Photogrammetry and GIS to investigate modern landscape change in an early Roman colonial territory in Molise (Italy)

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ABSTRACT
Legacy data in the form of historical aerial imagery can be used to investigate geomorphological change over time. This data can be used to improve research about the preservation and visibility of the archaeological record, and it can also aid heritage management. This paper presents a composite Image-Based Modelling workflow to generate 3D models, historical orthophotos, and historical digital elevation models from images from the 1970s. This was done to improve the interpretation of survey data from the early Roman colony of Aesernia. The main challenge was the lack of high-resolution recent digital elevation models and ground control points, and a general lack of metadata. Therefore, spatial data from various sources had to be combined. To assess the accuracy of the final 3D model, the Root Mean Square Error (RMSE) was calculated. While the workflow appears effective, the low accuracy of the initial data limits the usefulness of the model for the study of geomorphological change. However, it can be implemented to aid sample area selection when preparing archaeological fieldwork. Additionally, when working with existing survey datasets, areas with a high bias risk resulting from post-depositional processes can be indicated.

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1. INTRODUCTION

Pedestrian field survey currently faces paradoxical developments. In the rapidly deteriorating archaeological landscapes of the Mediterranean as well as elsewhere, archaeologists are becoming ever more reliant on field survey data, especially those collected in earlier times with relatively good quality surface finds (so-called legacy datasets). At the same time, over the past decades there has been increasing attention for the various biases that may occur when sampling the archaeological record by pedestrian survey. Initially, much research has targeted methodological biases, amongst others to correct for the varying visibility of archaeological surface material during the surveys. This has led to a well-developed rigour in field survey practices documenting the present field conditions as systematic and well as possible [1]-[12]. The research presented in this paper focuses on one particular factor: the geomorphological change over time. Erosion and depositional

processes, as well as incisive anthropic actions such as mining, all influence the location and preservation of the archaeological record. Understanding geomorphological change can help to better assess the value of surface distributions of archaeological finds retrieved during field work, and at least in theory also to assess the reliability of legacy survey datasets.

Historical aerial images have since long been used to aid in the identification of archaeological features that in the meantime have been obscured or obliterated by more recent anthropic manipulations and/or natural events. More specifically, historical aerial photographs now also allow us to generate historical digital elevation models (hDEMs), historical orthophotos and 3D models of areas that have often been subjected to significant landscape change over the years. This can be done by using Image-Based Modelling (IBM) techniques such as photogrammetry, often using the principle of Structure from Motion (SfM).

When a recent digital elevation model (DEM) is subtracted from an earlier one, a map of the occurred geomorphological

change can be extracted, thereby generating useful new data. The generation of hDEMs from historical aerial images is not always straightforward. Common problems with the generation of hDEMs consist of poor or lacking metadata, low image resolutions, and the absence of contemporary GPS ground control points (GCPs). These factors can complicate generating new data from historical photographs. Additionally, the comparison of data with different coverages, resolutions, and levels of precision can cause problems, which makes estimating the difference between two DEMs to investigate geomorphological change challenging.

Issues concerning hDEM generation are often resolved by using GPS GCPs on locations that are visible in both historical and recent remote sensing data, or by creating new GCPs from accurate (and often more recent) maps in a Geographic Information System (GIS) and using those in the IBM software. An alternative is to co-register the created DEMs to ones that are currently available, as demonstrated by Sevara et al. [13]. Common workflows use ground control points that were recorded in the field with a GPS, therefore establishing deviations of less than 10 cm [14]-[18] or use highly accurate recent DEMs for co-registration [19]-[22]. These resources were not available in the region under investigation, therefore the objective of this study was to assess the feasibility of a composite workflow using legacy data that was lacking any physical GCPs. One potential source of error is the manual placement of the control points, in both GIS and IBM software, since this mostly relies on the resolution of the images and the competency of the user. Furthermore, the quality of the final result largely depends on the quality of the initial data. As previously mentioned, in the case of this research no GCPs or high-resolution DEM were available, which significantly complicated the IBM procedure. Therefore, the usefulness of this procedure for further research and analysis was investigated by assessing its accuracy after several improvements.

The landscape of Italy has changed significantly over the past century [23], which has a big impact on the archaeological remains. This makes it a good location to investigate the various factors influencing the surface data obtained through pedestrian surveys. The Landscapes of Early Roman Colonization (LERC) project operates in this changing landscape. The research presented in this paper was carried out using data provided by the Aesernia Colonial Landscape Project, which was started in 2011 by Dr. T. D. Stek as an EU Marie Curie Fellowship at Glasgow University, and subsequently, in 2013, continued in the larger framework of the LERC project, a collaboration between Leiden University and the Royal Netherlands Institute in Rome (KNIR), funded by the Netherlands Organisation for Scientific Research (NWO) [24]. The LERC project investigates the early Roman colonisation process in Italy, mainly by pedestrian surveys and remote sensing [24]. This paper focuses on the landscape surrounding the Latin colony of Aesernia (263 BCE), around the modern town of Isernia, situated in the Molise region in south-central Italy (Figure 1).

In section 2 the study area and the various data sources utilised in this research will be discussed, and some of the issues mentioned. The next two sections describe the methods and the results, followed by a discussion highlighting some issues and limitations. Finally, in the concluding section the main applications and limitations are stated.

2. STUDY AREA AND DATA

The colony of Aesernia was established in 263 BCE, and the territory was previously known as a relatively undocumented area within the Molise, except for the landscape research carried out in the 1980s [25]. In the past decade, extensive research has been done in this area by means of field survey, various types of aerial photography and remote sensing, and geophysics.

Significant issues in the region include the modern urbanisation and changes in land use, which are happening at a fast pace around the town of Isernia. Therefore, the initial stages of the LERC project focused on the area around the town. Although the current trend in Mediterranean pedestrian survey focuses on the collection of off-site data in a smaller sample area, where fields are selected for their good visibility, the LERC project covered the majority of fields, including those with low visibility [26]. This variation in visibility can be attributed to factors such as differences in land use (e.g. freshly ploughed vs. overgrown) and geomorphological change. Both are thought to have impacts on the collection and interpretation of pedestrian survey data, which is why they have been subject to further investigation.
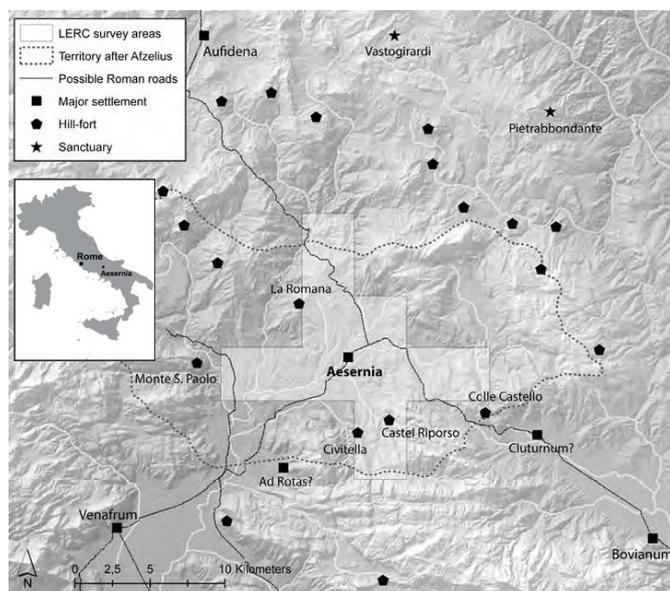

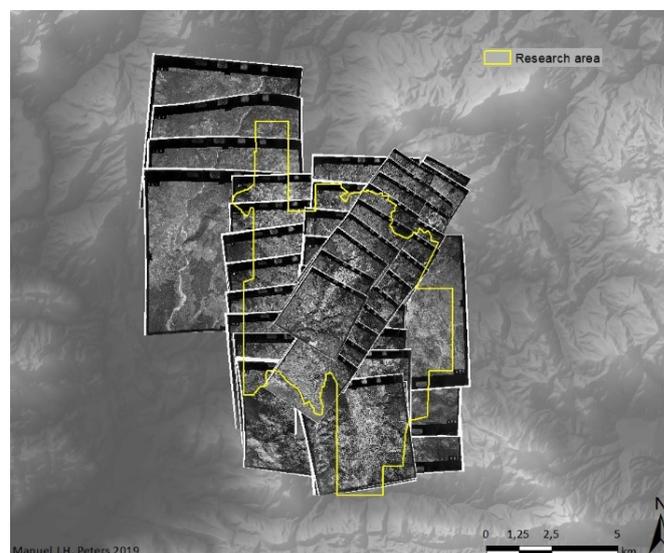Figure 1. LERC research area around Aesernia [3], [26].

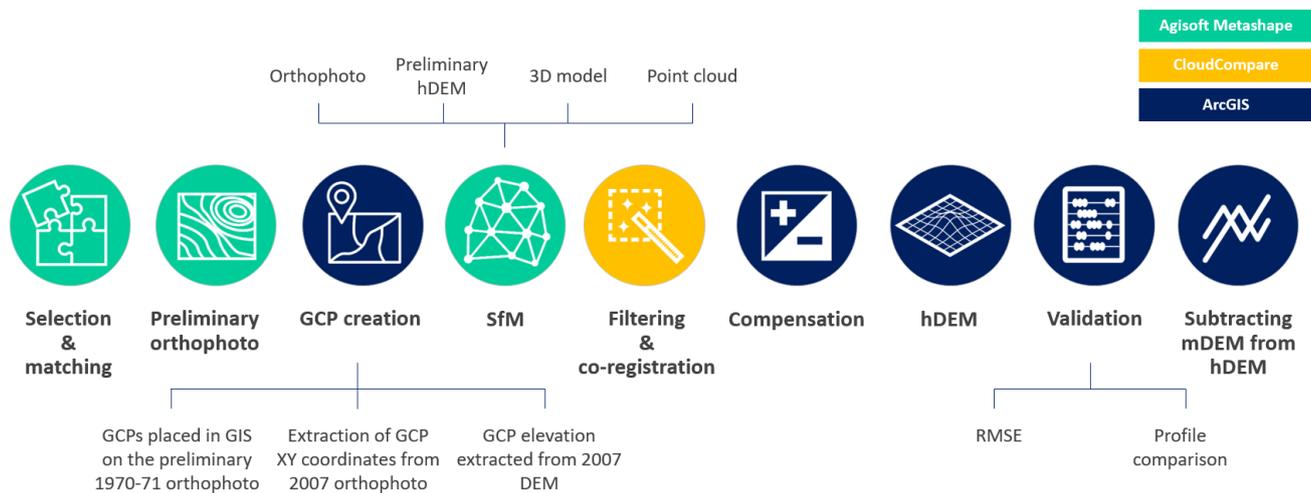Figure 2. Aerial image coverage for 1970-71 around Isernia.

Figure 3. Composite IBM workflow.

For the present analysis, several data sources were used, including legacy data consisting of 53 aerial photographs from the Isernia area (Figure 2). These were produced in 1970-71 for cartographic purposes by the Società per Azioni Rilevamenti Aerofotogrammetrici (SARA) [27]. The images had been digitised with a resolution of 300 dpi (1970 set) and 600 dpi (1971 set). The type of scanner and its parameters were unknown at the time of writing, therefore possible errors related to factors such as resolution, distortion, and glare were unknown. The average flight height was not exactly known either, and neither were yaw, pitch, and roll, which meant that camera properties, including focal length, could not be used. These are typical issues related to the use of legacy data, since this data is usually not created for modern research purposes.

Additionally, a regional orthophoto of the Isernia area from 2007 was provided by the geoportal of the regione Molise (using the AutoGR tool developed by Dr. Gianluca Cantoro). The TINITALY/01 DEM released by the Istituto Nazionale di Geofisica e Vulcanologia (INGV) in 2007 was used as control DEM. This is a composite DEM that is commonly used in recent archaeological research [28]. In Molise, the root mean square error (RMSE) of the TINITALY DEM (modern DEM or mDEM) is 3.76 m in the non-urban areas, and 4.51 m in the urban areas [29], [30]. A hillshade visualisation of this DEM was used as base map for several figures (1, 2, 6, 9, 10) in this paper.

Agisoft Metashape Professional 1.5.2 build 7838 was used to create the various models using SfM, CloudCompare 2.10.2 was used for modifying and co-registering the point clouds. ArcMap 10.4.0.5524 was used to run the GIS procedure, and ArcScene 10.4.0.5524 to visualise the data in 3D. All data was processed in the EPSG:32633, WGS84 / UTM 33N coordinate system.

3. METHODS

To accommodate the limitations of the original data, a composite workflow involving SfM, point cloud processing software, and GIS was designed (Figure 3). First, a preliminary model using 53 images from 1970-71 was built using SfM. Although all images were of sufficient quality, they had borders that could leave traces during the creation of the 3D model and the DEM, and therefore needed to be removed. This was done by manually going over every picture and creating a mask by selecting the area that had to be removed. Areas that were of low quality because of glare were also removed in this way.

Once the preliminary model was created, GCPs were placed in a GIS environment on the resulting orthophoto. This was done by using features that appeared unchanged and were easily recognisable on the 1970-71 and 2007 orthophotos, such as corners of buildings and intersections of roads. The XY coordinates were obtained based on the 2007 orthophoto, and the elevation values were extracted from the mDEM. This data was then imported into the SfM software, where the GCP locations had to be modified manually by keeping the SfM and GIS software side by side (Figure 4). The coordinates were given for each GCP in Easting (m), Northing (m), Altitude (m). An accuracy of 3 meters was set, considering the resolution of the images when visually placing the markers in horizontal space for the XY coordinates, and the vertical accuracy of the DEM07, which generated the elevation value.

When all GCPs and their coordinates were added, the process to generate the model was initiated again, starting with the alignment of the photos, this time using high accuracy, with a key point limit of 120000, and no tie point limit. This resulted in a sparse point cloud consisting of 387692 points. Then, the camera alignment was optimised, in order to achieve a higher accuracy and to correct for possible distortions, using the focal length radial distortion coefficients k1, k2, k3, and k4; tangential distortion coefficients p1, p2, p3, and p4; and affinity and skew (non-orthogonality) transformation coefficients b1 and b2 [20]. Additionally, the point cloud variance was calculated. Then, by using gradual selection, points with high reprojection error (above 0.25 m) were removed, as well as points with a reconstruction uncertainty above 10 m and with a projection accuracy below 2.5 m. The filtering steps resulted in a removal of
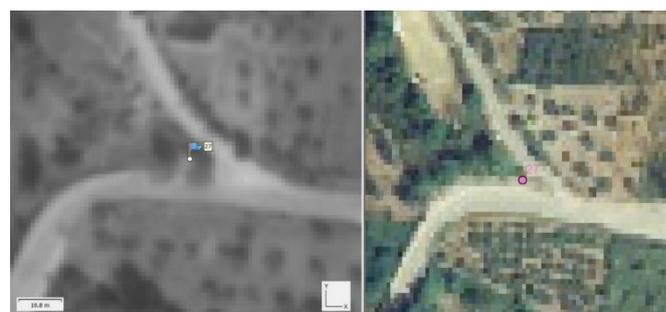

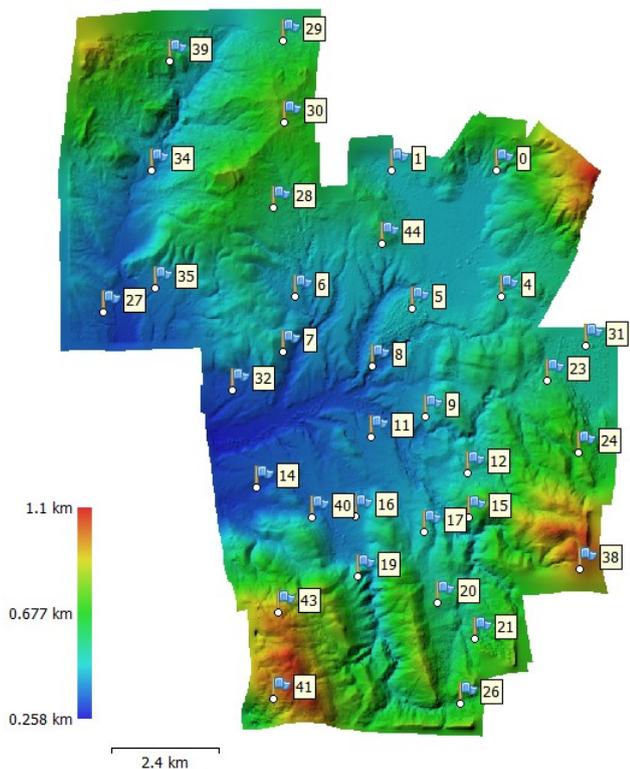Figure 4. Placing GCPs in Metashape (left) by comparing them to the image in ArcMap (right).

Figure 5. hDEM after cleaning, including GCP locations.

Figure 6. Geomorphological change (erosion and sedimentation).

195061 points from the point cloud, with a final number of 192631 tie points. This filtering removed points that could result in later outliers in the DEM. Next, the bounding box was set to select the area that would be used in further processing. No clipping of the area was done at this stage however, since the hDEM would later be clipped by the research area in ArcMap.

After this, the dense cloud was built, using high quality and moderate depth filtering, to avoid removing more complex landscape features, and pixel colour was calculated. The mesh was built using the height field surface type, and the dense cloud as source data. The polygon count was set to high, in order not to lose any detail. Interpolation was enabled, so that holes generated in the previous filtering steps could be filled.

The next step was to build the texture. While this is not necessary to create an orthophoto or DEM, it does provide a better 3D visualisation of the area. The mapping mode was orthophoto, blending mode mosaic. In workflows containing black and white images, colour correction is often disabled, since this is generally only useful for data sets with extreme brightness variation. In this case however, the orthophoto would be used for the classification of the forested areas. This was primarily done based on pixel colour, which therefore had to be as accurate as possible.

The hDEM (Figure 5) was built using the dense cloud, since this generally produces more accurate results, and has a shorter processing time. Although the DEM that was obtained had a resolution of 2 m, it was decided to export it at a 10 m resolution, in order to be comparable with the mDEM. The orthomosaic was generated in the same reference system, using the Mosaic blending mode, colour correction was not used. The orthophoto and hDEM could then be exported as geotiff files. The no-data value was set at 255.

Ground points were classified using a 15 degrees maximum angle, 2 m maximum distance, and 25 m cell size. The ground point clou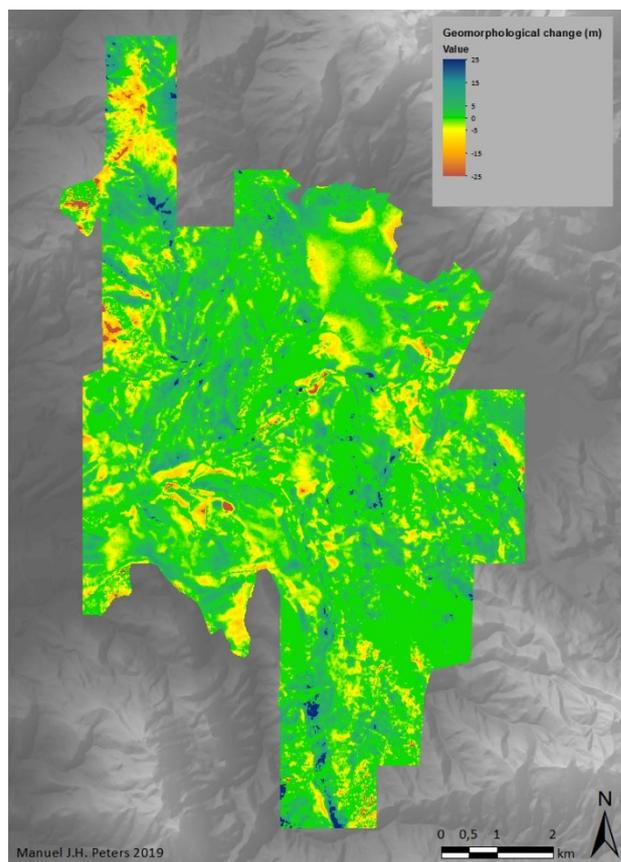d (hDEM) was then further modified in CloudCompare. An additional filtering step was carried out using Statistical Outlier Removal, using 10 points for the mean distance estimation and 1.00 as the standard deviation multiplier threshold. Duplicate points were removed as well, and the point cloud was downsampled to a 2.5 m resolution to speed up processing. Then, the hDEM was co-registered to the mDEM using an iterative closest point (ICP) algorithm. This co-registration procedure corrected the hDEM, decreasing the tilt and modifying the scale to better fit the mDEM. This resulted in a decrease in RMSE on the whole hDEM area from 13.95 m to 7.49 m.

The hDEM was then rasterised to a grid size of 10 metres to be comparable with the mDEM. An additional compensation was carried out by measuring the deviation of the hDEM in 101 new GCPs in supposedly stable areas, interpolating these values with the application of Kriging. In this case, ordinary Kriging was used with a linear semivariogram, since this model fitted the GCPs best. The Kriging window was set at 12 points, with a maximum distance of 7000 m. The resulting raster showed the deviation of the hDEM across the research area, which was most significant near the edges of the model (as can be expected with this type of model), especially on the north and south sides. The deviation map was then subtracted from the hDEM, and the mDEM was subtracted from the compensated hDEM, showing the geomorphological change in the area. In order to exclude areas with vegetation or buildings from the geomorphological change model, these were masked by a combination of automated classification based on the grey values of the historical orthophoto and manual adjustments of the mask. The resulting model shows both the positive (presumably sedimentation) and negative (presumably erosion) change in the landscape (Figure 6).

Figure 7. Detail of 1970-71 3D model. Orange line representing 5 km.

4. RESULTS

The 3D model generated by the SfM procedure was sufficient for a visual study of the landscape surrounding Isernia (Figure 7). In order to determine its suitability for the determination of geomorphological change, an accuracy assessment was carried out. The north-south and east-west profiles of the various DEMs were compared (Figure 8), showing that the co-registration resolved a significant amount of tilt both in the north-south and east-west planes (DEM70-71_coreg). The additional compensation using the deviation surface obtained with Kriging resulted in another improvement (DEM70-71_final).

The RMSE of the hDEM relative to the mDEM was calculated, and the total RMSE was calculated using the relative and the mDEM RMSE (Formulas (1), (2); Table 1). The final hDEM had an RMSE of 5.87 m. Although this is a significant possible error when dealing with landscape change, this is mostly
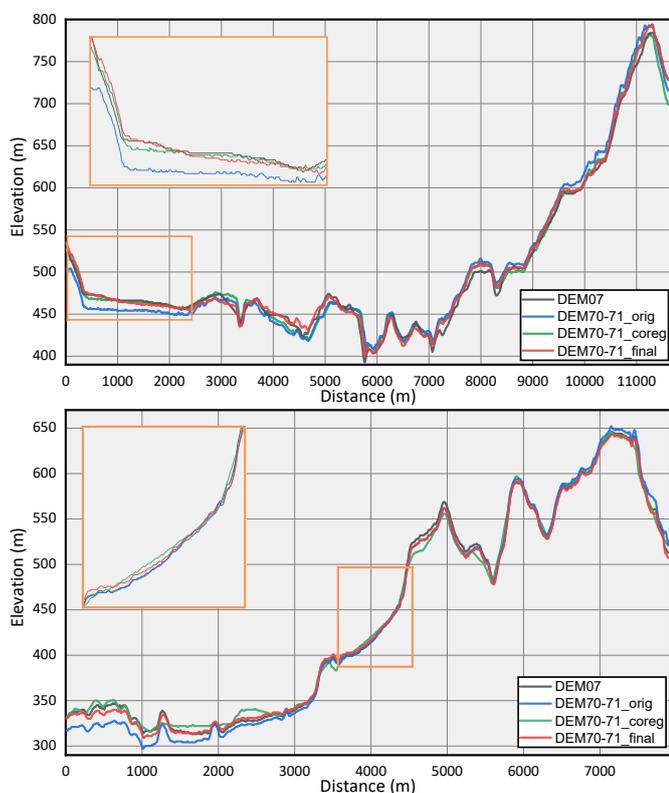

Figure 8. Profile comparison between elevation models in north-south (top) and east-west (bottom) direction.

Table 1. RMSE values.

	Relative RMSE	Total RMSE
Before compensation	6.48 m	7.49 m
After compensation	4.51 m	5.78 m

due to the original data quality. Considering the fact that the original 2007 DEM has an RMSE between 3.76 m and 4.51 m in the Molise region, and a resolution of 10 m, the 5.87 m RMSE of the final hDEM was deemed an acceptable result

$$RMSE_{\mathrm{rel}} = \sqrt{\frac{\sum_{i=1}^{n}(hDEM - mDEM)^2}{n}} \qquad (1)$$

$$RMSE_{\mathrm{tot}} = \sqrt{RMSE_{\mathrm{rel}}^2 + RMSE_{\mathrm{mDEM}}^2} \, . \qquad (2)$$

Even though there are limits due to the RMSE of the final hDEM, the resulting geomorphological change map obtained by subtracting the mDEM from the hDEM serves as a useful indication of the changes around Isernia. The resolution is not high enough to allow detection of more subtle changes; however, especially since in this procedure no physical GCPs are necessary, it may be used to better select the sample areas during the planning of archaeological fieldwork. Additionally, its results can assist the interpretation of the data collected by the pedestrian surveys. As such, it can help improve existing archaeological models, for example about site distribution, in a way not dissimilar to the soil map analysis by Casarotto et al. [31]. A good example of the changing landscape in the area can be found south of the town of Isernia, where a quarry has expanded dramatically in a few decades, leaving a lasting effect on the landscape (Figure 9).

The mask that was created to exclude forested areas from the geomorphological change map, can also provide a visual indication of the rapidly changing land use in the area. Plots of land are no longer being used for agriculture and have been abandoned and subsequently reforested, which can clearly be seen when comparing the situation in 1970-71 with the situation in 2007 (Figure 10).

5. DISCUSSION

An important challenge with the presented research was the need to use input from different sources to create the hDEM, and the deviations related to this approach. In order to create a georeferenced model, GCPs with X, Y, and Z values are required. The historical aerial photos were not georeferenced, which is normally solved by using either GPS GCPs with XYZ values and error below 10,0 cm, or by utilising LiDAR data to co-register the hDEM. This kind of data was not available for the current research, which heavily influenced the IBM workflow.

Due to data limitations, there are possible errors originating from the use of the 2007 orthophoto to extract XY values and the 2007 DEM to extract z values, and combining these into GCPs, rather than collecting GPS coordinates in the field and importing these as markers. Creating and placing GCPs manually like this increases the chance of user error. Since the procedure is based on a visual comparison of the recent and historical images with varying resolutions, it is possible to have an error of several metres in XY value. The current research focuses mostly on changes in Z value, but the aforementioned bias should not
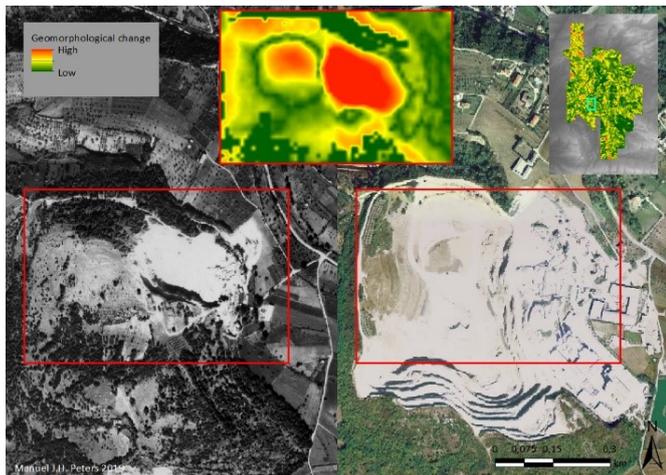
Figure 9. Geomorphological change due to mining activities.

Figure 10. Masked forest (right), reforestation since 1970-71 (left).

be neglected, since a change in the horizontal plane can result in significant changes in elevation, especially in irregular terrain.

The accuracy of the final model depended on the resolution and accuracy of the 2007 orthophoto, the 2007 TINITALY DEM, the 1970-71 historical aerial photographs, and the user error when placing the various GCPs. While the resolution and accuracy of the 2007 DEM was known, this was not the case for the 2007 orthophoto and the 1970-71 aerial images. Further limitations were imposed because the properties of the scanner used to digitise the original images were unknown. Therefore, scanner deformities may have been introduced, contributing to possible errors in the final model. This research made an attempt at correcting some of these errors by applying filtering, co-registration, and compensation, leading to significant improvements.

6. CONCLUSIONS

The main goal of this research was the creation of a composite IBM workflow to build historical landscape models from historical aerial photographs using SfM, and extracting information about geomorphological change. By applying data from other sources such as a more recent orthophoto and DEM to obtain ground control points in GIS that could then be entered in the SfM software, it was possible to create historical orthophotos and hDEMs. The hDEM for 1970-71 was further filtered and co-registered to the mDEM from 2007. Subsequently, it was corrected by applying interpolation to create a vertical deviation surface from other GCPs. This resulted in a compensated hDEM that was then subtracted from a modern DEM in order to observe geomorphological change, while areas with buildings or vegetation were masked.

Although there are severe limitations resulting from the quality of the initial data in this case study, the proposed composite workflow appears effective for the creation of more accurate historical 3D models and geomorphological change maps of rapidly evolving landscapes. Geomorphological change has an inherent duality, both positively (uncovering) and negatively (displacing/covering/destroying) influencing the visibility of the archaeological record. Despite this, geomorphological change maps can be used to provide feedback for planning pedestrian surveys and to interpret their data critically, possibly assisting in the assessment of its accuracy and the improvement of archaeological models.
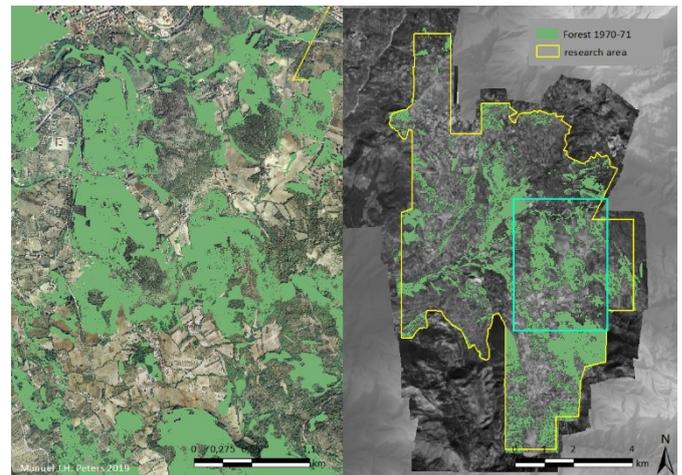
REFERENCES

[1] P. Attema, Two Challenges for Landscape Archaeology, in P. Attema, G. J. Burgers, E. van Joolen, M. van Leusen and B. Mater (eds), New Developments in Italian Landscape Archaeology. Theory and methodology of field survey. Land evaluation and landscape perception. Pottery production and distribution, University of Groningen, 13-15 April 2000, BAR International Series, vol. 1091, 2002, pp. 18-27.
DOI: 10.30861/9781841714691

[2] J. Bintliff, P. Howard, A. Snodgrass, The Hidden Landscape of Prehistoric Greece, Journal of Mediterranean Archaeology, vol.12, No. 2, 1999, pp. 139-168.
DOI: 10.1558/jmea.v12i2.139

[3] A. Casarotto, Spatial patterns in landscape archaeology. A GIS procedure to study settlement organization in early Roman colonial territories, PhD thesis, Leiden: Leiden University Press, 2018. ISBN: 9789087283117.

[4] R. C. Dunnell, The Notion Site, in J. Rossignol and L. Wandsnider (eds), Space, Time, and Archaeological Landscapes, New York: Plenum Press, 1992, pp. 21-41. ISBN: 978-03-064-4161-5.

[5] H. Feiken, Dealing with biases: three geo-archaeological approaches to the hidden landscapes of Italy, PhD thesis, Groningen: Barkhuis, 2014. ISBN: 978-94-914-3167-8.

[6] R. Francovich, H. Patterson, Extracting meaning from ploughsoil assemblages, Oxford: Oxbow Books, 2000. ISBN: 978-19-001-8875-3.

[7] J. García Sánchez, Method Matters. Some Comments on the Influence on Theory and Methodologies in Survey Based Research in Italy, in R. Cascino, F. De Stefano, A. Lepone and C. M. Marchetti (eds), TRAC 2016, Proceedings of the Twenty-Sixth Theoretical Roman Archaeology Conference, Sapienza University of Rome, 16th-19th March 2016, Rome: Edizioni Quasar, 2017, pp. 151-164. ISBN: 978-88-7140-770-8.

[8] C. Haselgrove, Inference from Ploughsoil Artefact Samples, in C. Haselgrove, M. Millet and I. Smith (eds), Archaeology from the Ploughsoil Studies in the Collection and Interpretation of Field Survey Data, Sheffield: University of Sheffield, 1985, pp. 7-29. ISBN: 978-09-060-9054-1.

[9] J. Lloyd, and G. Barker, Rural settlement in Roman Molise. Problems of archaeological survey, in G.Barker and R.Hodges (eds), Archaeology and Italian Society, Oxford: BAR International Series, vol.102, 1981, pp. 289-304. ISBN: 978-08-605-4120-2.

[10] M. B. Schiffer, A. P. Sullivan and T. C. Klinger, The design of archaeological surveys, World Archaeology, vol. 10, No. 1, 1978, pp. 1-28.
DOI: 10.1080/00438243.1978.9979712

[11] N. Terrenato, The visibility of sites and the interpretation of field survey results: towards an analysis of incomplete distributions, in R. Francovich, H. Patterson, G. Barker (eds), Extracting meaning from ploughsoil assemblages. Oxford: Oxbow Books, 2000, pp. 60-71. ISBN: 978-19-001-8875-3.

[12] P. M. V. van Leusen, Pattern to process: methodological investigations into the formation and interpretation of spatial patterns in archaeological landscapes, PhD thesis, Groningen: Rijksuniversiteit Groningen, 2002.

[13] C. Sevara, G. Verhoeven, M. Doneus, E. Draganits, Surfaces from the Visual Past: Recovering High-Resolution Terrain Data from Historic Aerial Imagery for Multitemporal Landscape Analysis, Journal of Archaeological Method and Theory, vol. 25, 2018, pp. 611-642.
DOI: 10.1007/s10816-017-9348-9

[14] Y. C. Hsieh, Y. C. Chan and J.C.Hu, Digital Elevation Model Differencing and Error Estimation from Multiple Sources: A Case Study from the Meiyuan Shan Landslide in Taiwan, Remote Sensing, vol. 8, No. 3, 2016, pp. 199-220.
DOI: 10.3390/rs8030199

[15] S. Ishiguro, H. Yamano, H. Oguma, Evaluation of DSMs generated from multi-temporal aerial photographs using emerging structure from motion–multi-view stereo technology, Geomorphology, vol.268, 2016, pp. 64-71.
DOI: 10.1016/j.geomorph.2016.05.029

[16] C. Sevara, Top Secret Topographies: Recovering Two and Three-Dimensional Archaeological Information from Historic Reconnaissance Datasets Using Image-Based Modelling Techniques, International Journal of Heritage in the Digital Era, vol. 2, No. 3, 2013, pp. 395-418.
DOI: 10.1260/2047-4970.2.3.395

[17] C. Sevara, Capturing the Past for the Future: an Evaluation of the Effect of Geometric Scan Deformities on the Performance of Aerial Archival Media in Image-based Modelling Environments, Archaeological Prospection, vol.23, No.4, 2016, pp. 325-334.
DOI: 10.1002/arp.1539

[18] J. Vaze, J. Teng, G. Spencer, Impact of DEM accuracy and resolution on topographic indices, Environmental Modeling & Software, vol. 25, No. 10, 2010, pp. 1086-1098.
DOI: 10.1016/j.envsoft.2010.03.014

[19] G. Verhoeven, D. Taelman, F. Vermeulen, Computer Vision-Based Orthophoto Mapping Of Complex Archaeological Sites: The Ancient Quarry Of Pitaranha (Portugal-Spain),

Archaeometry, vol. 54, No. 6, 2012, pp. 1114-1129.
DOI: 10.1111/j.1475-4754.2012.00667.x

[20] G. Verhoeven, F. Vermeulen, Engaging with the Canopy - Multi-Dimensional Vegetation Mark Visualisation Using Archived Aerial Images, Remote Sensing vol. 8, No. 9, 2016, pp. 752-769.
DOI: 10.3390/rs8090752

[21] G. Verhoeven, M. Doneus, Ch. Briese, F. Vermeulen, Mapping by matching: a computer vision-based approach to fast and accurate georeferencing of archaeological aerial photographs, Journal of Archaeological Science, vol. 39, No. 7, 2012, pp. 2060-2070.
DOI: 10.1016/j.jas.2012.02.022

[22] F. J. Aguilar, M. A. Aguilar, I. Fernández, J. G. Negreiros, J. Delgado, J. L. Pérez, A New Two-Step Robust Surface Matching Approach for Three-Dimensional Georeferencing of Historical Digital Elevation Models', IEEE Geoscience and Remote Sensing Letters, vol. 9, No. 4, 2012, pp. 589-593.
DOI: 10.1109/LGRS.2011.2175899

[23] P. Panagos, P. Borelli, J. Poesen, C. Ballabio, E. Lugato, K. Meusburger, L. Montanarella, C. Alewell, The new assessment of soil loss by water erosion in Europe, Environmental Science & Policy, vol. 54, 2015, pp. 438-447.
DOI: 10.1016/j.envsci.2015.12.011

[24] T. D. Stek, J. Pelgrom, Landscapes of Early Roman Colonization: Non-urban settlement organization and Roman expansion in the Roman Republic (4th-1st centuries BC), TMA, vol. 50, 2013, pp. 87.

[25] G. Chouquer, M. Clavel-Lévêque, F. Favory, J.-P. Vallat, Structures agraires en Italie centro-méridionale, Cadastres et paysages ruraux. Rome: Publications de l'École Française de Rome, 1987.

[26] T. D. Stek, E. B. Modrall, R. A. A. Kalkers, R. H. van Otterloo, J. Sevink, An early Roman colonial landscape in the Apennine mountains: landscape archaeological research in the territory of Aesernia (Central-Southern Italy), in S.De Vincenzo (ed), Analysis Archaeologica vol.1, Edizioni Quasar, Rome, Italy, 2015, pp. 229-291. ISBN: 978-88-7140-592-6.

[27] http://www.saranistri.com, accessed on 13 April 2019.

[28] S. Tarquini, L. Nannipieri, The 10 m-resolution TINITALY DEM as a trans-disciplinary basis for the analysis of the Italian territory: Current trends and new perspectives, Geomorphology, vol. 281, 2017, pp. 108-115.
DOI: 10.1016/j.geomorph.2016.12.022

[29] S. Tarquini, I. Isola, M. Favalli, F. Mazzarini, M. Bisson, M. T. Pareschi, E. Boschi, TINITALY/01: a new Triangular Irregular Network of Italy, Annals of Geophysics, vol. 50, No. 3, 2007, pp. 407-425.
DOI: 10.4401/ag-4424

[30] S. Tarquini, S. Vinci, M. Favalli, F. Doumaz, A. Fornaciai and L. Nannipieri, Release of a 10-m-resolution DEM for the Italian territory: Comparison with global-coverage DEMs and anaglyph-mode exploration via the web, Computers & Geosciences, vol.38, No.1, 2012, pp. 168-170.
DOI: 10.1016/j.cageo.2011.04.018

[31] A. Casarotto, T. D.Stek, J. Pelgrom, R. H. van Otterloo and J. Sevink, Assessing visibility and geomorphological biases in regional field surveys: The case of Roman Aesernia, Geoarchaeology, vol. 33, No. 2, 2017, pp. 177-192.
DOI: 10.1002/gea.21627

[32] M. J. H. Peters, Bypassing the Bias. Applying lmage-Based Modelling and GIS to Assess the Effect of Geomorphological Change, Topography, and Visibility on Survey Data from the Early Roman Colony of Aesernia, ltaly, MSc thesis, Leiden: Universiteit Leiden, 2019.