor 5.0 was used to evaluate the geomorphological consistency of the filtering results through a visual approach. This visual approach is commonly used as a complement to quantitative evaluation to assess the geomorphological stability of DTM processing results at various levels of vertical exaggeration (Jenny & Hurni, 2011).

At higher levels of vertical exaggeration, the differences between the methods become increasingly apparent. The CSF-derived DTM still demonstrates a stable and realistic representation of the land surface, while the Raw DTM and Simple Outlier Elimination methods exhibit amplification of vegetation noise that resembles topographic features, especially on steep slopes. This confirms that although elevation statistics are not affected by Z-factor variations, the filtering method's ability to maintain geomorphological consistency is crucial for DTM quality under high-escalation visualization conditions. Thus, CSF not only excels quantitatively but also demonstrates visual robustness across varying levels of vertical exaggeration.

A visual comparison between Z-factors 1.0 and 5.0 demonstrates the difference in sensitivity in displaying DTM surface details. At Z-factor 1.0, surface relief is visualized more proportionally, so differences between filtering methods are still relatively subtle, and vegetation noise is not fully exposed. Visualization at this level better represents the general surface condition and is suitable for interpreting elevation statistics and global evaluation of DTM quality. Conversely, increasing vertical exaggeration at Z-factor 5.0 significantly enhances relief contrast, making small elevation variations more easily identifiable visually. This condition causes vegetation noise and processing artifacts to appear more clearly, especially in the Raw DTM and the Simple Outlier Elimination method, which exhibits rough surface textures and pseudo-peaks that resemble natural topographic features. Thus, Z-factor 5.0 serves as an effective visual diagnostic tool to reveal the

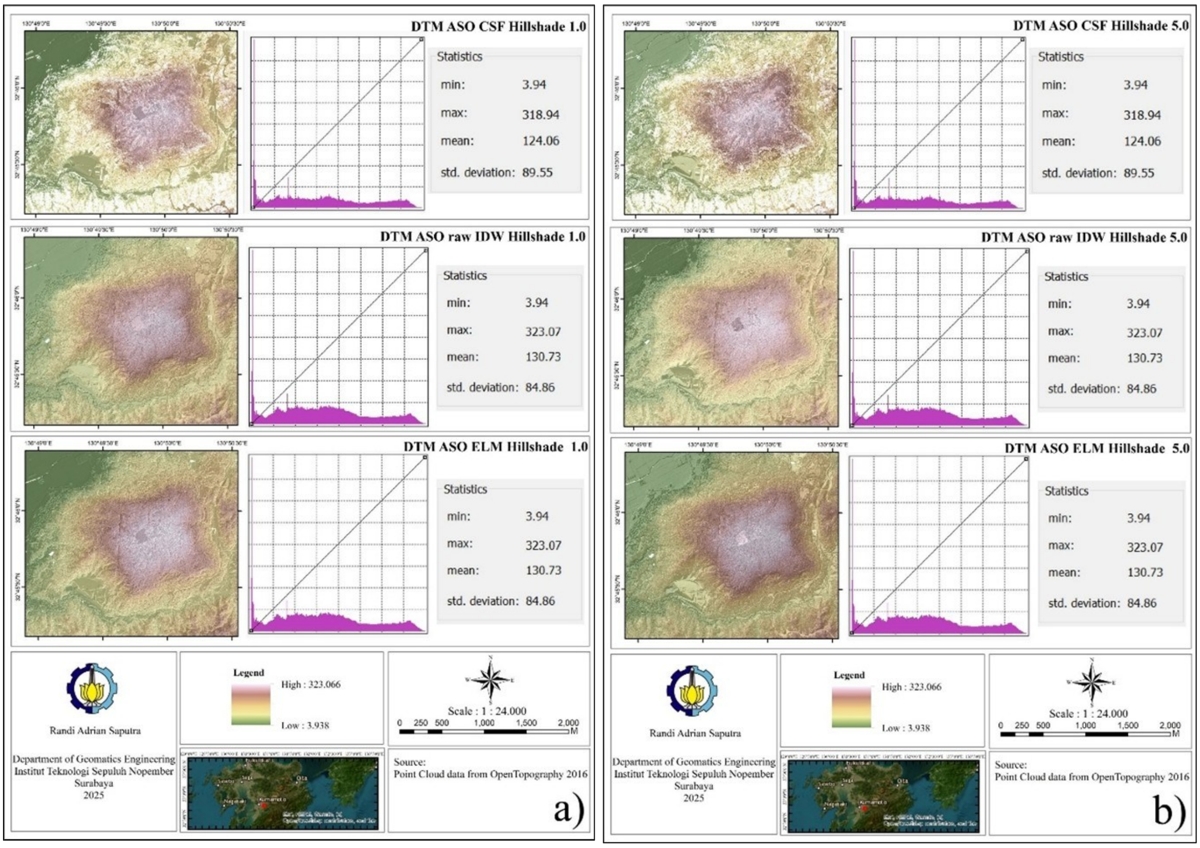

Figure 2. Digital Terrain Model Visualization Results Map: a) Z factor 1.0, b) Z factor 5.0.

limitations of filtering methods that are less adaptive to vegetation and topographically complex terrain.

The CSF-derived DTM exhibits superior surface continuity compared to the Raw and ELM methods. Unlike statistical filters that process points in isolation, the CSF algorithm treats the terrain as a physical surface by simulating the movement of a flexible cloth over an inverted point cloud. This mechanical approach allows the algorithm to bridge small gaps and ignore low-lying vegetation that often creates 'spikes' or 'noise' in other methods. This results in a smoother, more realistic representation of the land surface, even when subjected to extreme vertical exaggerations. According to Zhang et al. (2016), this simulation-based approach is particularly effective because it relies on the physical properties of the 'cloth' such as rigidness and resolution rather than simple elevation thresholds, making it more robust in maintaining terrain shape while effectively suppressing non-ground features.

Overall, the visual difference between Z-factor 1.0 and Z-factor 5.0 highlights the importance of using a multi-scale approach in DTM quality evaluation. While Z-factor 1.0 provides a general overview suitable for statistical analysis, Z-factor 5.0 allows for a more critical evaluation of geomorphological stability and filtering method reliability. This approach strengthens the comparative results between methods and provides a solid basis for concluding the most appropriate filtering method for complex topographic environments. Overall, the visual comparison between Z-factor 1.0 and Z-factor 5.0 highlights the importance of a multi-scale approach in DTM evaluation. While Z-factor 1.0 is suitable for standard statistical analysis, Z-factor 5.0 reveals critical geomorphological artifacts and filtering reliability. For ineffective methods like ELM, the primary limitation identified is the lack of spatial context in its filtering logic. To achieve more promising results with limited datasets, future research should explore integrating local slope constraints or adaptive neighborhood analysis into simple statistical filters to help them distinguish between canopy and ground points on steep slopes. Conversely, for effective methods like CSF, the results could be further optimized by fine-tuning the 'cloth' elasticity to account for localized sharp ridges, which are sometimes overly smoothed. This dual evaluation approach not only confirms CSF as the most appropriate method for Mount Aso's complex topography but also provides a roadmap for future filtering refinements in similarly data-constrained environments.

CONCLUSION

Cloth Simulation Filter proved to be the most effective and robust ground filtering method in complex and densely vegetated mountainous areas. This success was quantitatively proven through a significant decrease in the Average Raw DTM elevation value from 130.73 m to 124.06 m in the CSF DTM, as well as a decrease in the maximum elevation, confirming the successful elimination of vegetation noise. In addition, visualization results at various levels of vertical exaggeration indicate that the CSF can maintain the consistency of the land surface geomorphology more stably than other methods. The simple statistical filtering method of Outlier Elimination proved to be ineffective for ground filtering in densely vegetated areas. The statistical results of the ELM DTM are identical to those of the Raw DTM, explaining that vegetation noise is spread collectively and not as extreme statistical outliers.

RECOMMENDATIONS

Additional research is needed that focuses on 1) optimizing CSF parameters to mitigate filtering artifacts that cause an increase in standard deviation; and 2) comparative testing of CSF with more adaptive interpolation methods, such as Kriging, to determine its effect on noise and the quality of the final DTM.

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