2D/3D SOIL CONSUMPTION TRACKING IN A MARBLE QUARRY DISTRICT

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ABSTRACT:

Complex extractive districts, such as the marble quarries in the Apuan Alps (northern Italy), require soil consumption monitoring over the years that could be achieved through high-resolution remotely sensed data. To derive 2D and 3D indicators with appropriate resolution for annual monitoring of high-resolution changes in soil consumption, aerial images, LiDAR acquisitions, satellite data, and Remotely Piloted Aircraft Systems (RPAS) acquisitions were used. In particular, open-access Sentinel-2 multispectral satellite imagery with a spatial resolution of 10 m was used to assess cover changes (2D), and then refined by manual interpretation for 5 years (2016-2021). 3D changes were detected by comparing free aerial LiDAR data from 2009 and 2017, integrated with two stereo models obtained from Pléiades high-resolution satellite images from 2020 and 2022. 3D changes observed over the years by algebraic elevation comparison, performed in QGIS 3.x environment, highlight quarries characterized by intense mining activities (extracted marble blocks, characterized by positive elevation differences) and quarry area management (debris disposal and service infrastructure construction, characterized by negative elevation differences). The combined use of 2D and 3D change indicators can be challenging in order to correctly represent soil consumption over the years. A dual 2D/3D webgis client have been developed for proper representation of 2D/3D spatial indicators of ongoing extraction activities in the Carrara marble basin: high-resolution images have been served as tiled data, while 2D/3D spatial indicators are served as static and/or tiled vector data. Open-Source libraries have used in data processing, serving and representation inside a map interface.

1. INTRODUCTION

Industrial quarrying and mining activities have been identified as a major source of environmental impacts caused by mining waste (Sarraf et al., 2004; Darwish et al., 2011; Piccini et al., 2019). In particular, with regard to Marble Quarry Waste (MQW) and Marble Cutting Waste (MCW, in italian *marmettola*), mining activity within the Carrara industrial basin has caused massive transformations of the landscape, with the growth of waste over very large areas, and the dynamics of karst water in the Apuan Alps has been affected, causing environmental impacts on both groundwater and surface water (Piccini et al., 2019; Nannoni et al., 2021).

Nowadays, monitoring surface and volume changes plays an important role in assessing the current status of waste disposal activity, especially since only a few quarries are allowed to host extractive waste. In order to properly assess the sustainability of the authorized activities, regional and national laws oblige quarry owners to issue a report on MCW/MQW production rates to monitoring agencies: these data are available in the Regional Environmental Information System (SIRA) of the Regional Environmental Agency of Tuscany (ARPAT). As highlighted in Licciardello et al. (2021), the tracking of extracted volumes disposed in situ for quarries in the Carrara basin over the years is a valuable additional resource for ARPAT control planners, which has allowed them to prioritize environmental controls based on waste management performance and to monitor the achievement of sustainable waste management goals. As part of a project involving ARPAT, several remote sensing methods were used to derive areal and volumetric datasets, which were used to calculate a set of experimental indicators related to the potential impact of MQW/MCW on the entire Carrara industrial basin (Licciardello et al., 2021). The indicators proposed in this work are targeted at local monitoring of individual quarries, while those already in the literature were limited to monitoring of high-level plans, being mainly based on (a) the life cycle assessment (LCA) method applied to building materials (Bianco et al., 2016; Zabalza et al., 2011), (b) the influence of the adoption of industrial best practices (Zabalza et al., 2011), (c) other hybrid approaches (Capitano et al., 2018), or (d) the restoration of natural habitats (Zhang Q. et al., 2018), are mainly aimed at monitoring regional plans that require Strategic Environmental Assessment (SEA) (Huang et al., 2007)

The multidimensional nature of the proposed indicators, which vary over time and space, requires further work to facilitate the use of the indicators by decision makers. With this in mind, the development of appropriate user interfaces, based on dynamic web maps with time-dependent data and 3-D representations highlighting critical areas, plays an important role in planning environmental monitoring.

1.1 Study area

Carrara's industrial basin (Fig. 1), located in Apuan Alps (Tuscany, northen Italy), is characterized by an area of about 10.76 km^2 with more than 100 quarries still in activity (Fig. 1). In detail, it is historically divided in the four basins of Miseglia (southern area), Torano (western area), Fantiscritti (central area) and Colonnata (eastern area).

Marble quarrying plays a crucial role in the local economy; in fact, the size of quarries and extraction capacities have increased significantly over the years, thanks in part to the introduction of new extraction technologies such as the use of explosives, cutting wires and cutting machines. This has led to massive waste production, which is often disposed of in neighbouring areas (*ravaneti*) or used to build provincial and service roads (Fig. 1).

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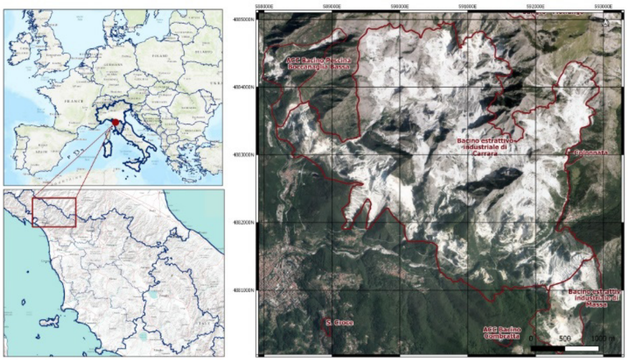

Figure 1. Carrara industrial basin (44°05'53" N - 10°07'44" E – WGS84): 1:50.000 general view. Background: 2019 orthoimage.

Waste from past mining activities has caused major geomorphological changes, mainly due to the removal of marble debris for subsequent exploitation in industrial processes. On the other hand, historic ravines (pre-21st century processing waste) are evidence of past industrial mining techniques and are now under protection as part of Carrara's industrial heritage. Currently, regional laws prohibit new waste disposals: quarry owners are allowed only temporary disposals, subject to authorization from public authorities.

2. MATERIALS AND METHODS

2.1 Aerial and satellite imagery

Both 2D and 3D land use monitoring was carried out using free aerial and satellite imagery and leveraging Open-Source geospatial software for processing and disseminating data useful for planning and monitoring management. Publicly available Aerial imagery and LiDAR acquisitions and satellite imagery freely granted by the European Space Agency (ESA) (Tab. 1) were used to derive high-resolution annual change monitoring indicators, with spatial resolution between 50 cm and 1 m in both 2D and 3D domains.

Year	Flight/Satellite	Platform	Sensor	Reference scale
2009	CGR S.p.a.	aerial	optical	1:2.000
2012	AGEA	aerial	optical	1:10.000
2012	CGR S.p.a.	aerial	LIDAR	~1:10.000 (pixel size : 1m)
2013	AGEA	aerial	optical	1:10.000
2016	AGEA	aerial	optical	1:5.000
2017	CGR S.p.a.	aerial	Optical+ LIDAR	1:5.000
2018	Plèiades	satellite	optical	~1:10.000 (pixel size : 1m)
2019	AGEA	aerial	optical	1:5.000
2020	Plèiades	satellite	optical	~1:10.000 (pixel size : 1m)

Table 1. High resolution aerial images/LIDAR surveys available by Geoscopio WMS services. Satellite images availability was granted by the European Space Agency (ESA) via the Airbus GeoStore platform.

Remotely Piloted Aircraft Systems (RPAS) acquisitions with 5 cm spatial resolution were used to assess both 2D and 3D indicators' suitability in five sample quarries.
Given the size of the Area of Interest (AOI) of the Carrara basins, which is up to 2.5 km x 2.5 km, satellite and stereo aerial images were used to obtain accurate terrain models by photogrammetric reconstruction useful for 3D land use monitoring, while medium-resolution (10 m) multispectral satellite imagery and high-resolution (50 cm-1 m) aerial imagery were used for 2D land-use monitoring and regulation of quarry areas by public agencies (natural soil loss, restoration of depleted areas, debris removals/disposals).

2.2 2D/3D coverage changes' detection

Open-access Sentinel-2 multi-spectral satellite images with 10m of spatial resolution have been used to assess coverage changes over 5 years (2016-2021); the results have been subsequently refined by manual interpretation. Both semi-automatic methods based on spectral distances and machine learning techniques have been used to identify areas affected by extraction activities in QGIS 3.x environment over Sentinel-2 images.
Free OGC Web Map Services (WMS) made available by the Tuscan Regional Information System have been used to assess changes highlighted by semi-automatic methods: aerial high-resolution images between 2010 and 2019 have been evaluated by visual photointerpretation, allowing to extend to 10 years the 2D soil consumption assessment over the whole area. Comparison of highlighted 2D changes to regulated areas like mapped debris disposals and quarries' property limits have been used to check both proper developments of extraction activities and debris management compliancy with environmental regional regulations.

3D changes have been tracked by comparison of 2009 and 2017 free aerial LiDAR data made available for download by the Tuscan Regional Information System, integrated with two stereo models obtained from 2018 and 2020 Pléiades satellite high resolution images, being the latter a new tri-stereo acquisition, freely granted by European Space Agency (ESA) following Project Proposal id 61779 ("Quarry activity monitoring in Apuan Alps"). 50 cm Stereo satellite panchromatic images have been processed by using Open Source stereo processing pipelines in Docker virtual environments, obtaining high precision digital surface models (height precision around 1m) after vegetation filtering. In detail, according to Licciardello (2021), s2p library and command line tools (De Franchis et al., 2014) and AMES Stereo Pipeline (Shean et al., 2016; Beyer et al., 2018) have been used by means both available single pairs combinations (left/right, left/center, right/center images) and the whole triplet (left/center/right images) of 2020 tri-stereo new acquisition. Moreover, various available stereo matching and sub-pixel refinement methods available in NASA AMES Stereo Pipeline (ASP) have also been tested. Mid-2018 images, while not natively acquired for stereo processing, have been processed as a single stereo pair with both stereo pipeline to enhance areas subjected to major changes. Global 3D changes detected over the years by elevation algebraic comparison, performed in QGIS 3.x environment, highlight (a) quarries characterized by intense extraction activities (extracted marble blocks, characterized by positive quotas differences), and (b) quarry area management with varying debris disposals and service infrastructures, characterized by negative quotas differences.

2.3 2D/3D representations

Since 2D changes must comply with both regional and municipal regulation related to environmental impact assessment (EIA) procedures, accurate selection of spatial datasets has been done aiming to offer an environmental alert system to environmental policy makers and managers. Additional datasets published with the 2D mapping interface includes (a) cadastre layers covering each quarry surface, (b) authorized extractive areas, and (c) debris disposals' coverage.
By intersecting these datasets with both 2D and 3D changes' indicators environmental policy makers and managers can assess environmental management quality of each quarry, thus identifying local mismatch between desired results and (a) debris management, (b) natural soil loss and (c) progress of restoration activities for exhausted quarries.
Historical high resolution BW aerial imagery (1-2m), freely available by WMS OGC regional services, can be used to evaluate long-term dating of debris disposals from 1978 to 2003 (1978, 1988, 1996 and 2003 surveys); high resolution RGB acquisition campaigns, regularly acquired on a 3-years basis starting from 2007, can be used in more recent evaluations. Being valuable tools for extraction authorizations' EIAs, all these layers should be made available in the 2D web interface.

Figure 2. 1978 and 2012 BW high resolution aerial images of Mount Bettogli debris disposals.

In addition to a 2D view of both 2D/3D indicators, a 3D view can offer to environmental controls' managers and dedicated personnel a user-friendly point of view over quarry area changes. Since point cloud at various resolutions are available for the Carrara basin, coming from both aerial and RPAS surveys, reconstructed mesh publishing has been preferred over point cloud data. While WebGL Point Cloud Viewers as Potree are a valuable solution for publishing large point cloud datasets in an efficient way, since terrain texture information is a valuable support in terrain changes' identification a mesh-based solution has to be preferred.

Mesh viewers are typically adopted in Cultural Heritage data dissemination; 3DHOP (Potenziani et al., 2015), coupled with Nexus Multi-Resolution mesh format (Cignoni et al., 2005; Ponchio et al., 2015), both developed by Visual Computing Lab of CNR-ISTI, are widely used in Cultural Heritage applications.
A full open-source stack can be established to publish textured meshes starting from point clouds and orthorectified photos: large textured mesh, when assembled in multi-resolutions formats, can be published in a WebGL client-side 3D viewer (Potenziani, 2018). While CloudCompare and/or Meshlab can be used in mesh creation and editing, Nexus command line tools allow supported formats (.obj or ply) mesh conversion in multiresolution format.

Finally, 3DHOP web viewer, fully portable over up-do-date modern browsers with full WebGL support, can be used for multiresolution model publishing, allowing stacking of multiple 3D models over a single web interface (see the Temple of Luni web viewer sample).

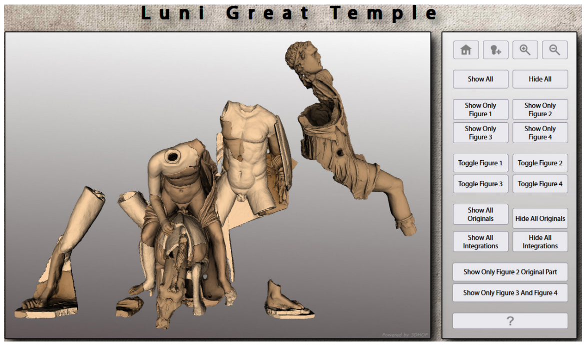

Figure 3. Luni Great Temple's 3DHOP Sample Viewer. Right tab's buttons allow selective visualization of single sculptures.

3. RESULTS

3.1 2D and 3D changes' indicators

The change in land cover detected between 2009 and 2020 were evaluated using different satellite photos, as shown in the previous paragraph, summarizing the result obtained in Fig. 5. The land cover classes, shown in Tab. 2, were digitized on all available images, limited to quarry areas (Fig. 4). The land cover datasets obtained from the high-resolution interpretation were processed for each survey period.

Class	Content
QUARRY AREA	Service roads and infrastructures, block storage areas, working areas
ROAD	Service roads not included in active areas
WASTE DISPOSAL	MQW disposals, including restored inactive areas by MCW filling.
ROCK/BARE SOIL	Bare soil/rock with/without grass subjected to quarry area expansion
VEGETATION	Trees, bushes.

Table 2. Classes used in land cover change digitizing.

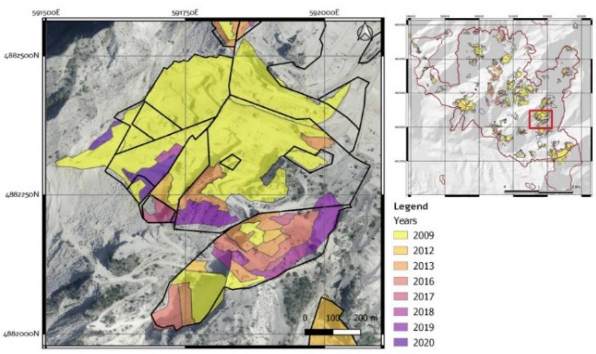

Figure 4. Sample site with yearly detected changes areas (1:5000). Black outlines represent quarries' own properties extents. Background: 2019 orthoimage.

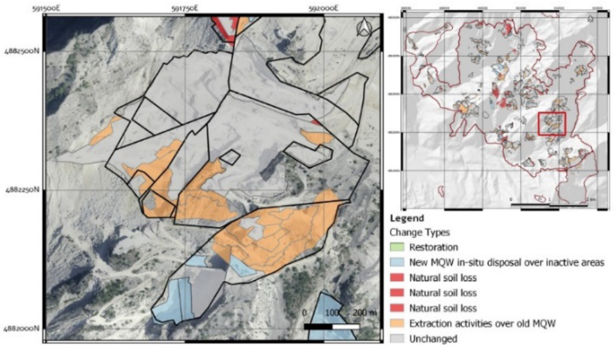

Figure 5. Sample site with land cover changes between 2009 and 2020 (1:5.000): relevant change types between 2009 and 2020: (a) Natural Soil Loss (red), Extraction Activities Over Old MQW (orange), New MQW in-situ Disposals Over Inactive Areas (cyan). Black outlines represent quarries' own properties extents. Background: 2019 orthoimage.

In summary, changes in land cover occurred mainly in the years between 2013 and 2016. The areas subject to natural soil loss and QWM removals between 2009 and 2020 are higher than those affected by QWM fills. However, natural soil loss between 2017 and 2020 was significantly reduced compared to the interval of years 2009-2016. The detail of these data is shown in a previous work (Licciardello et al., 2021).
Taking into account the vertical accuracy of the extracted terrain models, maps of relevant elevation changes between the 2017 reference model and the combined 2020 ASP stereo models were made for a number of test areas (4 sites). In detail, a threshold (5 m) was used to highlight areas subjected to intense mining between 2017 and 2020, identifying both areas characterized by negative elevation changes (marble cuts), thus affected by intense mining over the years, and areas with positive elevation changes, corresponding to zones used for temporary waste disposal. In long-data waste disposal, for example, negative and positive elevation changes make it possible to identify new waste disposals and/or the presence of major landslides. The detail of these data is shown in the work of Licciardello (2021).

3.2 Dual 2D/3D webgis

A 2D prototyping webgis and originally developed at the Tuscan Regional Environmental System for Environmental Open Data Publishing, based on OpenLayers 6.x, integrated with Bootstrap 3.x and jQuery 2.x, has been adapted to host the aforementioned dataset collection: (a) authorized areas, (b) 2D/3D indicators (c) recognized alerts over authorized areas and debris disposals, and (c) historical BW aerial imagery.

Figure 6. 2D web interface. Active layers: (a) background: 2017 BW orthoimage (b) foreground: 3D changes between 2017 and 2012.

A textured mesh of the Aerial LiDAR survey of a Carrara basin has been generated in MeshLab; the resulting mesh has been converted in Nexus multi-resolution compressed file format with *nxsbuild* and *nxscompress* commands. Compressed textured mesh size has been found to be about 5 times lesser than original point cloud size. The resulting model quality was assessed by using the *nxsview* command.

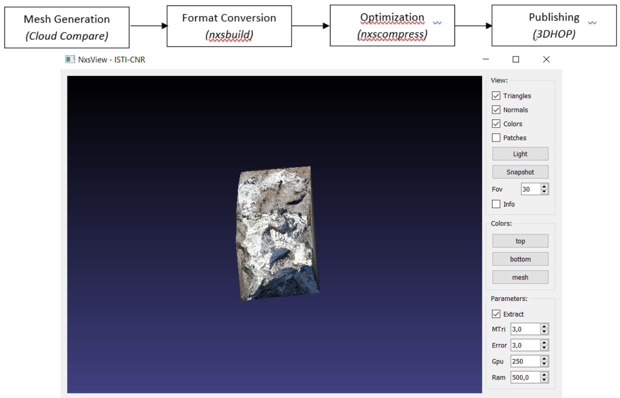

Figure 7. Point clouds processing chain and final result in Nexus visual interface (multi-resolution textured mesh of Torano extractive basin from 2017 aerial LiDAR survey)

3DHOP sample interfaces were adapted for proper visualization of two superimposed 3D models coming from (a) 2012, and (b) 2017 LiDAR surveys.

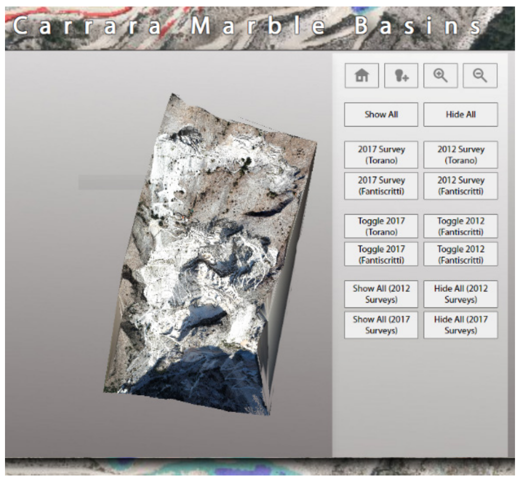

Figure 8. 3D web interface

4. DISCUSSION AND CONCLUSIONS

The combined usage of both 2D and 3D changes' indicators can be challenging in term of proper representation of soil consumption dynamics over the years: while decision makers need a quick and easy access to both 2D and 3D data, web technologies suitable for a proper representation have been developed in very different contexts, making their integration quite complex. While a 'classical' 2D webgis client Openlayers or Leaflet-based can be enough to highlight 2D changes and – with some limitations – 3D changes as elevation differences, a 'true' 3D visualization environment must be set to track ongoing extraction activities aiming to assess both (a) compliance to authorized extraction plans by public bodies and (b) proper debris management in quarry areas. In addition, 3D web viewers are mainly targeted to represents point clouds or CAD drawings, making very difficult the integration of 2D, 2.5D (Terrain Models) and 3D (extracted volumes) data. A dual 2D/3D webgis client have been developed for proper representation of 2D/3D spatial indicators of ongoing extraction activities in the Carrara marble basin: high resolution images have been served as tiled data, while 2D/3D spatial indicators are served as static and/or tiled vector data. Open-Source libraries have used in data processing, serving and representation inside a map interface. For each quarry included in the Carrara basing, both area limitations and authorized areas for extraction activities have been superimposed over the spatial indicator layers, thus allowing users to easily locate areas subjected to intense extraction activities and to evaluate compliance to sustainability plans and environmental management prescriptions issued by public bodies. 2D and 3D indicators are in progress to be used in prioritizing environmental controls' planning: this novel application would require a proper scoring system based on the degree of compliance to both environmental management prescriptions and performances mainly in the field of quarry and marble slurry waste management.

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