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Benchmarking Local Registration Algorithms on Multi Temporal and Multi Spatial Point Clouds

Tommaso Mainiero [1], Jad Ghantous [1], Nives Grasso [1], Vincenzo Di Pietra [1]
[1] Department of Environment, Land and Infrastructure Engineering, Politecnico di Torino, Turin, Italy –
tommaso.mainiero@polito.it, jad.ghantous@polito.it, nives.grasso@polito.it, vincenzo.dipietra@polito.it,

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Abstract

Climate change is driving an increase in the frequency and intensity of extreme events in mountainous environments, amplifying geomorphological hazards and the need for accurate multi-temporal topographic monitoring. However, the integration of multi-source datasets remains challenging due to geolocation inconsistencies, heterogeneous data quality, and complex terrain conditions.
This study presents a systematic benchmarking framework to evaluate the performance of local point cloud registration algorithms and their impact on geomorphological change detection. Three widely used methods—Iterative Closest Point (ICP), Point-to-Plane ICP, and Generalized ICP (GICP)—were tested across two alpine case studies in Italy (Rio Cucco catchment and Belvedere Glacier), considering different surface types and initial alignment conditions.
Results demonstrate that registration performance is strongly controlled by surface morphology, with rocky areas ensuring stable and accurate alignment, while vegetated surfaces introduce significant uncertainties. Point-to-Plane ICP emerges as the most computationally efficient method, whereas GICP provides improved robustness under complex conditions.
The study further highlights that integrating robust outlier rejection significantly improves statistical consistency and reduces LoD95. The proposed approach provides a reproducible framework for optimizing co-registration strategies and improving the accuracy of geomorphological monitoring in high-relief environments.

1. Introduction

Climate change is associated with an increase in the frequency and intensity of extreme weather events worldwide, including rainfall-induced landslides and severe storms, particularly in mountainous and high-altitude environments. (Paswan et al., 2023; Li et al., 2024) These processes are exerting significant impacts on terrestrial environments, leading to a growing occurrence of natural hazards. This trend underscores the critical need for effective geomorphological monitoring. In this context, geomatic techniques are increasingly employed to detect, quantify, and analyse geomorphological changes with high spatial and temporal resolution (Romeo et al., 2026.). Nevertheless, mountainous and high-elevation environments represent particularly challenging settings for geomorphological surveying and monitoring activities. In addition, the integration of multi-source datasets poses significant challenges in terms of data harmonization. These challenges are related to differences in sensor types, acquisition conditions, processing workflows, georeferencing accuracy, and intrinsic data quality, all of which may affect the robustness of subsequent analyses. Moreover, even datasets acquired from similar platforms at different times may suffer from geolocation inconsistencies, especially in mountainous areas, where steep terrain, sky occlusions, long GNSS baselines and geometric distortions can significantly impact positional accuracy. To overcome this, registration of the point cloud products is often a necessary step, rather than relying solely on GNSS-based positioning and RTK corrections. (Belloni et al., 2025)

In this study, we tested different point cloud registration algorithms to assess their performance in geomorphological monitoring applications. The tested algorithms include the standard Iterative Closest Point (ICP), Generalized ICP (GICP), and Point-to-Plane ICP methods (Besl & McKay, 1992). Performance evaluation considered both computational efficiency and registration accuracy, enabling a comparative analysis of their suitability for detecting geomorphological changes.

2. Case studies

Two study areas in Italy were selected to test the point cloud registration algorithms, both located in mountainous environments and highly exposed to hydro-morphological hazards.
The first case study is the Rio Cucco catchment (0.65 km², Friuli Venezia Giulia), a particularly vulnerable area with documented geomorphic events in 2003 and 2018 that caused significant landscape changes. The site is one of the pilot areas of the MORPHEUS project (GeoMORPHomEtry throUgh Scales for a Resilient Landscape), a national initiative aimed at multi-scale geomorphological monitoring. Two LiDAR datasets were considered for this site. The first, provided by Eagle FVG, the official web portal of the Friuli Venezia Giulia region, was acquired in 2017 with a mean point density of 190.08 points/m², referenced in RDN2008 / UTM Zone 33N. The second dataset, acquired in June 2024 using a DJI Zenmuse L1 sensor mounted on a DJI Matrice 300 RTK platform, was subsampled to a mean density of 171.38 points/m² and registered in the same coordinate system. This latter dataset was previously used in Ghantous et al. (2025) to investigate topographic changes between 2017 and 2024.
The second case study concerns the Belvedere Glacier, located near the municipality of Macugnaga (Valle Anzasca, Piedmont, Italy), a region highly exposed to gravitational debris-flow events, the most recent of which occurred in the summer of 2024. The glacier is of particular interest for multi-temporal monitoring and has been studied in collaboration with ARPA Piemonte and the MOHYCAM project, involving Politecnico di Torino and Politecnico di Milano. The MOHYCAM initiative (Multi-scale Observation of HYdrological processes and Climate-driven glacier dynamics with Advanced Monitoring) aims to improve understanding of glacier evolution and associated hydro-

morphological hazards. Two point cloud datasets and one DEM were considered for this case study. The monitoring campaign was designed and conducted jointly by the Department of Civil and Environmental Engineering (DICA) of Politecnico di Milano, the Department of Environment, Land and Infrastructure Engineering (DIATI) of Politecnico di Torino and the DREAM projects (DRone tEchnology for wAter resources and hydrologic hazard Monitoring), involving teachers and students from Alta Scuola Politecnica (ASP). (Gaspari et al., 2025, Ioli et al., 2022, Ioli et al., 2024, De Gaetani et al., 2021) The point cloud datasets were acquired on 25–27 July 2022 and 24–26 July 2023 using a DJI Zenmuse P1 sensor mounted on a DJI Matrice 300 RTK platform. Point clouds were generated through photogrammetric processing using a fixed network of 22 GCPs installed along the glacier perimeter. The point density was heterogeneous: the 2022 point cloud has 66.5 points/m² (2469 images, global RMSE 0.116 m computed on 19 control points) , whereas the 2023 dataset has 18.6 points/m² (1473 images, global RMSE 0.068 m computed on 9 control points) . The DEM was generated from the same photogrammetric processing used for the 2022 point cloud, with a ground sampling distance (GSD) of 0.2 m. All datasets are projected in RDN2008 / UTM 32N, the Point clouds are referenced to the ellipsoidal vertical datum, the DEM is referenced to the orthometric vertical datum ITALGEO05. The DEM was included as an input dataset to evaluate the effectiveness of data harmonization procedures and to assess potential impacts on geomorphological analysis results due to the different altimetric datums.

3. Methodology

3.1 Data pre-processing methodology

To better assess the effectiveness of the registration algorithms, a preprocessing of the datasets was first performed.
The LiDAR point clouds of the Rio Cucco catchment, provided by the MORPHEUS project, was divided into several sub-areas (patches) to benchmark the performance of the registration algorithms under varying initial alignment and terrain conditions (Figure 1). Patches were selected to represent distinct geomorphological contexts, including dense vegetation (Patch 2) and rock outcrops (Patch 4), also both the patches were standardized to a voxel size of 0.3 m to facilitate algorithm comparison. Figure 1 illustrates the spatial distribution of the patches within the catchment. For the analysis, patches 2 and 4 were examined in detail because they represent the extremes of registration difficulty, caused both by temporal variability and by the type of target observed. Patch 4 corresponds to a rock-dominated area and allowed for robust registration, whereas patch 2, characterized by dense vegetation, presented significant registration challenges. To assess the robustness of the algorithms, artificial misalignments were introduced to the initial registration. Specifically, translations of ±1.5 m and rotations of 15° were applied to simulate errors in georeferencing and to evaluate algorithm performance under suboptimal initial alignment conditions (Figure 3A). Both scenarios—using the original georeferencing and introducing artificial errors—were tested to comprehensively assess registration accuracy and reliability.

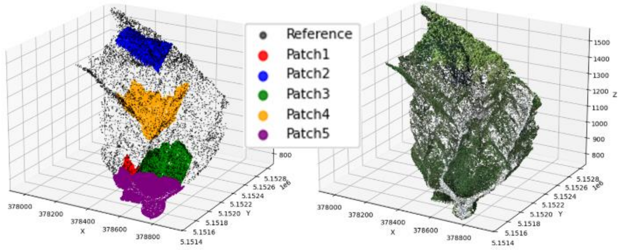

Figure 1. Overlays of Registered and Reference Point Clouds for Patch 1.

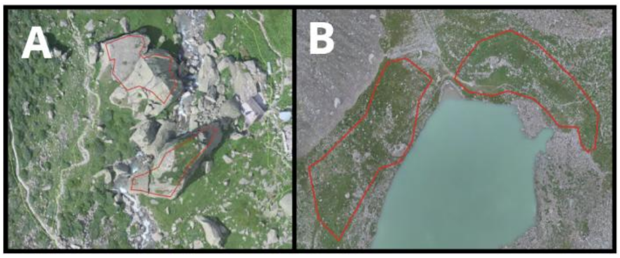

Figure 2. Panel (A) shows an example of a stable area composed of exposed rock, while panel (B) illustrates a stable area including both rock and vegetation. Both areas were selected within the Belvedere Glacier study site.

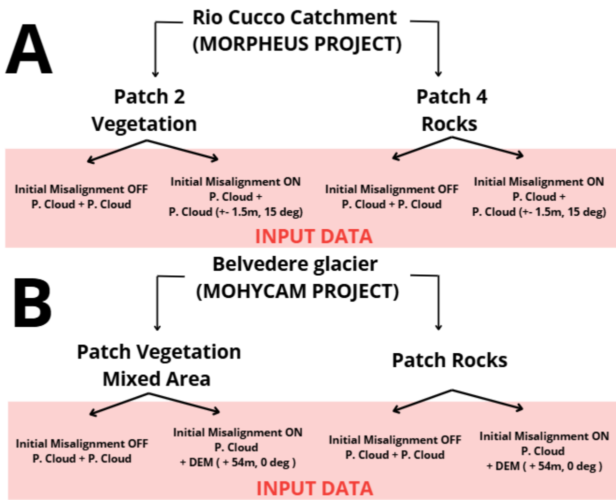

Figure 3. Panel A shows the input patches extracted from the Rio Cucco catchment dataset, including Patch 2 - vegetation and Patch 4 - Rock, both tested under conditions with and without initial misalignment (1.5 m translation and 15° rotation). Panel B shows the input patches extracted from the Belvedere Glacier dataset, including vegetation and rock patches, as well as rock-only patches, tested with and without initial misalignment (54 m vertical translation).

For the MOHYCAM dataset, which includes both point clouds and a DEM, the registration of the products was performed on selected stable areas well distributed in the study area, treated as patches, to evaluate the performance of registration algorithms in a high-mountain context, where steep slopes, heterogeneous surfaces, and complex terrain can significantly impact alignment accuracy. It is crucial to use stable areas when performing registration over very large and geomorphologically complex surfaces, such as glaciers, as these zones provide reliable reference points that are minimally affected by temporal changes, thereby ensuring accurate alignment and reducing errors in areas with strong morphological variability.
Two types of stable zones were defined:

Small rocky areas, consisting exclusively of erratic boulders and exposed bedrock outcrops, similar to patch 4 of the Rio Cucco study (Figure 2A). Larger mixed areas, including rocky elements as well as patches of vegetation and alpine meadows, analogous to patch 2 (Figure 2B). These zones are more heterogeneous and represent a greater challenge for registration because of variable surface characteristics and temporal changes.

Also in this case, the input datasets were selected to reproduce initial misalignments, similarly to the approach adopted for the Rio Cucco catchment. When evaluating the performance of co-registration starting from correctly geolocated products, two point clouds were used. In contrast, when assessing the robustness of the algorithms introducing initial misalignment under differing vertical reference systems, both a point cloud and a DEM were employed, introducing a vertical discrepancy of approximately 50 meters between the products to simulate challenges arising from mismatched altimetric references (Figure 3B)

3.2 Point cloud registration and performance assessments methodology

The present research extends previous work by evaluating multiple local registration algorithms implemented in a Python environment. The tested methods include the standard Iterative Closest Point (ICP), Generalized ICP (GICP), and Point-to-Plane ICP algorithms (Besl & McKay, 1992). The aim of testing these local registration methods was to benchmark the capabilities and limitations of different algorithms with respect to varied initial alignment conditions. Each algorithm was applied to several sub-areas (patches) of the Rio Cucco catchment and the Belvedere Glacier to evaluate performance under varying initial alignment and terrain conditions. Performance evaluation followed Fontana et al. (2021), using the 50th percentile (median) error, cloud-to-cloud mean distance, and computation time as primary metrics. These metrics were computed by first estimating, for each point of the registered source cloud, the nearest-neighbor distance to the target cloud. For each point, a geometric scaling factor was then defined as the Euclidean distance between the point and the centroid of the registered source cloud. A normalized, dimensionless error was obtained as the ratio between the nearest-neighbor distance and this scale factor, with a small constant added to avoid numerical instability near the centroid. The formulas used are as follows:

$$d_i = \|p_i - q_i\| \; ; \; c = \frac{1}{N}\sum_{i=1}^{N} p_i \; ; s_i = \|p_i - c\| \; ; e_i = \frac{d_i}{s_i + \varepsilon}$$

where d_i =Nearest-neighbor distance
c = centroid position
s_i = Euclidean distance between the point and the centroid
e_i = the the nearest-neighbor distance normalized with is the Euclidean distance between the point and the centroid

From the resulting distribution of normalized errors, several statistical descriptors were derived, including the median (F.C._Median), representing a robust estimate of the typical error; the 95th percentile (F.C. 0.95Q), describing the upper tail of the distribution; the standard deviation (F.C. std), capturing dispersion; and the maximum value (F.C. max), indicating the worst-case misalignment. All F.C. metrics are dimensionless and directly comparable across datasets, with lower values indicating better registration performance.

In parallel, a robust statistical framework based on Difference of DEMs (DoD) analysis was implemented to evaluate improvements in detecting and quantifying geomorphological changes, as well as to assess the uncertainties of the DoD itself when registration is applied. This approach ensures that the evaluation does not rely solely on registration performance metrics but also considers the quality and reliability of the derived geomorphological change detection.

The statistical framework is composed of exploratory data analysis (EDA), outlier rejection techniques, and normality assessment. The EDA allows for a comprehensive characterization of the DoD statistical sample distribution by computing descriptive statistics such as mean, median, standard deviation, minimum and maximum values, range, coefficient of variation, skewness, kurtosis, median absolute deviation (MAD), and normalized median absolute deviation (NMAD), as well as by analyzing graphical representations including boxplots, empirical probability density functions, and cumulative distribution functions. This analysis is applied to the DoD computed over stable areas, both before and after outlier rejection, enabling the estimation of the Level of Detection at 95% confidence. Outlier rejection is implemented through multiple complementary approaches. A first method is based on the application of a significance level, symmetrically removing extreme values in both tails of the distribution. A second approach relies on the boxplot method, where outliers are identified as values falling outside the interval defined by the interquartile range (IQR). The formulas used are as follows:

$$IQR = Q_3 - Q_1$$

$$x_i \; is \; OUTLIERS \; if \colon \begin{cases} x_i < \; Q_1 - 1.5 \, IQR \\ \quad\quad or \\ x_i > \; Q_3 + 1.5 \, IQR \end{cases}$$

where Q_1 is 25th percentile
Q_3 is 75th percentile

A third method is based on NMAD, which provides a robust, scale-independent measure of dispersion and is particularly suitable for skewed or non-Gaussian distributions, allowing for asymmetric filtering of extreme values based on the intrinsic variability of the data. The formulas used are as follows:

$$MAD = median \; (| \; x_i - median \; (x)|)$$

$$\mathrm{NMAD} = 1.4826 \; \mathrm{MAD}$$

$$x_i \; is \; OUTLIERS \; if \colon | \; x_i - median \; (x)| > kNMAD$$

$$k = 1,2,3,4$$

Finally, the normality of the DoD distribution is assessed using both graphical and statistical methods. Q–Q plots are used to compare the empirical distribution with a theoretical normal distribution, with the goodness of fit quantified through the coefficient of determination (R^2). In addition, the Anderson–Darling test is applied as a formal statistical test of normality, with particular sensitivity to deviations in the tails of the distribution, which are critical in geomorphological change detection.

4. Workflow algorithm

The proposed workflow (Figure 4) is structured as a modular pipeline designed to support statistically robust multi-temporal geomorphological analysis through the integration of point cloud registration, DEM generation, and DoD-based change detection. The pipeline begins with a data ingestion and harmonization phase, in which multi-source datasets, including point clouds and DEMs acquired at different times, are standardized.

A stable area selection and clipping step is then performed, using predefined vector polygons representing geomorphologically stable zones.

The core registration phase is carried out on the clipped stable areas. Multiple local registration algorithms, including Point to Point ICP, Point-to-Plane ICP, and Generalized ICP, are tested and benchmarked under varying initial alignment conditions. The pipeline evaluates their performance and automatically selects the most suitable method, which is then used within an adaptive multi-scale registration framework to estimate the optimal transformation between datasets. The estimated transformation is subsequently applied to the input datasets to generate aligned DEMs over stable areas, which are used to compute a Difference of DEMs (DoD). This enables the estimation of the Level of Detection (LoD95), providing a quantitative measure of uncertainty associated with elevation changes. Once the transformation parameters are validated, they are propagated to the full-area datasets. This ensures that the alignment derived from stable zones is extended to regions affected by geomorphological changes. Finally, the workflow performs a geomorphological analysis on the full-area DoD, producing spatially distributed maps of elevation change, volumetric estimates, and associated statistical descriptors. The entire process is fully documented through automated reporting, including structured summaries and logs, ensuring reproducibility and transparency of the analysis.

5. Results

In the first set of figures (Figure 5), the performance metrics defined by Fontana et al. (2021) are presented for the different registration methods, applied to each type of natural surface (vegetation and rock) in both the Rio Cucco catchment and the Belvedere Glacier. The aim is to evaluate their effectiveness and to identify the most suitable registration method as a function of the input data characteristics. The x-axis represents the tested registration methods, namely Point-to-Point ICP, Point-to-Plane ICP, and Generalized ICP, while the best-performing method for each dataset is highlighted in red. The y-axis reports computation time together with the performance metrics, including the median, 95th percentile, and standard deviation of the normalized nearest-neighbor distances. In the second set of figures (Figure 6), once the optimal registration method has been identified, the impact of registration on the statistical properties of the DoD over stable areas is analyzed. In particular, the figures show how the application of registration improves the Level of Detection of the datasets in a geomorphological change detection framework. The x-axis represents four different scenarios, considering the presence or absence of registration and the application or omission of outlier rejection. The y-axis reports statistical descriptors including mean, standard deviation, LoD95%, and the coefficient of determination (R^2) derived from Q–Q plots used for normality assessment.

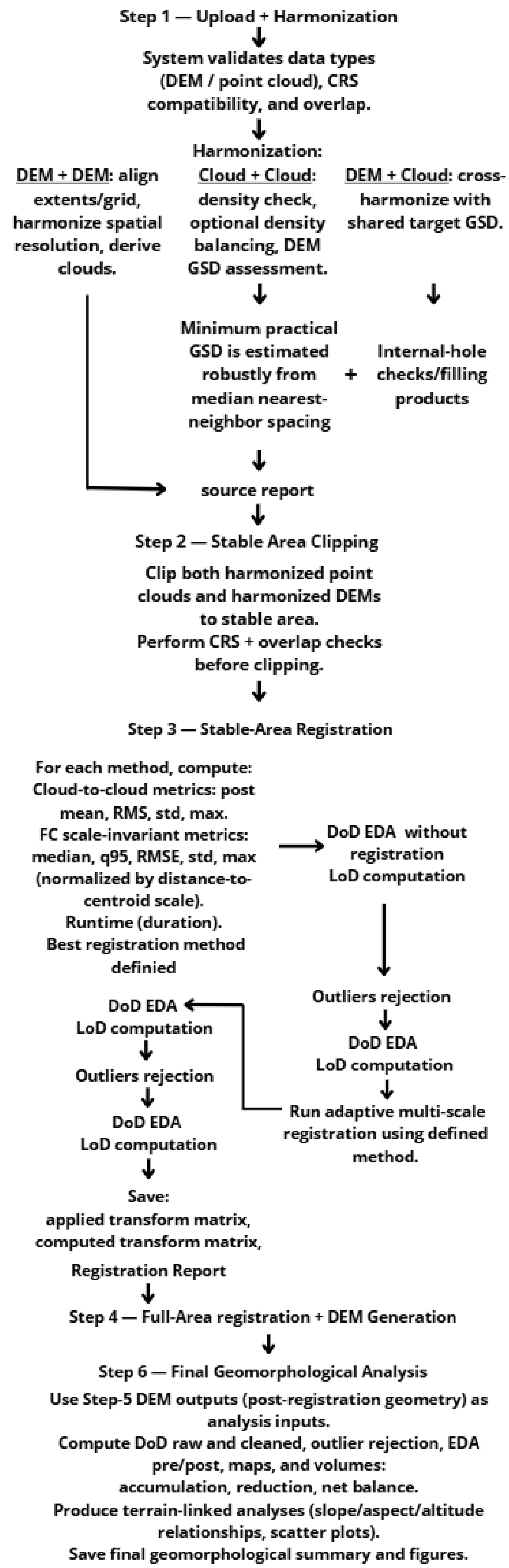

Figure 4. The figure illustrates the workflow of the proposed algorithm, highlighting the different processing steps of the pipeline.

6. Results discussion

The results clearly highlight that surface type plays a fundamental role in determining registration performance. In general, vegetated areas exhibit lower performance compared to rocky surfaces, due to the intrinsic temporal variability, structural complexity, and lower geometric stability of vegetation. In contrast, rock-dominated areas provide stable and well-defined features that significantly enhance registration accuracy and convergence. In the Rio Cucco catchment, vegetation patches show that Point-to-Plane ICP consistently achieves the best performance under both correct initial alignment and misaligned conditions, with slightly improved results in the absence of initial misalignment. In contrast, Generalized ICP and Point-to-Point ICP can produce worse results than the non-registered case when datasets are already well aligned, while all methods provide improvements when initial misalignment is introduced. For the Belvedere Glacier, vegetation scenarios behave differently. Under correct initial alignment, all methods produce comparable results, although Point-to-Point ICP is significantly slower in terms of computation time. When initial misalignment is introduced, GICP clearly outperforms the other methods, although all algorithms still improve the alignment compared to the non-registered case. In all scenarios where registration is performed over rocky surfaces, the tested algorithms show very similar performance, indicating that well-defined and stable geometries reduce the sensitivity to the choice of method. In the Rio Cucco case, registration does not significantly alter the results regardless of the presence of initial misalignment, and all methods achieve comparable improvements. However, Point-to-Plane ICP consistently provides the fastest convergence. For the Belvedere dataset, the best results are often observed in the absence of both registration and initial misalignment, while the application of registration leads to comparable performance across all methods, with Point-to-Plane ICP and GICP being the most computationally efficient. The analysis of computational time confirms that Point-to-Plane ICP is the fastest method in the majority of cases (7 out of 8 scenarios), representing an effective compromise between computational efficiency and accuracy. Standard ICP is generally slower and exhibits significantly higher computation times, particularly in vegetation-dominated areas where convergence becomes more challenging. GICP shows intermediate behaviour overall but proves to be more robust in complex scenarios, such as highly heterogeneous or vegetation-rich environments. The median computation times across the eight analyzed patches are 19.26 s for ICP, 10.81 s for Point-to-Plane ICP, and 25.99 s for GICP. The DoD-based analysis on stable areas reveals a clear trend: when no initial misalignment is present, the combined use of registration and outlier rejection generally produces the best results, although improvements may be limited due to the already good initial alignment. In contrast, in the presence of significant initial misalignment, registration becomes essential and leads to substantial improvements, particularly in recovering the correct alignment. In these cases, the transition from no registration to registration often yields the largest performance gains. At the same time, the results emphasize the importance of evaluating not only mean error but also dispersion and distribution characteristics. Reliable improvement is typically associated with a reduction in both mean and standard deviation, as well as a distribution that more closely approximates normality, as indicated by higher R^2 values. Vegetation scenarios remain the most challenging, consistently producing weaker metrics due to their higher sensitivity to residual misalignment and noise. An important outcome of this study is that outlier rejection plays a critical role in improving DoD quality. In several cases, applying outlier filtering alone results in greater reductions in dispersion and LoD95 compared to applying registration without filtering. This demonstrates that robust statistical filtering is not merely a secondary step, but a key component of the workflow that can significantly enhance the reliability of geomorphological change detection.

7. Conclusions

The results demonstrate that misregistration errors directly propagate into spurious elevation differences in Difference of DEMs (DoD) analyses, significantly affecting the reliability of geomorphological change detection. Consequently, the selection of an appropriate registration algorithm, tailored to the specific terrain characteristics, is a critical step for accurate monitoring of climate-induced topographic evolution and natural hazards. The proposed benchmarking framework provides a systematic approach for evaluating registration performance under varying geomorphological conditions and initial alignment scenarios. It offers practical guidance for algorithm selection and establishes a robust baseline for future developments. The analysis highlights a strong dependence of registration performance on surface morphology and point-cloud characteristics. Patches located on rocky, well-defined surfaces consistently achieved the lowest median errors and fastest convergence, whereas areas characterized by dense vegetation and complex terrain exhibited limited improvement and less stable convergence. These findings confirm that local registration algorithms perform best when a reasonable initial alignment is available and when the terrain geometry is well defined. Conversely, large misalignments, irregular morphology, and low-texture surfaces introduce ambiguities that negatively affect convergence stability and accuracy. Among the tested methods, Point-to-Plane ICP proved to be the most computationally efficient in the majority of cases, representing a good compromise between speed and performance. Standard ICP showed higher computational costs and reduced efficiency in complex environments, particularly in vegetated areas. GICP demonstrated more stable behavior across heterogeneous conditions, achieving a balanced trade-off between robustness and computational demand, especially in challenging scenarios. The application of outlier rejection techniques consistently improved the statistical robustness of the DoD analysis, generally reducing the standard deviation and the Level of Detection (LoD95), even in cases where the mean elevation change remained relatively stable. This highlights the importance of integrating robust statistical filtering within the geomorphological analysis workflow. Overall, accurate co-registration of multi-temporal datasets is essential for reliable detection and quantification of geomorphological changes. The integration of registration benchmarking with DoD-based statistical analysis provides a comprehensive framework for improving the quality and interpretability of geomorphological monitoring in complex environments.

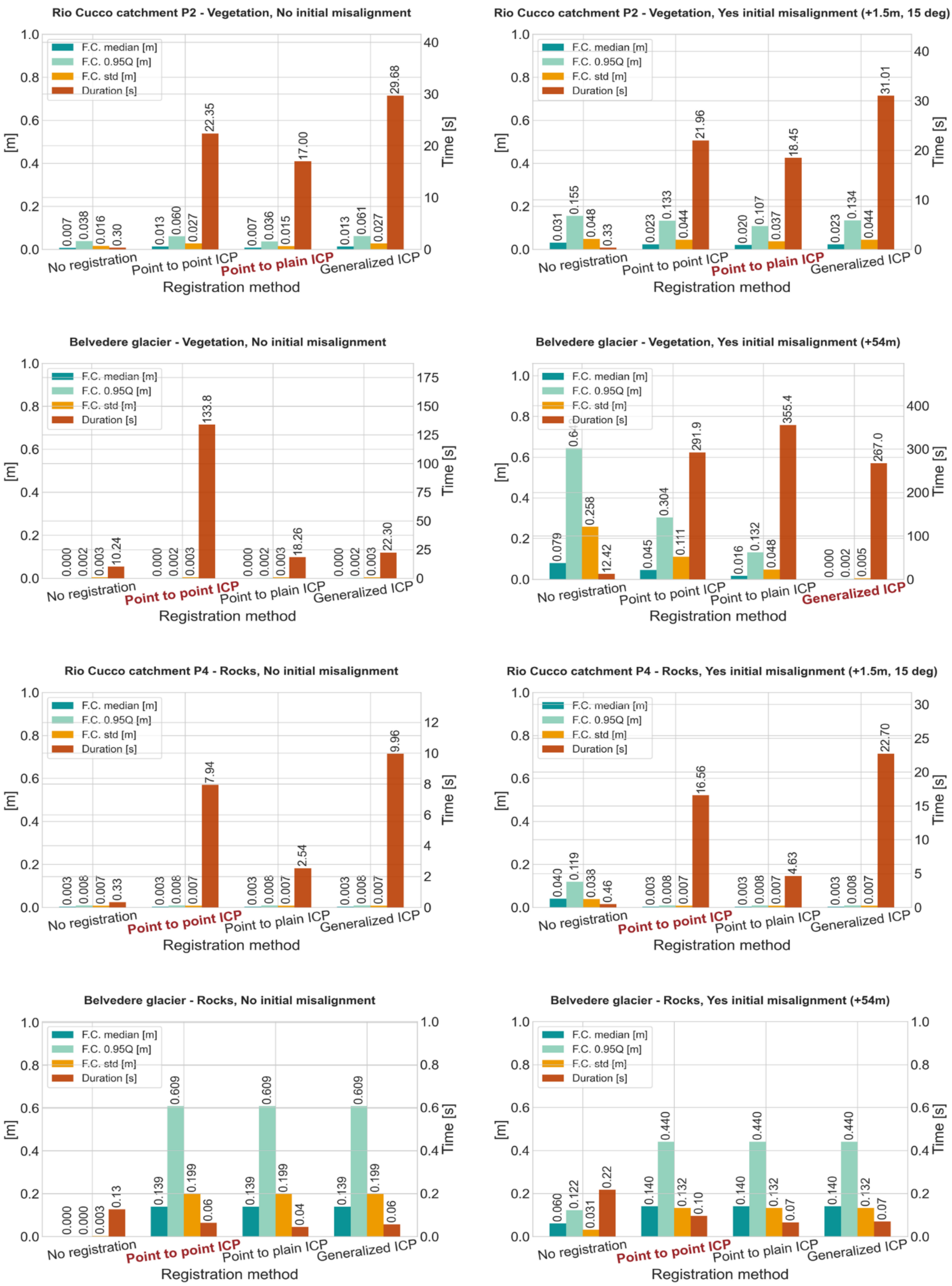

Figure 5. The plots show the performance metrics of the point cloud registration algorithms, as defined by Fontana et al. (2021), together with the corresponding computation times. The best-performing algorithm for each case is highlighted in red along the x-axis.

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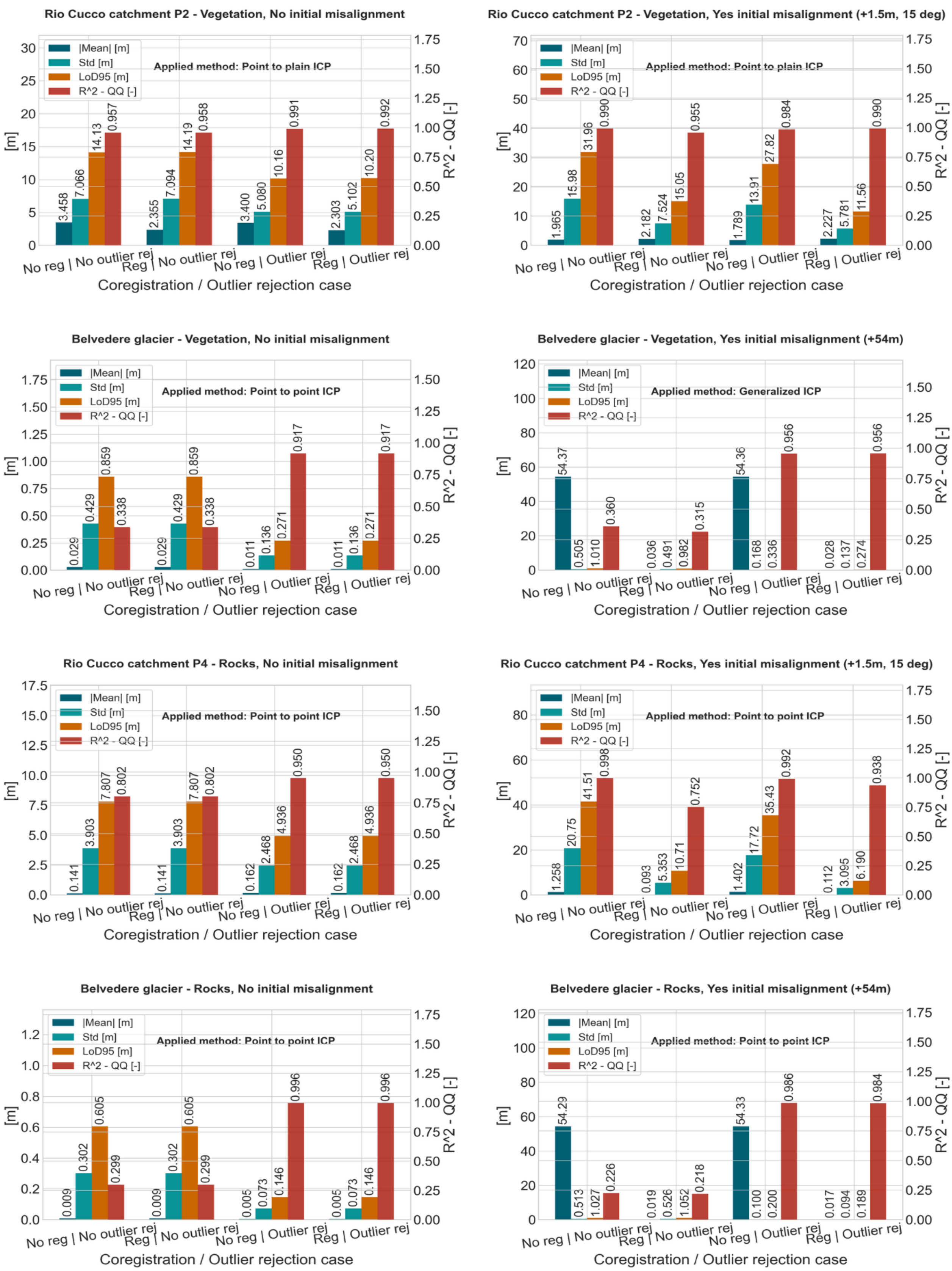

Figure 6. The plots show the results of the exploratory data analysis (EDA) and normality tests applied to the DoD over stable areas, before and after outlier rejection, using the best-performing registration algorithm previously identified

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