# From Remote Sensing to Decision Support System for Industrial Quarry Basins

Cinzia Licciardello(✉), Antonio Di Marco(✉), Stefania Biagini(✉), Khalil Tayeh(✉), and Diego Palazzuoli(✉)

ARPAT, via Nicola Porpora 22, 50144 Firenze, Italy
{c.licciardello,a.dimarco,s.biagini,k.tayeh, d.palazzuoli}@arpat.toscana.it

**Abstract.** Remote Sensing data and techniques play a great role in quarry and mining activity monitoring: UAVs, aerials and terrestrials LiDAR and optical sensors are widely used in quarry management in evaluating extraction phases and compliancy to working stages. Environmental management of large quarry areas requires not only precise 3D data to assess yearly volume changes, but also availability of datasets useful in monitoring compliancy to natural soil consumption previsions and water/extraction waste management rules issued by public authorities.

Integration of both remotely sensed and environmental information systems' data is required to define waste production indicators related to extraction activities. A novel set of indicators over Carrara extractive basin has been proposed by integrating surface and volume changes over the years with production and waste management data: the proposed indicators have been evaluated over all active quarry located in Carrara extraction basin.

The indicators, integrated in a Decision Support System (DSS), can be used to classify all quarries by environmental management performances' scores, thus allowing planning of in-situ controls related to water and marble quarry/cutting waste (MQW/MCW) management according to risk management quantitative criteria.

Prototyping time-varying data on dynamic maps and 3D navigation interfaces have been proposed to support environmental controls' planners in yearly extraction waste production and land cover changes monitoring.

## 1 Introduction

Quarry and mining industrial activities have been identified as a major source of environment and natural resources loss and degradation caused by extraction wastes [1, 2, 12]: Marble Cutting Wastes slurry (MCW, in Italian '*marmettola*') is involved in Apuan Alps' karst water dynamics leading to both groundwaters and surface waters' environmental impacts [12, 14]. Regarding to Marble Quarry Waste (MQW), centuries of intense extraction activity in the Carrara industrial basin led to massive landscape changes and permanent in-situ debris disposals' growth over extensive areas (see Fig. 1). Nowadays only few of them are allowed to receive, for a limited time, additional debris volumes,

© Springer Nature Switzerland AG 2022
E. Borgogno-Mondino and P. Zamperlin (Eds.): ASITA 2021, CCIS 1507, pp. 385–404, 2022.
https://doi.org/10.1007/978-3-030-94426-1_28

while their permanent in-situ disposal is regarded as unauthorized waste deposit and therefore forbidden by both regional and national regulations. Indeed, surface and volume changes' tracking play a relevant role in assessing current activity state of MCW in-situ disposals.

Sustainable use of marble resources requires both (a) limitation of MCW and MQW production by properly identifying promising extractive areas and proper planning of marble cuts [10], and (b) proper management of MCW and MQW in producing new building material, included the exploitation of historical in-situ MCW/MQW disposals [10, 13].

Regional laws require that quarry owners must issue yearly report of ornamental stones, other sub-products and MCW/MQW production rates to both local and public bodies involved in activities authorization processes. In addition, according to national laws MCW and MQW yearly reports (Environmental Reporting Model, i.e., 'MUD' report) must to be issued by owners to regional and national authorities charged by general waste managements' controls: these data stored in the ARPAT Regional Environmental Information System (SIRA).

Environmental controls in quarry areas issued by ARPAT are primarily focused on both assessing proper water cycle and waste management according to both national and regional regulations; such controls require both careful planning and rapid response capabilities in some limited cases. Tracking MCW/MQW volumes' *in-situ* disposals for Carrara basin's quarries over the years would be a valuable additional resource, allowing – if combined with existing data sources available in the Regional Environmental system – to both prioritize environmental controls basing on waste management performances and to monitor sustainable waste management's goals achievement.

A regional project issued in 2016 involved the Regional Environmental Agency of Tuscany (ARPAT) in developing new waste monitoring methodologies basing on recent remote sensing advances: a number of remote sensing methods have been used for deriving areal and volume datasets, which have been then used to calculate a set of experimental indicators related to potential MQW/MCW impact over the whole industrial Carrara basin. These indicators have been integrated in a prototyping Decision Support System (DSS) to allow *in-situ* controls' planners to decide appropriate time intervals between each control.

Many environmental impact and state/response indicators have been studied for high-level plans monitoring; while impact indicators are primarily based on Life-Cycle Assessment (LCA) method applied to buildings materials [15, 20], the influence of best industrial practices adoption [20] or other hybrid approaches [16], state/response indicators are primarily targeted to assess natural habitat restoration [11]. While these indicators are more suitable to regional plan monitoring, indicators proposed in this work are targeted to local monitoring of single quarries.

The multidimensionality nature of the proposed indicators, varying in time and space, requires additional work to ease indicators usage by decision makers. Therefore, development of proper user interfaces based on dynamic web maps with time-dependent data and 3D representations highlighting critical areas play an important role in environmental controls' planning.

## 2 Study Area

Carrara industrial basin, located about 1.5km from Carrara city center, is centered on the geographic coordinates (WGS84) 44°05′53.412”and 10°07′44.922” (Fig. 1); the basin covers an approximate surface of 1076 ha and hosts dozens of inactive quarries, while 104 are still active. The whole area is historically divided in the four main basins of Miseglia (south area), Torano (west area), Fantiscritti (central area) and Colonnata (east area).

Starting from pre-roman times marble extraction have played a key role in local economy. Quarry dimensions and extraction capabilities have increased over the years, due to the introduction of new extraction technologies like explosives’ usage (XVI century), cutting wire (first decade of XX century), cutter machines (last decades of XX century) leading to massive waste production usually disposed in nearby areas (*ravaneti*) or used to build both provincial and service roads (Fig. 1).

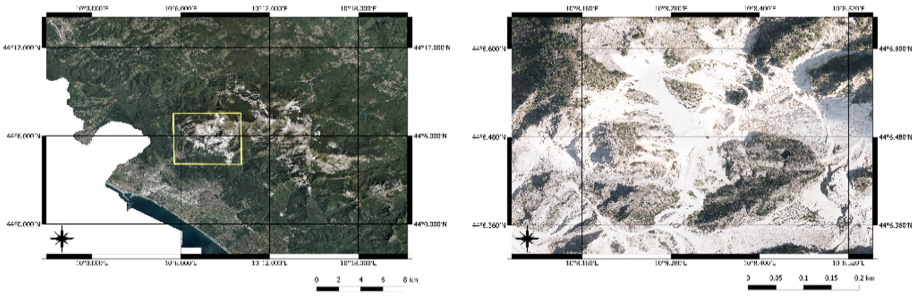

**Fig. 1.** Carrara industrial basin: 1:100.000 general view (left) and 1:2.000 detail (right) with quarries and old in-situ MCW/MQW disposals. Background: 2019 orthoimage.

As stated before, nowadays only temporary MCW/MQW in-situ disposals are allowed, subjected to a prior approval of MCW/MQW management cycle by public authorities in presence of removal plans at the end of extraction activities. Old-dated *in-situ* MCW/MQW disposals coming from past extraction activities are a source of geomorphological changes, due to the removal of marble debris for subsequent exploitation in industrial processes where calcium carbonate plays an important role. On the other hand, historical *ravaneti* (pre-XXX century MCW/MQW disposals) are the witness of past industrial extractions’ techniques and are now under protection as part of Carrara’s industrial heritage.

## 3 Materials and Methods

### 3.1 Datasets

Remote Sensing techniques play a great role in yearly monitoring extraction activities in Carrara industrial basin: while UAV and/or terrestrial LiDAR are often used for single

quarry surveys, the basin's extension and morphology make very challenging their usage at basin scale.

Aerial/satellite high resolution images and aerial LiDAR surveys allow a cost-effective basin coverage; aerial high resolution orthoimages acquired on a tri-annual basis by National Agency for Agriculture Founding (AGEA) are publicly distributed by Tuscany Regional Information System by mean of Geoscopio Web Map Service (WMS).

Archived 2018 tasking tri-stereo 2020 high resolution Pléiades satellite images covering Carrara industrial basin have been granted to the Tuscan Regional Environmental Agency (ARPAT) by the European Spatial Agency (ESA) following Project Proposal id61779.

The large availability of high resolution orthoimage between 2009 and 2020 allow near yearly land cover changes identification, while 2012 and 2017 aerial LiDAR data allow elevation's change detection between 2012 and 2017. Stereo processing of 2020 Pléiades tri-stereo acquisition allows additional elevation's change detection between 2017 LiDAR terrain models and 2020 stereo extracted model.

**Table 1.** High resolution images/LiDAR surveys publicly available

| Flight/Satellite | Platform | Sensor | Year | Reference scale |
|---|---|---|---|---|
| CGR S.p.a | Aerial | Optical | 2009 | 1:2.000 |
| AGEA | Aerial | Optical | 2012 | 1:10.000 |
| CGR S.p.a | Aerial | LiDAR | 2012 | ~1:10.000 (pixel size: 1m) |
| AGEA | Aerial | Optical | 2013 | 1:10.000 |
| AGEA | Aerial | Optical | 2016 | 1:5.000 |
| CGR S.p.a | Aerial | Optical + LiDAR | 2017 | 1:5.000 |
| Pléiades | Satellite | Optical | 2018 | ~1:10.000 (pixel size: 1m) |
| AGEA | Aerial | Optical | 2019 | 1:5.000 |
| Pléiades | Satellite | Optical | 2020 | ~1:10.000 (pixel size: 1m) |

As stated before, yearly production data must be sent by quarry owners to Local and Regional bodies involved in authorization management: these data include production volumes of (a) ornamental stone (primary product), (b) other secondary products to be used in stone products, (c) debris. Top 15 quarries with the highest ornamental stone production rates have been selected for further comparison of reported production volumes and detected volume changes between 2017 and 2020.

National Waste Reporting actually in charge to quarry owners includes all waste products coming from extraction activities: only yearly reports between 2009 and 2019 of MCW in various physical states – gravelly, sandy, silty and slurry – have been extracted for each quarry located in Carrara extractive basin and joined to the vector point layers representing quarries' locations.

The Regional Ornamental and Building Stones dataset (BDPIOR)[1] made by LAMMA Consortium for the Tuscany Regional Administration has been used in assess volume changes in Carrara *in-situ* MQW disposals, being the official reference in delineating old *in-situ* MQW disposals until the approval of Carrara extractive basins' plans.

### 3.2 Land Cover Changes

Extraction activities lead to various land cover changes: natural soil loss occurs when portions of rock or vegetated soil are removed to access marble strata. Natural soil loss

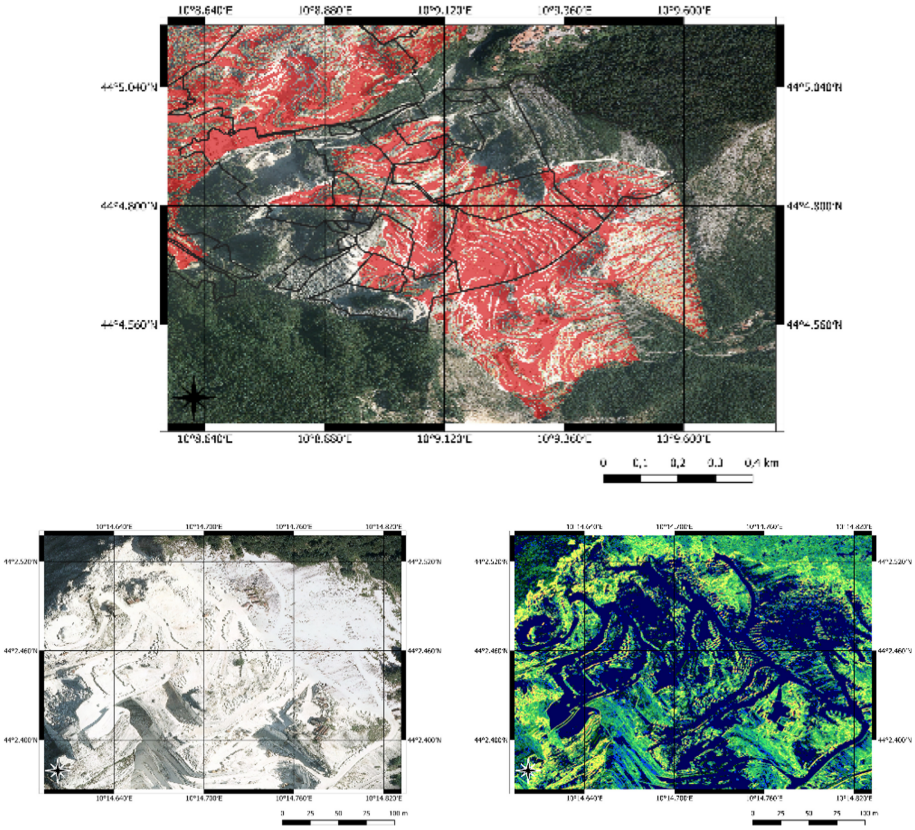

**Fig. 2.** 3D and 2D processing techniques for high resolution quarry areas classification. Upper image: 1:10.000 map with 2017 DEM slope analysis NW of Colonnata. In red: areas with slope < 15° identifying quarry extraction areas. Black outlines represent quarries' own properties extents. Lower left image: 2019 aerial 1:5.000 orthoimage. Lower right images: Structural Feature Set Texture Analysis (523 False Color Composite 8-set Haralick base set extracted with CNES Orfeo Toolbox) in a sample quarry (1:1.000).

[1] http://159.213.57.103/geoweb/CONTINUUM/BD_PIOR/BD_PIOR.zip.

can be mapped with (a) high resolution photo visual interpretation or (b) automatic and semi-automatic spectral classification techniques.

Due to artificial processes' complexity involving quarry areas, visual inspection and interpretations can be regarded as the preferred method to track land cover changes, while spectral classification can be used only for rough identification of both vegetated and artificial areas. Only advanced computer vision and texture analysis techniques [3, 4] combined with 3D information can be used to detect extraction areas characterized by regular block cuts, service areas and quarry MQW disposals: processed images can be used as ancillary bands to gain better spectral separability in spectral distance-based image classifiers (Fig. 2).

Image interpretation classes have been organized to obtain four relevant categories of land cover changes: (a) natural soil loss, (b) inactive quarries restoration by debris usage, (c) in-situ Marble Cutting/Quarry Waste (MCW/MQW) removals and (d) vegetation growth over inactive quarries and old MCW disposals. Identification of these changes requires mapping of four classes: active areas, in-situ MCW/MQW disposals, bare soil/rock and vegetation changes. These classes are consistent with IV level land cover class defined in Regional Official Land Cover dataset; the same classes have been used in the Extractive Basins' plan of the Carrara municipality.

**Table 2.** Classes used in land cover changes' digitizing

| Class | Content |
|---|---|
| Quarry area | Service roads and infrastructures, block storage areas, working areas |
| Road | Service roads not included in active areas |
| Waste disposal | MCW/MQW in-situ disposals, including restored inactive areas by MCW/MQW filling |
| Rock/Bare soil | Bare soil/rock with/without grass subjected to quarry area expansion |
| Vegetation | Trees, bushes |

Only three kinds of changes are relevant in assessing environmental impact of extractive activities over land use:

1. **Natural soil loss**: changes from vegetation/rock/bare soil to quarry area/road/MCW and/or MQW disposal
2. **MCW/MQW removal**: changes from MCW/MQW to quarry area, due to industrial exploitation of old in-situ disposals
3. **MCW/MQW fills**: changes from quarry areas to MCW/MQW, due to filling of unused quarries (final restoration activities)

Land cover changes data are presented in paragraph 4.

### 3.3 Volume Changes

As stated before, 3D changes from different acquisitions are a valuable tool to boost both automatic image classification and identification of extraction sites: both LiDAR aerial data and high-resolution satellite stereo acquisitions can be used to obtain precise localization, taking into account elevation precision influence on elevation changes assessment. In the latter case, a digital surface model (DSM) has been extracted from Pléiades tri-stereo acquisition by using s2p stereo pipeline [6] within a Docker container: the surface model has been compared with 2017 LiDAR DSM to assess both surface and volume changes between 2018[2] and 2020 over authorized areas and in-situ MCW/MQW disposals (Fig. 3).

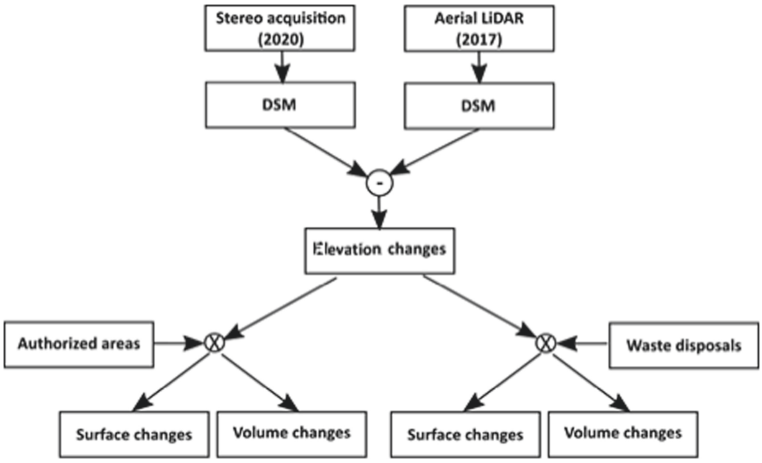


**Fig. 3.** Processing chain of LiDAR and stereo satellite acquisition for automatic surface and elevation change detection

Manual digitizing of both extracted and in-situ volumes has been done over 11 sample quarries showing values higher than 5 m: this threshold has been selected in accordance with the 2–3 m Root Mean Square Error (RMSE) assessed for tri-stereo extracted terrain models in urban environment [7] to highlight relevant elevation changes.

## 4 Results

### 4.1 Land Cover Changes

Both high resolution aerial and 2018/2020 satellite photos in Table 1 have been used in digitizing changes from 2009 to 2020: digitization of all land cover classes in Table 2 has been done over all available images inside each authorized quarry areas.

[2] Late 2017 LiDAR acquisition (end of October) has been intended as initial 2018 reference, due to the small number of working days remaining until the end of 2017 (November/first days of December). Their contribution to both blocks and waste production is then negligible compared to February/October working days.

Land cover dataset derived from high resolution photo interpretation has been processed over each sensing period (Fig. 4).

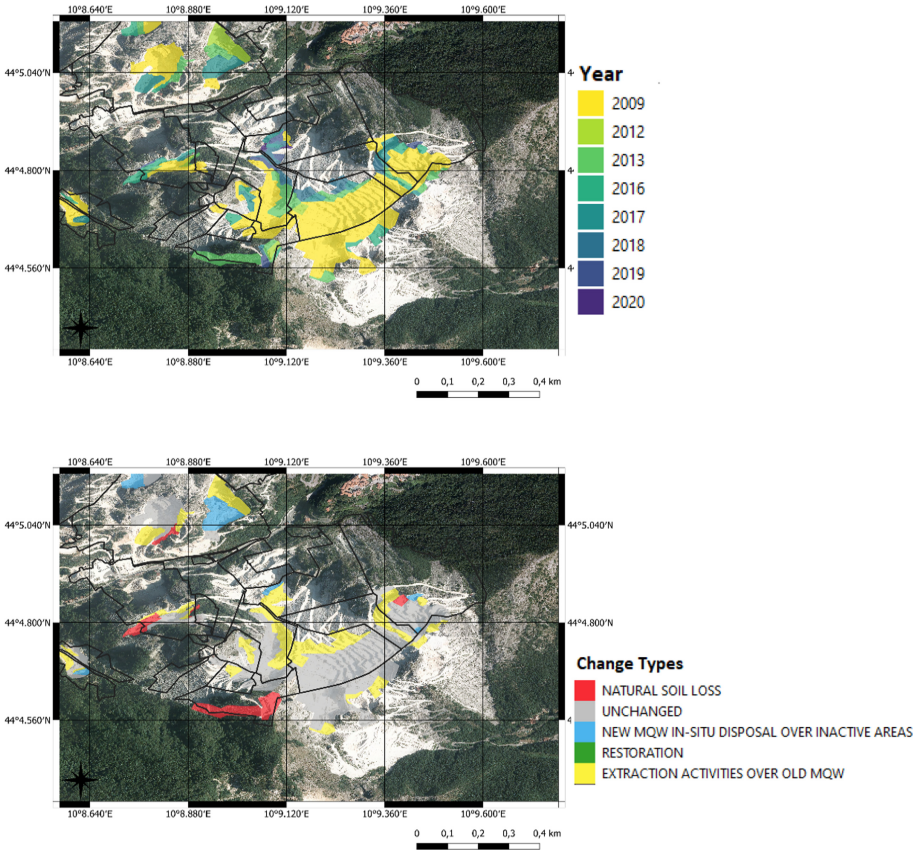


**Fig. 4.** Sample site with land cover changes between 2009 and 2020 (1:5.000). Upper image: yearly detected changes. Lower image: relevant change types between 2009 and 2020: (a) Natural Soil Loss (red), Extraction Activities Over Old MCW/MQW (yellow), New MCW/MQW in-situ Disposals Over Inactive Areas (cyan). Black outlines represent quarries' own properties extents. Background: 2019 orthoimage. (Color figure online)

As stated in Table 3, land cover changes occurred mainly between 2013 and 2016. Areas subjected to natural soil loss and MCW/MQW removals between 2009 and 2020 are higher than the ones interested by MCW/MQW fills, being respectively the 29% and 35% of total land cover changes' surface; however, between 2017 and 2020 natural soil loss has been significatively lowered with respect to years 2009–2016.

### 4.2 Volume Changes and Waste Management Indicators

3D volume changes precision has been assessed by comparison with reported production and MCW/MQW data only in 11 of the first 15 sample quarries showing the highest

**Table 3.** Land cover changes by category: (a) old MCW/MQW removal (b) inactive quarry areas restoration by filling with MCW/MQW (c) natural soil loss near expanding quarry areas

| 2009–2020 land cover changes | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Time interval | MCW/MQW removal | | MCW/MQW fills | | Natural soil loss | | Total | |
| | Area ($m^2$) | % (year) | Area ($m^2$) | % (year) | Area ($m^2$) | % (year) | Area ($m^2$) | % tot |
| 2009–2012 | 6.87 | 71.4 | 1.99 | 7.9 | 0.76 | 7.9 | 9.62 | 11.4 |
| 2012–2013 | 11.26 | 46.7 | 4.33 | 35.3 | 8.52 | 35.3 | 24.11 | 28.5 |
| 2013–2016 | 9.29 | 31.7 | 3.68 | 55.6 | 16.31 | 55.6 | 29.34 | 34.7 |
| 2016–2017 | 4.76 | 48.8 | 2.78 | 22.8 | 2.23 | 22.8 | 9.77 | 11.6 |
| 2017–2018 | 5.20 | 85.0 | 0.10 | 13.4 | 0.82 | 13.4 | 6.12 | 7.2 |
| 2018–2019 | 3.66 | 72,5 | 0.50 | 17.5 | 0.88 | 17.5 | 5.04 | 6.0 |
| 2019–2020 | 0.49 | 90 | – | 10.0 | 0.06 | 10.0 | 0.55 | 0.6 |
| **2009–2020** | **41.53** | **49.1%** | **13.38** | **15.8%** | **29.57** | **35%** | **84.54** | **–** |

production rates, since in four of them extracted 2020 terrain models cannot be used due to matching errors in complex morphology areas.

Figure 5 highlight the good agreement between the whole volume reported (production + waste, in blue) and extracted volume/in-situ MCW/MQW (in orange/gray) detected by both semi-automatic and manual methods. On the top chart, reported global volumes (production + waste) of samples 7, 10 and 11 appears to be from 30% to 75% lower than the ones calculated with semiautomatic methods. While in the case of samples 10 and 11 this can be related to in-situ displacement of extracted volumes (grey bars), sample 7 shows a lack of agreement between reported and calculated volumes. Further investigations for this quarry highlighted unsatisfactory 2020 DSM accuracy.

Extracted and in-situ MCW/MQW volumes on the second chart are evaluated using manually digitized contours: while extracted volumes show minimal differences with the ones obtained by semiautomatic methods, in-situ MCW/MQW volume is far lower except for sample 8. In addition to require better DSM precision, these results highlight that in-situ MCW/MQW is mainly composed of low-height disposals that might have been discarded in manual digitizing.

Thus negligible in volumes with regard to MQW, MCW (*marmettola*) represents the main driver of environmental impact affecting water resources [12, 14]: marble powder, mixed with cooling water and/or other fluids, can be found in nearby rivers thus resulting in a major source of additional costs in water depuration processes.

The amount of MCW can be estimated in three different ways: (a) as a percentage (5–3%) of block production, due to cutting and refining operations, (b) from yearly national waste Reporting contents, or (c) as predicted values during activity authorization. Marble blocks production is reported from quarry owners and verified during transportation at weigh stations, while waste reports only include the amount of MCW sent to waste

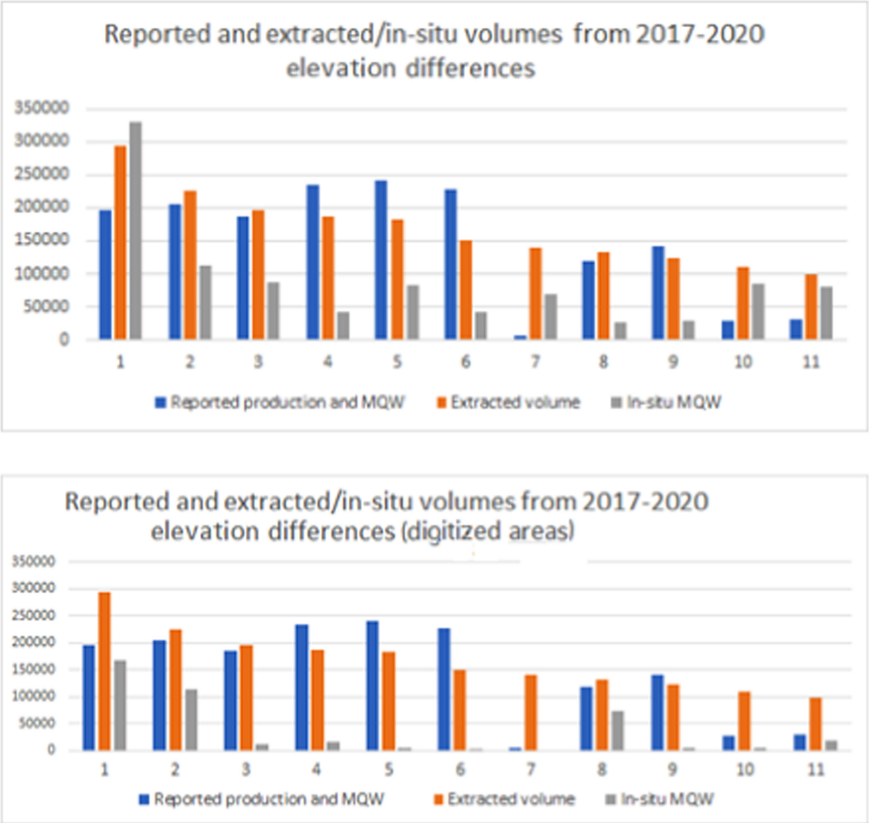


**Fig. 5.** Reported (blue, including production and MCW/MQW) and extracted volumes from DSMs differences in sample quarries, including extracted (orange) and in-situ (grey). Top: automatic volume extraction, bottom: extraction from manually-digitized areas. (Color figure online)

treatment plants, thus excluding untreated MCW used on site for service infrastructure management.

Other extraction wastes, mainly debris (MQW), have to be removed from extraction site or used for building infrastructures and service roads: 3D elevation differences from DSMs can be used to highlight disposals areas and roughly quantify waste volumes. Indicators used to assess both fine-grained debris are explained in the next two sections.

### 4.3 Marble Cutting Waste ('marmettola')

Gravel, sandy, silty and slurry MCW are committed to external plants or used in quarry areas for service roads and wall management; in the latter case they can migrate through underwater basins to surface waters.

Committed MCW reports must be sent to national authorities: each waste category being treated outside production sites requires prior classification based on waste codes are established at European level (EWC codes).

MCW are classified with code 010413, i.e., 'wastes from stone cutting and sawing other than those mentioned in 010407': national reports from 2012 to 2019 issued by quarry owners have been normalized, geocoded and assigned to each quarry in order to extract MCW volume and weight values, taking into account special cases of both quarry and sawing plants' owners[3].

In order to check consistency of reported MCW quantities with estimated values from reported blocks production, silty MCW require weighting by the average estimated

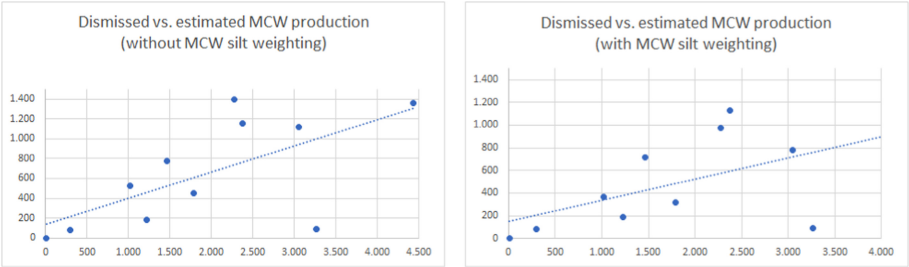


**Fig. 6.** Estimated MCW from blocks production (x axis) vs, reported production (left) and weighted reported production for silty fraction for sample quarries.

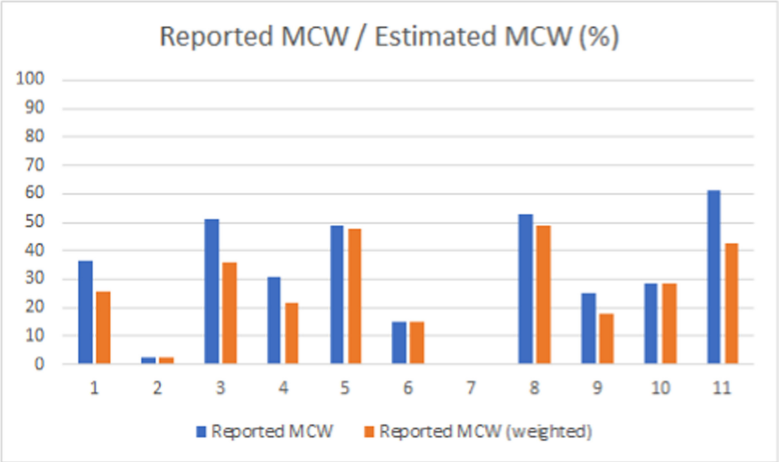


**Fig. 7.** Reported (sum and weighted sum) 2018–2020 MCW by sample quarries as a fraction of estimated MCW (5% of block production).

[3] Sawing plants are a major source of fine-grained wastes, but must not be taken into account in evaluating extraction activities impact of waste production over water resources located in extractive basins.

concentration of the solution, typically between 70% and 80%: avoiding this weighting factor leads to overestimation of reported MCW [21–23].

Figures 6 and 7 shows that the average ratio between reported and estimated MCW is around 25%, while a little amount of the sample shows very little agreement between estimated and reported production due to in-situ disposals. On the converse, Fig. 8 shows a different path for quarries with low production rates (<1.000 T of marble blocks): such results were somehow expected due to minor capabilities in MCW dismission for industrial purposes.

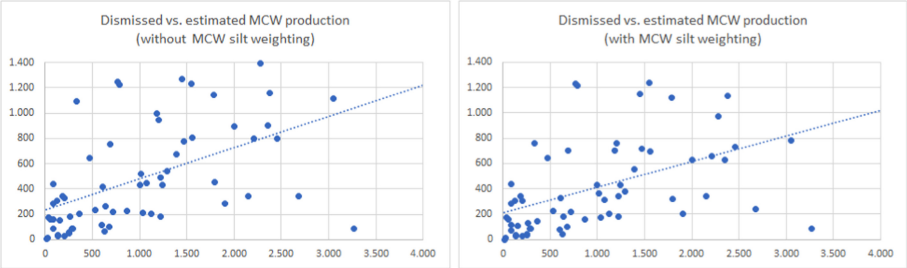


**Fig. 8.** Estimated MCW from marble blocks production (x axis) vs. reported production (left) and weighted reported production for silty fraction for all quarries with reported MCW and production. The trend is consistent with the one highlighted in Fig. 5 for sample data.

When ratio between reported and estimated MCW is largely below 50%, some further analysis is required to ensure consistency of MCW waste management policies with regional sustainability goals.

### 4.4 In-Situ Marble Quarry Waste (MQW) Disposals

As stated before, in-situ waste disposal is forbidden by both regional and national regulations while not explicitly authorized in very limited cases: 3D data coming from UAV, LiDAR and satellite stereo images can be used to track changes over areas covered by historical waste disposals.

Elevation changes of in-situ waste disposals can be related to terrain movements due to local instability: such occurrences, thus relevant to both workers and – in some cases – population safety monitoring, have not been taken into account in waste disposals' monitoring.

As stated before, historical waste disposals localization has been derived from the Regional Ornamental and Building Stones dataset (BDPIOR)[4] made by LAMMA Consortium for the Tuscany Regional Administration: elevation changes between 2017 aerial LiDAR survey and 2020 DSM extracted from Pléiades stereo images have been checked over these areas, while precise 6-month difference have been checked over a major waste disposal by two UAV survey-derived DSMs. This latter test, being limited for research purposes, has not been used in whole industrial area monitoring: other available UAV surveys, being limited to quarry active areas, have not been taken into account.

[4] http://159.213.57.103/geoweb/CONTINUUM/BD_PIOR/BD_PIOR.zip.

Each waste disposal has been related to a quarry basing on its inclusion on quarry authorized area (overlay) (Fig. 9).

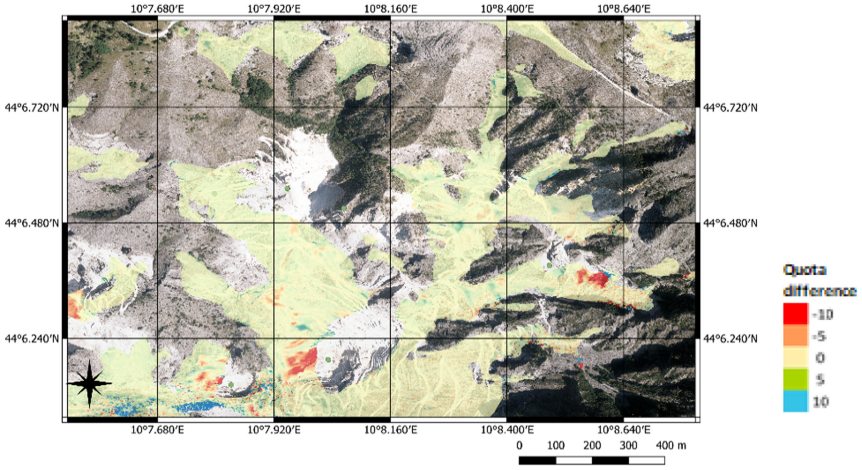


**Fig. 9.** 1:5.000 north-east area of Carrara industrial basin: elevation changes between 2017 and 2020 over digitized waste disposals' areas (dataset BDPIOR from LAMMA Consortium: in yellow). Excavated areas (red) and new disposals (blue) area highlighted. Background: 2019 orthoimage. (Color figure online)

Both extracted and disposed volumes over old MQW disposals areas have been evaluated by zonal statistics GIS techniques over 500 ha MQW area at global and sub-basin details: 4% of global old MQW surface has been subjected to extraction activities[5], while roughly 10% has been subjected to WQM disposals.

**Table 4.** In-situ MQW Surface and Volume Changes (2018–2020) for each sub-basin.

| Sub-basin | Area (ha) | | Volume ($m^3$) | |
|---|---|---|---|---|
| | Extracted | Disposed | Extracted | Disposed |
| Torano | 7,0175 | 13,2 | 675.706 | 7.556.162 |
| Fantiscritti | 8,0032 | 12,5 | 623.237 | 7.847.711 |
| Colonnata | 8,9262 | 27,7 | 939.528 | 11.479.306 |
| **Tot** | **23,9469** | **53,4** | **2.238.471** | **26.883.179** |

[5] Elevation changes greater than 5 m due to MCW/MQW landslides are negligible compared with the ones related to extraction activities.

### 4.5 MQW Disposals in Active Quarries

As stated before, temporary MQW disposals are allowed in active quarries' areas to be used as building materials for terrain and service infrastructures' management: authorized quarry areas have been digitized from national cadaster, following authorizations' maps produced by the Carrara Municipality for the Extraction Management Plan (PABE). While in most cases, especially for big quarries, reported MQW data are consistent with the ones estimated from 3D changes, small quarries seem to follow a slightly different pattern (Fig. 10).

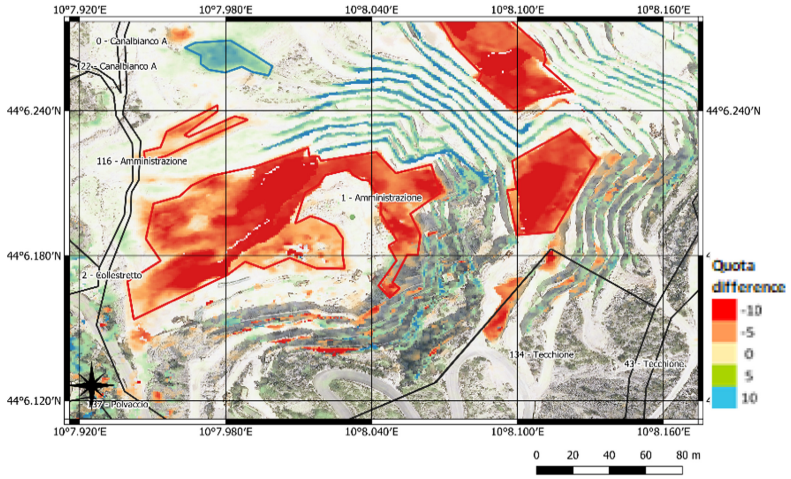


**Fig. 10.** Detail of 1:1.000 digitized areas for 2017–2020 volume changes evaluation (red: extraction areas, blue: disposals' areas), Black borders define authorized extraction areas. (Color figure online)

Two different approaches have been used in analyzing trends in MQW management: the first is based on accurate analysis of a subset[6] of quarries showing the highest production rates, while the latter relies on automatic extraction and data cleaning over all quarries with high production rates.

In the first case disposals areas have been digitized manually where elevation changes were over 4/5 m, taking into account elevation tolerances of the two 1 m × 1 m 2017 and 2020 DSMs[7]: volumes have been calculated in QGIS by applying digitized boundaries to the raster difference of the two DSMs. Figure 11, where x axis represents extracted volumes and x axis new MCW in-situ disposed volumes, highlights a good agreement

[6] Quarries included in the study are the top 10 showing relevant volume changes between 2017 and 2020 (over/near 100.000 $m^3$).

[7] While 2017 aerial LiDAR DSM dataset show very high precision (<1 m), elevation tolerance of 2020 stereo-derived DSM lies in the range 1–2 m. Elevation difference tolerances can be evaluated as the sum of the two tolerances (3 m), and 4 m has been chosen as reference level for excavation and MCW/MQW disposals' changes assessment.

for both methods, thus assessing a rough correlation between extracted volumes and new MCW disposals for the majority of the quarries under investigation.

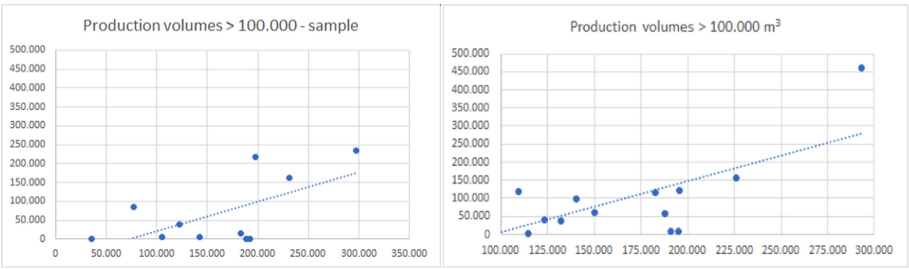


**Fig. 11.** Extracted volumes (x axis) vs. new MQW disposals in quarry areas: manually-refined areas over a quarry sample (left) and automatic area extraction (right)

Therefore, in both cases it can be stated that extracted volume equals new MCW disposals: taking into account fine debris, silt and sand volume expansion by using an average weight of 40–60%, average production rates and dismissed wastes can be evaluated as 60–40% of extracted volume.

### 4.6 Data Integration and Proposed Indicators

All derived datasets have been processed to extract both potential impact indicators and spatial data at global and local scale: trends of land coverage changes, MCW and production data have also been evaluated from 2012 to 2019.

Derived key indicators can be roughly classified as sustainable and environmental policies ones: sustainable policy indicators, relying mostly on reported production data, are more suitable in monitoring regional level plans subjected to Strategic Environmental Assessment (SEA), while the so-called environmental impact indicators are more suitable at municipal level, including environmental controls planning. Sustainability indicators at local scale can also be used in local policies' monitoring (i.e., quarry restorations and reusing od old *in-situ* MQW disposals) and assessment.

Table 4 highlights the indicators that could be included in a Decision Support System (DSS): each indicator, while not natively including a spatial component, can be 'spatially-enabled' with join operations based on quarry identifier (Table 5).

Chart representations of key indicators for sustainability policies have been established to highlight their trends over the years: production rate, i.e., the ratio between marble blocks and debris coming from quarry managers yearly reports, is a key indicator in measuring sustainability policies and can be examined over a temporal extent compared to planning targets at regional planning level. This dataset can be used, combined with volume changes, to obtain potential impact indicators to be used in environmental controls' planning (Fig. 12).

**Table 5.** Indicators to be included in the Decision Support System (DSS)

| Class | Indicators | Involved datasets |
|---|---|---|
| Sustainability | • Reported production rates<br>• Measured production rates<br>• MCW transferred to recycling industry<br>• Natural Soil Loss (area/volumes) | Production data<br>Reported MCW<br>Production data<br>Land cover |
| Environmental impact assessment | • Old in-situ MCW/MQW removals<br>• New in-situ MCW/MQW (area/volumes)<br>• Restored quarries | Land cover<br>DSMs<br>DSMs |

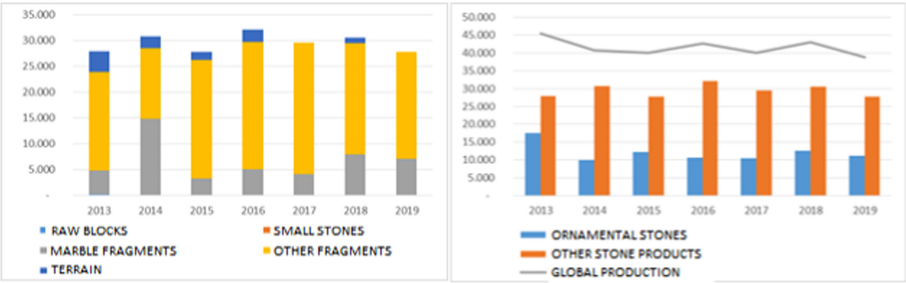


**Fig. 12.** Example of 2013–2019 production indicators for a sample sub-basin derived from owners' reports. Left image: sub-products' details in cubic meters per year (raw non-ornamental blocks, fragments, debris, small stones). Right image: production rates and trends for both ornamental stones and other derived stone products in cubic meters per year.

2018–2020 production data have been used, in association with 3D volume changes between 2017 and 2020 over a sample of 9 quarries[8], for assessing 2018–2020 consistency of MCW/MQW management and reusing. In the following charts (Fig. 13 and 14) reported 2018–2020 production rate, i.e., ratio between reported production and extraction debris, is compared to the ratio between reported 2018–2020 production and extracted volumes evaluated from elevation changes between 2017 and 2020 (estimated production rates referring to the whole extracted volume).

[8] Quarries included in the study are the top 9 showing relevant volume changes between 2017 and 2020 (over/near 100.000 $m^3$) with 2018 production data.

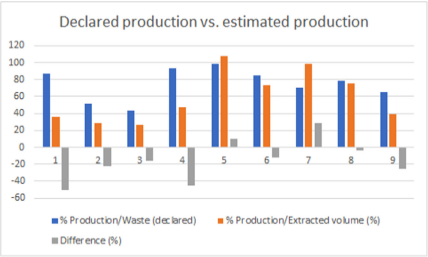


**Fig. 13.** Reported production rates compared with volume changes in sample sites. Blue: reported production rate, orange: production rate as ratio of production and extracted volume. Differences should be related to in-situ MCW/MQW temporary disposals and/or quarry area infrastructures' management. (Color figure online)

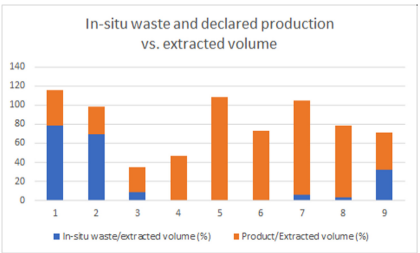


**Fig. 14.** Extracted volume comparison (%) with in-situ MCW/MQW changes during 2017–2020 (in blue) and production data (in orange) in sample sites. Sites 1, 2 and (partially) 9 show relevant in-situ MCW/MQW disposal, therefore requiring additional data check and/or in-situ control, while other sites are characterized by a quasi-absence of in-situ MCW/MQW disposals, therefore suggesting proper MCW/MQW management. (Color figure online)

## 5 Discussion

Waste management and land cover changes' indicators highlighted in paragraph 4, compared with production data and waste yearly reports, allow to assess waste management performances achieved by each quarry. Since long-dated MCW/MQW disposal (*ravaneti*) and quarry areas is forbidden, except for building new service infrastructures or repairing existing ones, these indicators allow to track in-situ waste management over the years.

While general criteria for environmental controls in quarries and mines have been established [25] and risk assessment methods have been proposed for controls prioritization in industrial plants with high potential environmental impact [24] by the European Union Network for the Implementation and Enforcement of Environmental Law (IMPEL), this work aims to fill the gap between the above frameworks and quarries' controls' planning. These indicators, established at quarry level, are intended to be integrated in a Decision Support System to give a 'risk score' mainly related to waste management performances.

Existing environmental impact indicators based on Life Cycle Assessment (LCA) methods, although useful in measuring global environmental performance of extractive activities, do not take into account local environmental impacts like MCW/MQW in-situ disposals, that are proven to be a source of groundwater and surface water quality loss in the Apuan karst.

Additional work has to be done on improving terrain models' availability over the years by integration of aerial/satellite stereo acquisition with periodic local UAS surveys in quarries with complex morphology unfit for stereo extraction of terrain models. Proposed indicators should be properly weighted to obtain a single environmental risk assessment score: when integrated with other indicators related to biodiversity preservation and land cover changes, they might be useful in high level environmental monitoring and controls planning.

## 6 Conclusions

A set of potential environmental impact and sustainability indicators for extractive activities in the Carrara industrial basin have been defined by integrating high resolution remotely sensed data, processed with s2p stereo pipeline to extract terrain models, with marble production and waste management datasets.

Two class of indicators have been established: the one related to quarry waste management (MCW/MQW) can be used in planning environmental monitoring and controls, while the other, related to MQW/MCW exploitation in the building materials' industry and land cover changes, is mostly intended for high level plans monitoring.

Integration in a web-based DSS of data and indicators useful in both production sustainability and environmental protection goals' monitoring over quarry areas in Carrara sub-basins is in progress: once the web-based DSS would be accessible to controls planners and decision makers, it could play a great role in increasing global sustainability of extraction activities.

**Acknowledgements.** The authors wish to thank the General Manager of ARPAT Quarries Spercial Project, dott. Gaetano Licitra, their colleague dott. Giovanni Menga for his precious contributions on MCW estimation from production data, and the local ARPAT services located in Pietrasanta and Massa for supporting the authors in planning and managing UAV sample surveys performed by the Department of Earth Sciences survey team of Florence University.

## References

1. Darwish, T., Khater, C., Jomaa, I., Stehouwer, R., Shaban, A., Hamzé, M.: Environmental impact of quarries on natural resources in Lebanon. Land Degrad. Dev. **22**, 345–358 (2011). https://doi.org/10.1002/ldr.1011
2. Sarraf, M., Larsen, B., Owaygen, M.: Cost of environmental degradation – the case of Lebanon and Tunisia. World Bank Environmental Economics Series, paper no. 97 (2004)
3. Haralick, R., Shanmugam, K., Dinstein, I.: Textural features for image classification. IEEE Trans. Syst. Man Cybern. **SMC-3**(6), 610–621 (1973). https://doi.org/10.1109/TSMC.1973.4309314

4. Xin, H., Zhang, L., Li, P.: Classification and extraction of spatial features in urban areas using high-resolution multispectral imagery. IEEE Geosci. Remote Sens. Lett. **4**(2), 260–264 (2007)
5. Bradley, F.: Marble quarrying – L'escavazione del marmo. Promorama (1999). ISBN 9788888761077
6. de Franchis, C., Meinhardt-Llopis, E., Michel, J., Morel, J.-M., Facciolo, G.: An automatic and modular stereo pipeline for pushbroom images. ISPRS Ann. Photogramm. Remote Sens. Spatial Inf. Sci. **II–3**, 49–56 (2014). https://doi.org/10.5194/isprsannals-II-3-49-2014
7. Poli, D., Remondino, F., Angiuli, E., Agugiaro, G.: Evaluation of pleiades-1A triplet on trento testfield. Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci. **XL-1/W1**, 287–292 (2013). https://doi.org/10.5194/isprsarchives-XL-1-W1-287-2013
8. Coeurdevey, L., Fernandez, K.: Pléiades Imagery. User Guide. Report No. USRPHR-DT-125-SPOT-2.0 (2012)
9. Liguori, V., Rizzo, G., Traverso, M.: Marble quarrying: an energy and waste intensive activity in the production of building materials. WIT Trans. Ecol. Environ. **108**, 197–207 (2008). https://doi.org/10.2495/EEIA080201
10. Vagnon, F., Dino, G., Umili, G., Cardu, M., Ferrero, A.: New developments for the sustainable exploitation of ornamental stone in carrara basin. Sustainability **12**(22), 9374 (2020). https://doi.org/10.3390/su12229374
11. Zhang, Q., Zhang, T., Liu, X.: Index system to evaluate the quarries ecological restoration. Sustainability **10**, 619 (2018). https://doi.org/10.3390/su10030619
12. Piccini, L., Lorenzo, T., Costagliola, P., Galassi, D.: Marble slurry's impact on groundwater: the case study of the apuan alps karst aquifers. Water **11**, 2462 (2019). https://doi.org/10.3390/w11122462
13. Dino, G., Chiappino, C., Rossetti, P., Franchi, A., Baccioli, G.: Extractive waste management: a new territorial and industrial approach in Carrara quarry basin. Italian J. Eng. Geol. Environ. **2017**, 47–55 (2017). https://doi.org/10.4408/IJEGE.2017-02.S-05
14. Nannoni, A., et al.: Innovative approaches for the sedimentological characterization of fine natural and anthropogenic sediments in karst system: the case of the Apuan Alps (Central Italy). Front. Earth Sci. **9**(2021), 1–16 (2021). https://doi.org/10.3389/feart.2021.672962
15. Bianco, I., Blengini, G.: An analytical and flexible approach for the Life Cycle Assessment of stone products. In: Proceedings SUM2016, Third Symposium on Urban Mining, 23–25 May 2016 (2016)
16. Capitano, C., Peri, G., Raimondi, C., Rizzo, G., Traverso, M.: Energy and environmental analysis of marble productive sites: "by phases" and "by single process" combined approach. Energy Procedia **148**, 1183–1190 (2018). https://doi.org/10.1016/j.egypro.2018.08.023
17. Capitano, C., Traverso, M., Rizzo, G., Finkbeiner, M.: Life cycle sustainability assessment: an implementation to marble products (2011)
18. Traverso, M., Rizzo, G., Finkbeiner, M.: Environmental performance of building materials: life cycle assessment of a typical Sicilian marble. Int. J. Life Cycle Assess. **15**, 104–114 (2010). https://doi.org/10.1007/s11367-009-0135-z
19. Capitano, C., Peri, G., Rizzo, G., Ferrante, P.: Toward a holistic environmental impact assessment of marble quarrying and processing: proposal of a novel easy-to-use IPAT-based method. Environ. Monit. Assess. **189**(3), 1–16 (2017). https://doi.org/10.1007/s10661-017-5825-6
20. Zabalza, B.I., Capilla, A.V., Aranda, U.A.: Life cycle assessment of building materials: Comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential. Build. Environ. **46**(5), 1133–1140 (2011). https://doi.org/10.1016/j.buildenv.2010.12.002
21. Mancini, R., Fornaro, M., Dino, G.A.: Impatto ambientale dei limi di segagione. Rapporto finale del Progetto Interreg-III (2005). http://www.naturalstoneinfo.com/download/interregIII.03.pdf

22. Torini, S., Bruno, P.: Piano Provinciale di gestione dei rifiuti speciali anche pericolosi. Volume terzo (2005). https://docplayer.it/20340276-Piano-provinciale-di-gestione-ii-stralcio-volume-terzo-dei-rifiuti-speciali-anche-pericolosi-legge-regionale-n-25-1998.html
23. Allegato, C.:Piano Regionale delle Attività Estrattive di recupero delle aree escavate e di riutilizzo dei residui recuperabili (P.R.A.E.R.) (2007). http://www.roccastradagovernodelterritorio.it/ambiente/caveminiere/praer%20cave/Allegato%20C.pdf
24. Kramers, R., Büther, H.: easyTools – risk assessment guidance book, report 2011/05. In: IMPEL, European Union Network for the Implementation and Enforcement of Environmental Law. Report adopted at IMPEL General Assembly in Copenhagen, 07–08 June 2012 (2012). http://impel.eu/wp-content/uploads/2014/08/easyTools_-Guidance-Book_-2012-06-21.pdf
25. Holzgraefe, G., et al.: Guidance for environmental and nature protection inspections of quarries and open cast mining in Natura 2000. In: IMPEL, European Union Network for the Implementation and Enforcement of Environmental Law. Report adopted at IMPEL General Assembly Meeting May 2018 (2018). https://www.impel.eu/wp-content/uploads/2018/06/FR-2017-19-1-Guidance-inspection-of-quarries-1.pdf