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Terrace Smoothing Using Open Source Tools In Digital Terrain Models

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Abstract

Extreme rainfall events have been occurring more frequently due to climate change causing several distress especially in the most vulnerable Italian territory. The region of Liguria is particularly prone to hazardous events due to the morphology of the terrain. Moreover, anthropogenic modifications of the land such as terraces are among the factors that impact the risk of a natural hazard after an extreme rainfall event. A particular extreme event occurred in autumn 2014, where rainfalls affected different areas in Liguria causing three casualties, severe structural damages and more than 1600 landslides. In this context, innovative spatial analysis procedures on land topography can increase the knowledge of morphological parameters, like the well-known connectivity index. The aim of this research is to develop a method to recover the land topography before the modification caused by terraces and therefore understand their impact from comparison. The selected area for this analysis is the catchment of Rupinaro River, Italy, which has been surveyed after the 2014 event by CNR IRPI. An Airborne Light Detection and Ranging survey was carried out and Digital Terrain Models (DTM) of 50 cm resolution were produced. To this topic, our contribution is a terrace smoothing methodology, which creates a DTM of Rupinaro area that is terrace free but conserves the original elevation values. That way, a terraced model and a nonterraced model can be compared to understand the impact of anthropogenic modifications on natural hazards. An iterative approach was used for the entire procedure including the creation of smoothed DTM. A combination of QGIS and Python were used for the entire terrace smoothing procedure. The terrace smoothing steps included visualizing the terraces and walls, creating a mask to sperate the terraces and the terrace walls, extracting centerlines of the terraces and walls, converting the centerlines into points, merging these centerline points, interpolating using triangulated irregular network, and smoothing the produced DTM. After a comparison of the original data and the produced data, we successfully recreated the original morphology of the area in a state without terraces. Consequently, this artificially smoothed model can be further studied to understand the impact of terraces on natural hazards such as landslides in the catchment of Rupinaro Italy.

Introduction

With the emergence of climate change, several studies are backing up the trends that this phenomenon will create a multitude of problems. Among such problems, is the increased frequency of extreme weather events such as storms, rainfall, floods, drought, heatwaves etc. Zhu (2013) found an increased likelihood of extreme storms while studying intensity duration frequency curves based on future climate projections in the United States. Furthermore, focusing on local issues, the Italian region of Liguria was the study focus with regards to extreme rainfall events especially after the occurrences of the extreme rainfall of 2011 and 2014. Faccini et al. (2018) discovered a trend of increased rainfall and temperature in Genoa which falls in line with the findings of IPCC (Intergovernmental Panel on Climate Change) with regard to weather behavior. Furthermore, there was evidence that supports this claim by noticing an increase in hourly recorded cloudbursts and maximum daily rainfall intensities, higher flood discharge per extreme event, and a notable rise in torrential rainfall during the 3-hour interval in recent flash floods compared to previous events. Liguria, like other Mediterranean areas, is a region historically known to have anthropogenic territorial modifications such as terraces since the Neolithic period (Godone et al., 2018). The authors state that in Rupinaro, the percentage of terraces range between 46 to 54 % with Liguria having between 20 to 30 % of its entire area being covered with terraces. There have been several studies related to terraces, their effects, and how to identify them. When it comes to the effects of terraces on natural hazards, the literature has showed that depending on the state the terraces are in they may contribute to the hazards in different ways. Giordan et al. (2017) stated that synthetic modifications to the morphology is one of the most important factors influencing rain triggered landslides. Moreover, based on Paliaga et al. (2020), terracing steep sloped areas may help in reducing the risk of landslides and collapses while abandoning these terraces may cause the opposite effect in increasing the risk of collapses. Thus, comparing the effects of a terraced environment with a nonterraced environment of the same properties (area & elevation) is essential to determine the land change effects on natural hazards. With regards to terrace identification, there are several scientific contributions to identify terraces. Del Val, et al (2015) adapted a slope-based approach to identify the terraces. Their method, which was adapted from another method developed by Demoulin et al. in 2007, relies on identifying variations in slopes and changes in profile curvature around hillslopes. By applying their method to the Oiartzun river valley, the authors, were able to identify fluvial terraced areas using a combination of fieldwork and aerial photographs to validate their findings. Another method in identifying terraces can be found in the work presented by Luo et al. (2020) who used remote sensing images and digital elevation models to identify the terraces. The study converted the information using a Fourier transformation basing the terrace identification on certain frequencies and predefined parameters. Furthermore, Winzeler et al. (2023) concentrated on identifying and delineating broad-base agricultural terraces in flat landscapes. They applied computer vision techniques to terrain derivatives calculated from digital elevation models. The study employed a supervised classification approach, using algorithms like random forest and neural networks, to classify terrace and non-terrace areas based on terrain derivatives. Their study focused on flat terrains instead of mountainous ones. In this proposed study, another approach to terrace identification was implemented. At the best of our knowledge, no other work was found that had a terrace smoothing study exclusively as the works were mainly focused on the identification. However, terrace smoothing is needed to study the complex relationships between such anthropogenic modifications and their effect on natural hazards. The goal of this study is to create a smoothed DTM to compare it with the terraced DTM. The produced model is propaedeutic to subsequent morphological studies and in particular on the analysis on connectivity index. The connectivity index according to Crema & Cavalli (2017) refers to the degree of connectivity or linkage between different parts of a landscape in terms of sediment transport where a high index reports easy transportation of sediments while a low index reports a difficult transportation of sediments. Crema & Cavalli (2017) created the software SedInConnect as an open-source tool to calculate the sediment connectivity index based on elevation values and other input data. This tool will be used to indicate the effects of terraces on the values of sediment connectivity.

Fig.1: (a) Terrace in Liguria (Photo: Matteo Badani) ; (b) Shallow Landslide on Stone Terrace (Source: Giordan et al. (2017)

Study Area

With regards to the area of interest for the study, the area chosen was that of the Rupinaro catchment in Liguria Italy. The Rupinaro catchment as seen in Fig.2 is an area situated in south east Liguria in the municipality of Chiavari which is in the province of the metropolitan city of Genoa. The catchment is situated between Mt. Anchetta and the Ligurian coast. The elevation data of this catchment spans between 1 m to 547 m as indicated by the DTM of the area. This catchment has been subjected to heavy rainfall events that have led to landslides. In the period between October and November of 2014, heavy rainfalls triggered landslides specifically in areas where there was anthropogenic modification of the land such as terraces that had been abandoned over time (Giordan et al., 2017). This makes this area a suitable candidate to test the terrace smoothing algorithm for an area historically known for the presence of terraces and the occurrence of natural disasters. To test the terrace smoothing algorithm, a smaller subset marked in orange was selected as the testing area. Area A was chosen based on the study by Godone et al. (2018), which had already identified terraces in this location. The area they examined aligns with Area A, and the designated orange polygon covers an area of 0.041 km².

The data behind this study was provided by CNR – IRPI in Turin. CNR – IRPI (2024) provided the DTMs of 50 cm resolution created from ALS LIDAR surveys of the area of Rupinaro in Liguria in the year 2014.

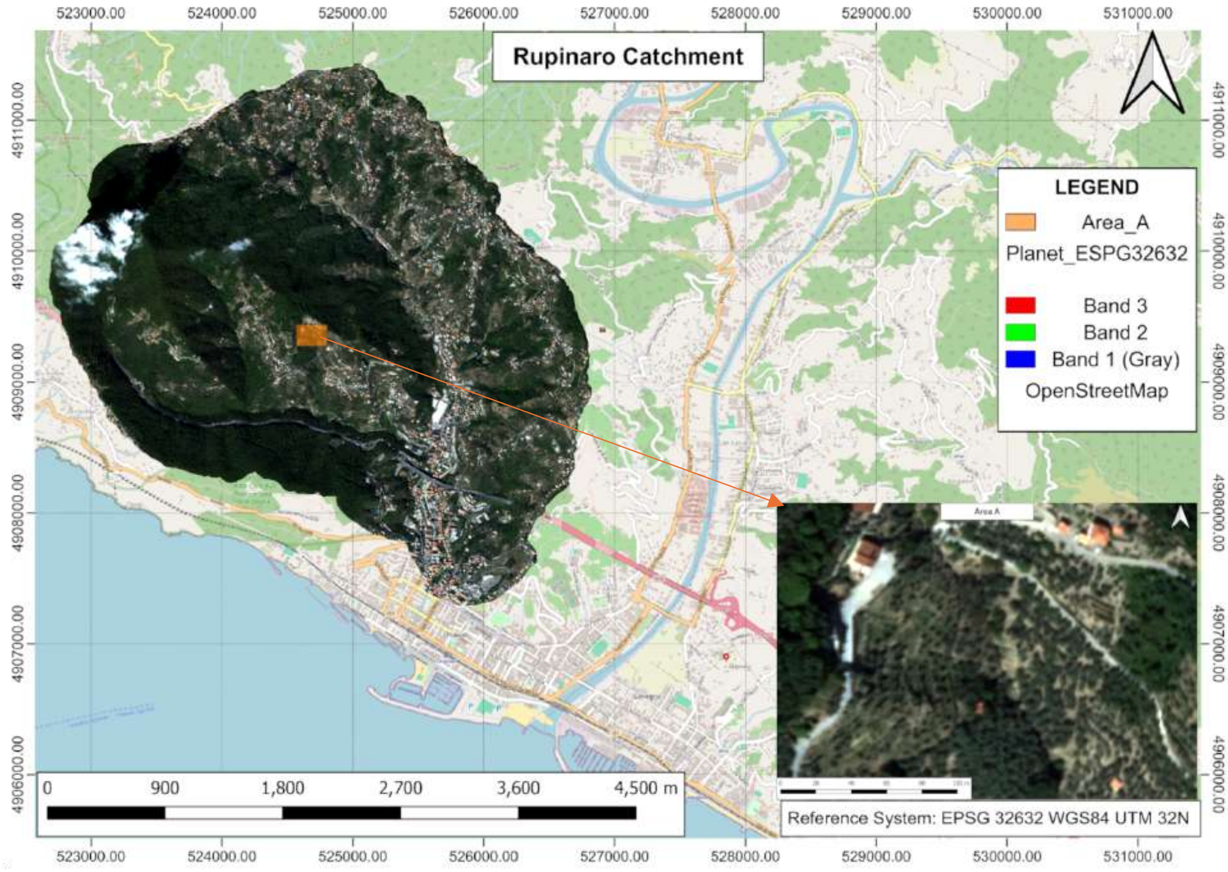

Fig.2: Study Areas in Rupinaro Italy

Area A was the primary test for the terrace smoothing task and after confirming the effects, the testing was conducted on the whole Rupinaro catchment that is seen in Fig.2

Methodology

Terrace smoothing was performed to generate an artificial DTM that accurately reflected the catchment morphology of the terrain before any human alterations. The challenge lay in creating a model with the same resolution as the terraced version while utilizing true elevation values extracted from the original DTM.

The workflow began with the original data of the Rupinaro catchment provided by CNR-IRPI dated back to 2014. It was then clipped to Area A to begin the testing. Fig.3 shows the proposed method that produces the desired smoothed DTM (without terraces) from the original DTM.

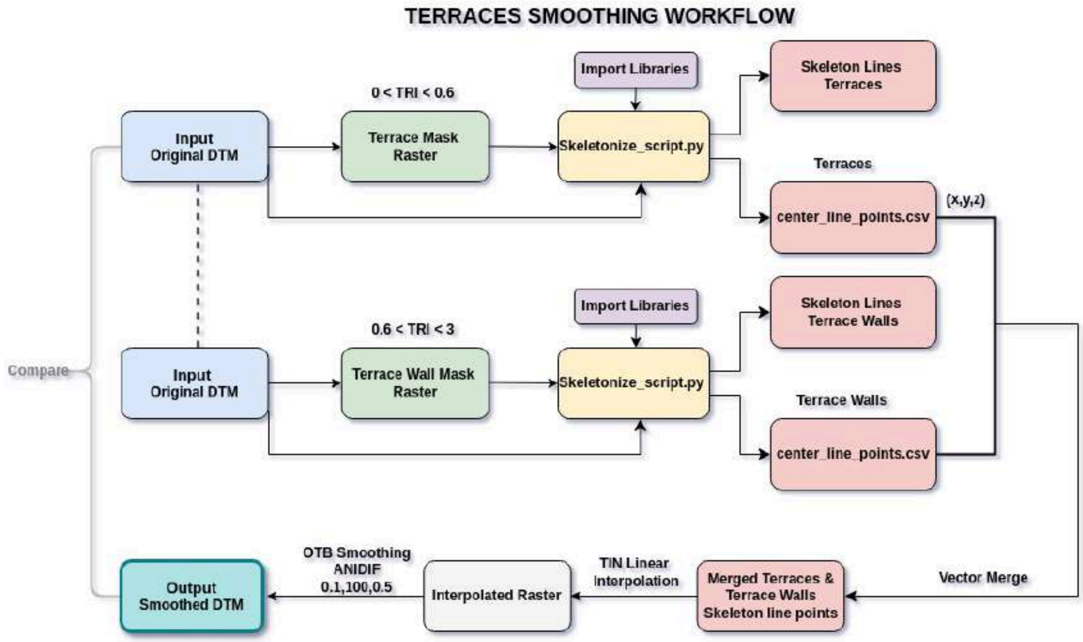

Fig.3: Terrace Smoothing Workflow

The first step was to enhance the contrast of the raster as a method to locate where the terraces were in the area. There were several methods to locate the terraces which included slope calculations, hillshade visualizations, and terrain ruggedness index. Based on several iterations of which tool worked best, the terrain ruggedness index was used to enhance the contrast of the terraces. The Terrain Ruggedness Index (TRI), as defined by Riley et al. (1999), is a geomorphometric parameter that quantifies surface roughness by considering the absolute elevations of neighboring cells in a Digital Elevation Model (DEM). It is calculated using the following equation:

$TRI = (\Sigma(zc-zi)^2)^2$:

- zc represents the elevation of the central cell.
- zi represents the elevation of one of the eight neighboring cells ($i = 1, 2, \ldots, 8$).

The TRI's sensitivity to local elevation differences makes it particularly useful in characterizing landslide terrains.

As seen in the Fig.4a, the terraces in Area A are clearly mapped out and visualized. However, it is important to note that this method also leads to the visualization of roads, and streets that could be mistaken for terraces. But the focus of this study is the mapping of terraces. With the TRI showing the location of potential terraces and terrace walls, the next step was to create a Binary mask showing the terraces and terrace walls separately. To do so, two separate masks should be created by taking advantage of the TRI radiometric variance. In particular, after several iterations, a specific threshold was found to separate terraces from terrace walls. The output of this process results in a binary raster (Fig. 4b and 4c) that classify the terraces and walls.

The following queries show the expressions used in raster calculator to create the terraces binary mask and the terrace walls binary mask respectively:

("TRI@1" >= 0) AND ("TRI@1" <= 0.6)

("TRI@1" >= 0.6) AND ("TRI@1" <= 3)

After creating both binary masks for the terraces and terrace walls, these products were now the input for a developed Python code. The entire concept of the terrace smoothing algorithm relies on the creation of skeleton lines.

Skeletonization is a digital image processing technique used to reduce the representation of a shape to a simplified structure. This skeleton reduces the shape into a simplified line whilst capturing the essential topology.

In other words, it resembles the "backbone" of a shape. According to Perumalla Srinivasa Rao and Kamatham Yedukondalu (2019), skeletonization algorithms are primarily utilized to extract feature parameters from an image. They are often a key component of thinning algorithms, which work by iteratively removing pixels from the boundary of an object while ensuring that the object's connectivity remains intact. This process gradually shrinks the object down to a thin representation that resembles a skeleton.

The developed Python code seeks to turn raster data into a .csv file that could be interpolated to become the final raster. Firstly, the libraries were imported which included rasterio , numpy, sk.image, and csv. The next process in the code was to create a skeleton mask for the terraces and the terrace walls. The skeleton mask is a type of binary raster which creates central lines in the active pixels of the previous binary raster. For the skeleton mask to be created, rasterio reads the binary mask to define the location of the central lines/skeleton lines. The skeleton lines were placed in the middle of the terraces or terrace walls depending on where the binary mask registered as a 1 value. After creating the skeleton raster, rasterio reads the DTM values so that the points could register the coordinates and elevation data on the location of the skeleton lines and convert them to points. Finally, the result is a .csv file that contains the coordinates and elevation data for the skeleton lines converted into points. This process was repeated twice, the first time was to create the .csv file for the terraces and the second time was to create the points for the terrace walls. Then, the .csv files were imported to QGIS with one being for terraces and the other being for terrace walls. As shown in the scheme, the points were merged just as shown in Fig.4d to create a dense number of points for the terraces and the terrace walls.

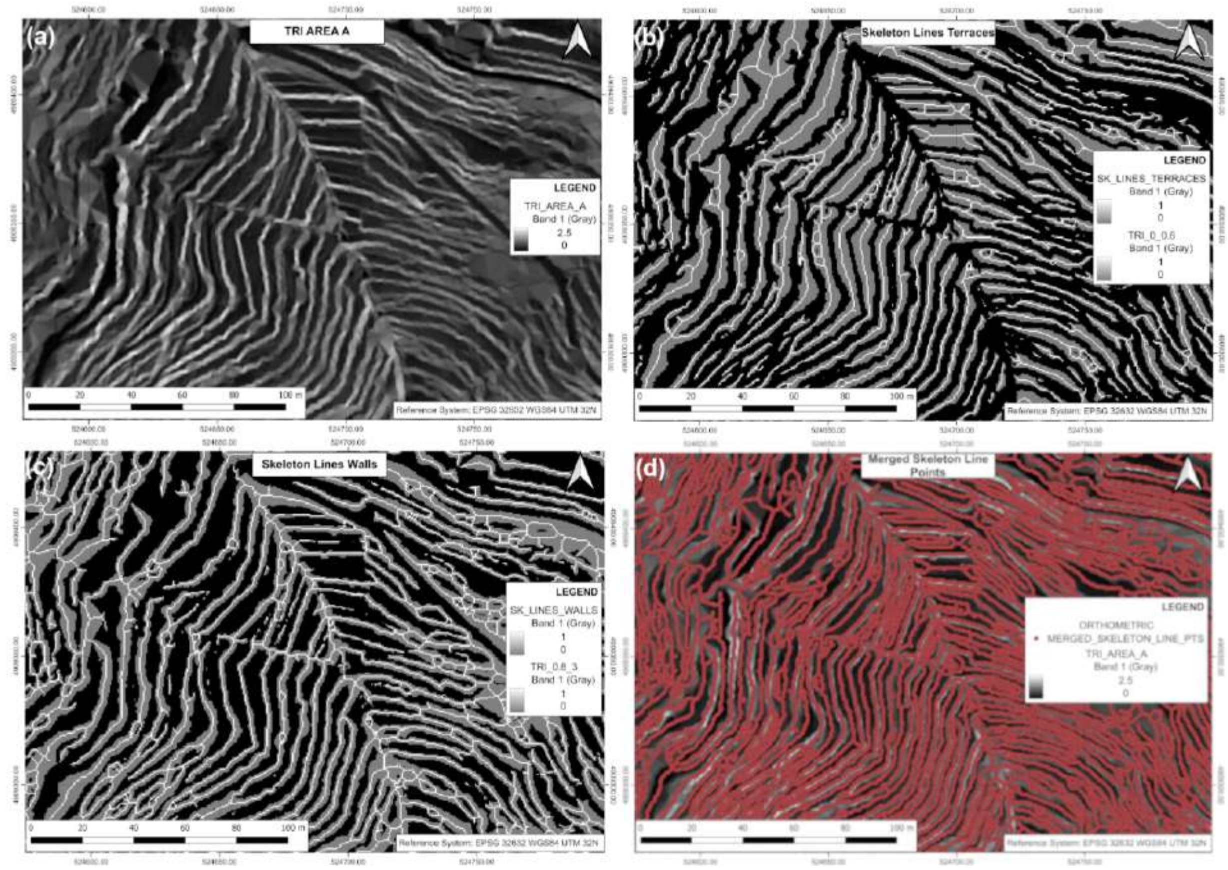

Fig.4: (a) TRI of Area A ; (b) Terraces with Skeleton Lines ; (c) Walls with Skeleton Lines ; (d) Merged Points

The merged points were used to create the interpolated DTM. Triangulated Irregular Network was used to create an artificial raster using the merged points from the terraces and terrace walls to recreate the original morphology.

After the interpolated DTM is produced, it was used as an input in the Orfeo ToolBox for smoothing to create the final DTM that recreates the morphology without the terraces.

According to Grizonnet et al. (2017) Orfeo ToolBox (OTB) is an open-source project designed for advanced remote sensing image processing. In its package is a wide suite of tools and algorithms accessible through various interfaces. In the case of this paper, OTB was installed in QGIS as a plugin.

Table.1: Parameters Used for Interpolation and Smoothing.

Parameters	
TIN Interpolation	
Method	Linear
Vector Layer	Merged points (as shown in Fig.4d)
Attribute	Elevation values
Resolution	0.5 m
OTB Smoothing	
Smoothing Type	Anisotropic Difference
Time Step	0.1
Number of Iterations	100
Conductance	0.5

The parameters used in the Orfeo ToolBox smoothing were an iterative step-based approach to achieve the best compromise between interpolation and smoothing.

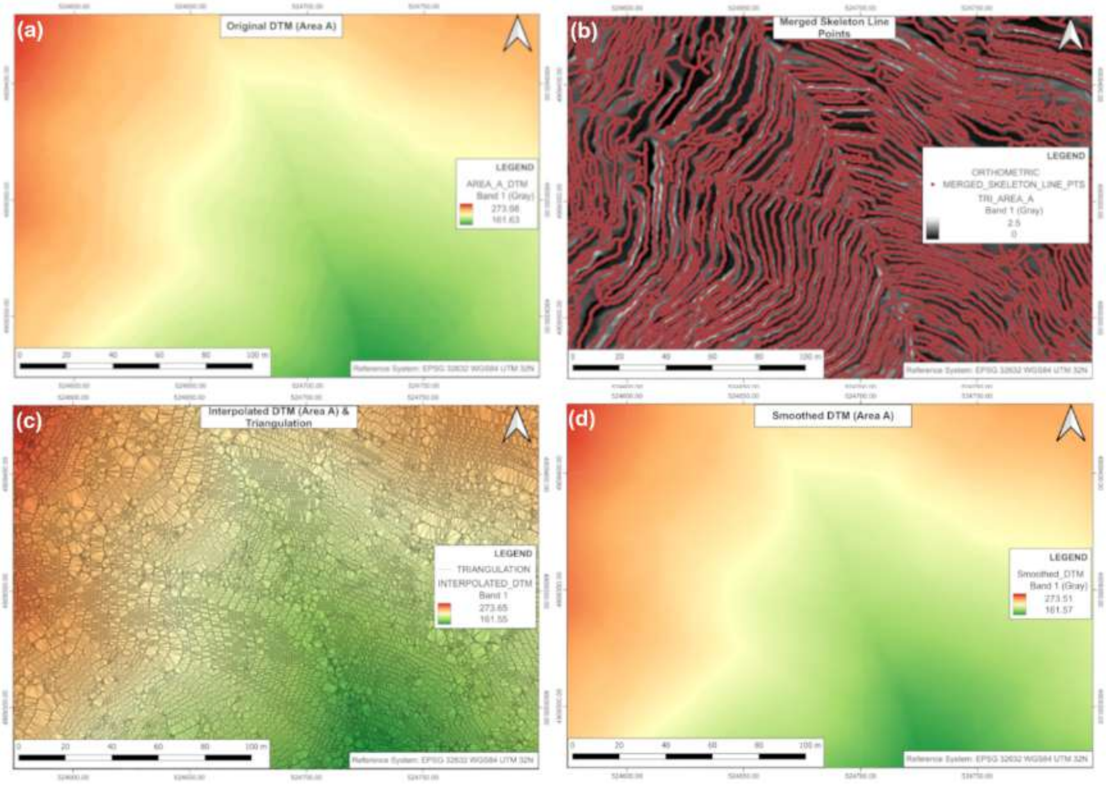

Fig.5: (a) Original DTM ; (b) Merged Points (same as Fig.4d) ; (c) Interpolated DTM ; (d) Smoothed DTM

After the creation of the smoothed DTM of Area A, the same procedure was repeated all over again for the Rupinaro catchment. Fig.6 shows the original and smoothed DTM of Rupinaro.

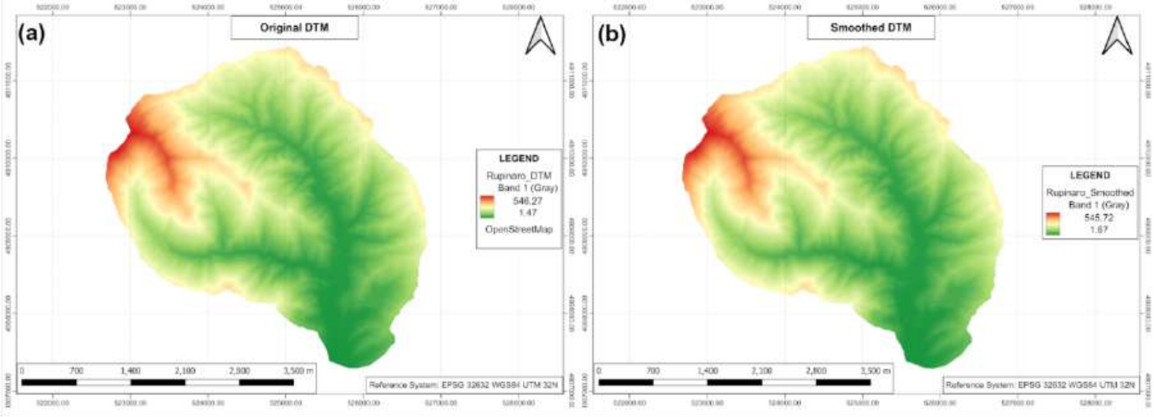

Fig.6: (a) Original DTM of the Rupinaro Catchment ; (b) Smoothed DTM of the Rupinaro Catchment

Results

To properly access the effectiveness of the smoothing algorithm, a comparison between it and the original data must be performed. The result that would have been expected is that the change would be evident on the terraces and the terrace walls while not affecting heavily the elevation values of the area. To view the differences between the smoothed DTM and the original DTM, a Difference of Digital Elevation (DoD) and Cloud to Cloud distance (C2C) comparison were used.

Fig.7 shows that the DoD on Area A yields values between 1.5 meters and - 2 meters and this falls in line with typical terrace heights. This was the result that was expected in the DoD. The differences are evident and highlighted in the figure below.

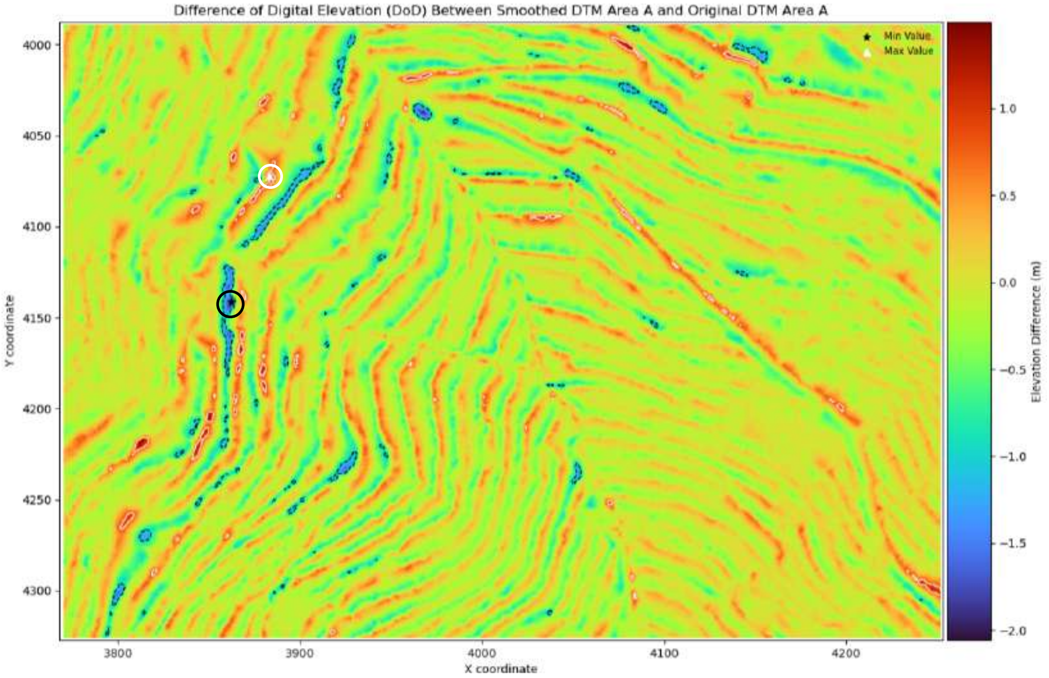

Fig.7: Difference of Digital Elevation of Area A

The calculation of the DoD was conducted on Python using numpy and rasterio as the main libraries for the calculations in the raster. Furthermore, the histogram alongside the different values and percentiles of the raster was produced.

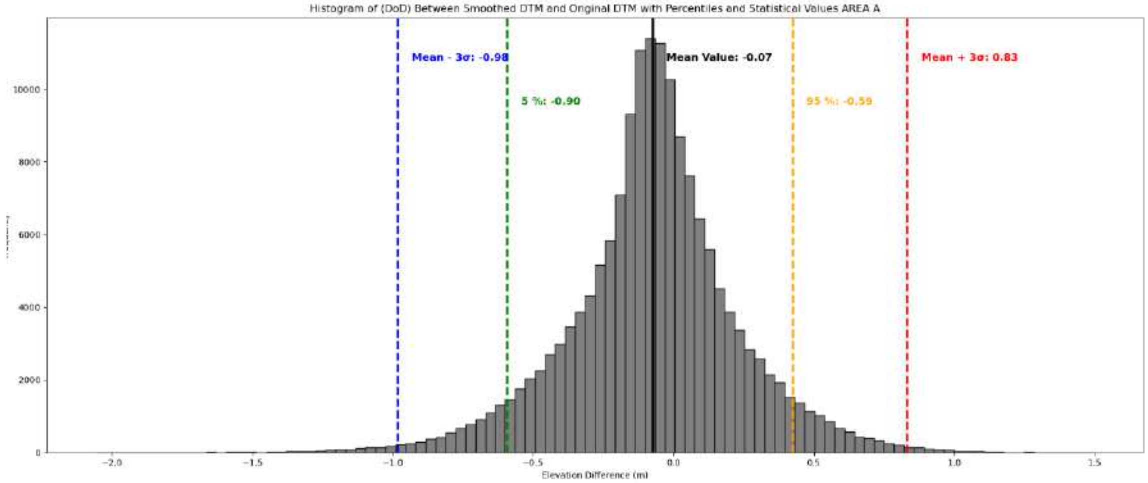

Fig.8: Histogram of values of Area A with Statistical Intervals

From Fig.8 it is evident that the histogram of values for the DoD between the smoothed raster and the terraced raster shows a gaussian distribution with the mean being - 0.07 m and standard deviation being 0.30 m. These values indicate that on average, taking into account the DoD between the two DTMs, the elevation values of the smoothed raster were conserved. The results of Fig.7 and Fig.8 are consistent with what was expected by conserving the overall elevation of the area while smoothing out the terraces.

After the conduction of the DoD between the two rasters on Area A, these rasters were imported to CloudCompare so that the cloud to cloud distance between them can be calculated. The compared raster was the smoothed raster and the reference was the original terraced raster. As clearly indicated by Fig.9a the green color signifies changes between 0.5 and 1.25 m regarding the two datasets. These values point to the differences due to the smoothing effect and removal of terraces.

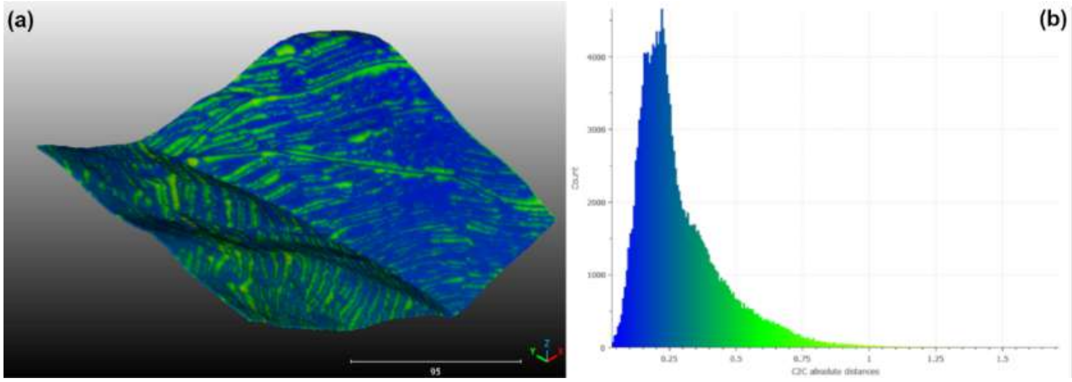

Fig.9: (a) C2C distance of Area A ; (b) Histogram of C2C distance

After the comparison between both datasets was conducted on Area A, the same procedure was applied on the Rupinaro catchment as a whole.

The first analysis to be performed was the DoD. Fig.10 shows the location of the different changes of elevation between the smoothed Rupinaro DTM and the original terraced DTM.

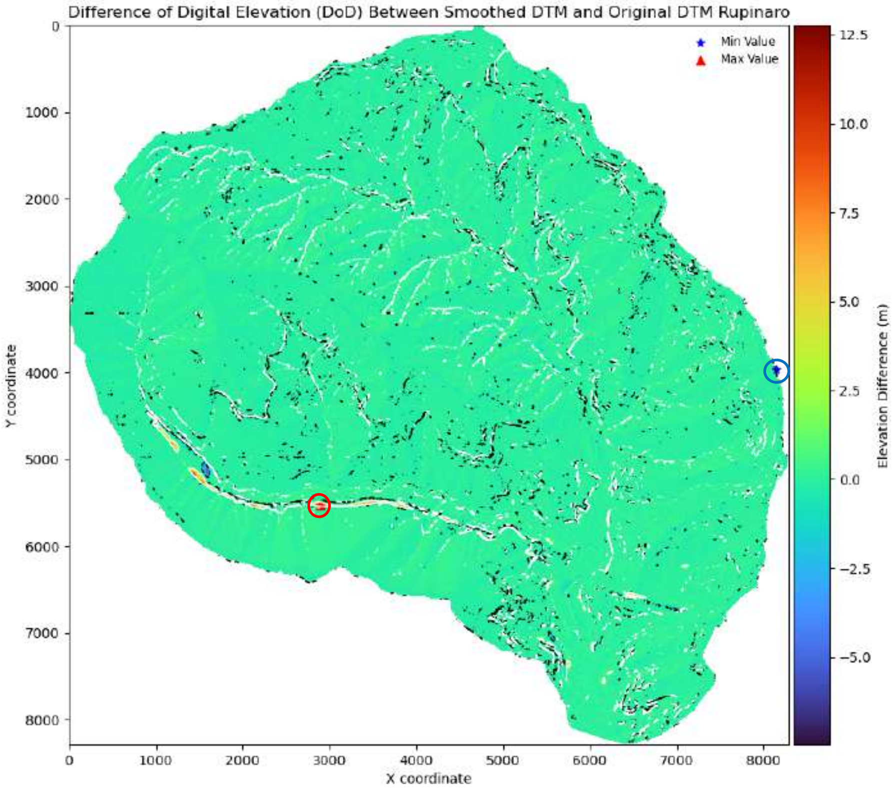

Fig.10: Difference of Digital Elevation of the Rupinaro Catchment

Fig.10 shows changes ranging from -7 m to 12.5 m for the entire catchment. The main change occurred in the location of a river current (positive change) and on the edge of the catchment (negative change) in elevation. With regards, to both extreme values, they might be due to the terrace smoothing algorithm mistaking roads, rivers and other flat or inclined areas as terraces or terrace walls. The river could have easily been mistaken as a terrace during the procedure. Exploring the histogram of values for the Rupinaro catchment difference of digital elevation, it shows a very similar behavior as the histogram for Area A which points to the terrace smoothing properly doing its job. Based on the mean value of - 0.01 m and the standard deviation of 0.45 m, it was evident that the results were in line with what observed previously in Area A. These values indicated a change in morphology without causing significant changes in the elevation values of the area. Furthermore, the cloud to cloud distance between the smoothed raster of the Rupinaro catchment and the terraced raster reiterated the findings observed in the difference of digital elevation comparisons.

Table.2: DoD Statistics For Area A and Rupinaro Catchment

DIFFERENCE OF DIGITAL ELEVATION (m)											
Data	**μ**	**σ**	**Min**	**Max**	**μ – 3σ**	**5th %**	**25th %**	**50th %**	**75th %**	**95th %**	**μ + 3σ**
A	-0.07	0.30	-2.05	1.49	-0.98	-0.59	-0.23	-0.07	0.09	0.42	0.83
RUPI	-0.01	0.45	-7.45	12.76	-1.37	-0.60	-0.23	-0.03	0.17	0.60	1.34

Table.3: C2C Distance Statistics For Area A and Rupinaro Catchment

C2C Distance (m)										
Data	**μ**	**σ**	**Min**	**Max**	**5th %**	**25th %**	**50th %**	**75th %**	**95th %**	**%<1m**
A	0.87	0.48	0.03	1.71	0.12	0.45	0.87	1.29	1.62	57.81
RUPI	5.87	3.26	0.25	11.49	0.81	3.06	5.87	8.68	10.92	7.03

Discussion

This research presented terrace smoothing as a new method for DTM manipulation. Regarding the methodology, the terrace smoothing workflow presented was based on an iterative approach. The task of terrace smoothing was aimed at recreating the geomorphology of the area prior to its anthropogenic modification of terracing. Without having original ground control points and historical data about the area prior to terracing, it would be very difficult to determine how close the procedure conducted was to the original state of the area. There were many limitations with regard to the procedure itself since the terrace identification was based on an observatory iterative approach in deciding what terrain roughness index was capable of showing the terraces and walls properly. With this manual procedure, the wrong characterization of rivers, roads and none terraced wall inclines that were mistaken for either terraces or terrace walls occurred. This proposed method also had limitations based on the resolution of the DTM. The resolution, which was 50 cm, was sufficient to show properly the location of the terraces and terrace walls, but a lower resolution DTM might not show the terraces clear enough to identify them using the method that was proposed during the research.

Furthermore, the interpolation procedure for the points produced during the skeleton line conversion is a computationally heavy process and in particular for an area that is a catchment. Thus, this manual method has to be limited by area because of how computationally demanding it was. It would be beneficial to experiment with other methods for the interpolation of the merged points. Moreover, it could also be beneficial to develop an automatic classification of terraces instead of an iterative manual one.

With regard to the results, the results are on par with what was expected towards the terrace smoothing workflow. The overall elevation of the DTM did not change drastically as indicated by the mean of values and standard deviation presented in the results. This meant that the DTM changed in its morphology by turning what was terraced into unterraced without changing the elevation data of the area. Future optimization of the identification of terraces could yield better results by not smoothing the mistaken roads, rivers and other anthropogenic features. For our objective, the smoothed DTMs produced in this research are meant to be used in evaluating the connectivity index. These DTMs will be input in SedInConnect to evaluate the effects of anthropogenic modifications such as terraces on landslides and hazards based on their sediment connectivity values. This proposed terrace smoothing method helps in further clarifying the relationship between terraces and the stability of the landscape.

Conclusion

In conclusion, the presented terrace smoothing workflow is a manual and simple approach to recreate the original morphology of an area without impacting the elevation values that it has. It is a method, that has its own advantages and disadvantages. The advantage of using such a method is the ability to recreate the DTM from existing data while the disadvantage is that it is bound by the resolution and computational power of the machine as a result of an area increase. The next step would be to compare the connectivity index of each DTM and see what the difference terrace smoothing causes. The final comparison would be to compare the interpolated DTM with the smoothed DTM when it comes to the connectivity index. If the difference between the anisotropic smoothed DTM and the interpolated one is negligible, then perhaps the last step of smoothing could be omitted. This is because the interpolated DTM already has the terraces removed from them because of interpolation of points. Finally, it could be interesting to develop an automatic terrace removal algorithm based on the findings of this research by combining the skeletonization code with an automatic terrace detection algorithm to produce an interpolated DTM based on these variables without removing other anthropogenic features that were previously mistaken in the terrace identification.

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