The use of Earth observation and decision support systems in the restoration of open-cast nickel mines in Evia, central Greece

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Abstract. We have developed a decision support system (DSS) for open mining areas which reflects and simulates the major decision steps of a mining expert (engineer, manager) during the formulation of a restoration plan. The software supports the mining expert to structure the various restoration alternatives and to explore both environmental and economic effects of the different measures. As key information layers we have included thematic maps derived from Earth observation (EO) data. The LARCO ferro-nickel mining area in Evia (central Greece) has been chosen as test site. EO can be used in the decision process by providing land cover and elevation information about the mine at various stages during its operation.

1. Introduction

Surface mining activities in Europe are estimated to occupy an area of 5–10 000 km² and range from large open-cast coal and base metal mines, to much smaller aggregate (rock, gravel and sand), industrial minerals (potash, clay) and building materials (granite and marble) quarries. Both national and European Union (EU) legislation demand a restoration plan before the mining activities start. In fact, most national governments as well as the EU have issued directives that require the restoration of mine sites to a semblance of their ‘pre-mining’ condition on the completion of mining activities. The planning and implementation of this task have traditionally been undertaken by ground-based surveys and augmented by aerial photography, which are both labour intensive and time-consuming, and hence costly, especially as regular updating is usually required.
Earth observation (EO) applications in the mining industry include the production of thematic maps for ground inspection and mineral alteration maps for exploitation (e.g. Goetz et al. 1983, Fraser 1991, Ferrier et al. 2002). Recently, the monitoring of reclamation activities by Landsat Thematic Mapper (TM) data also has been demonstrated (e.g. Schmidt and Glaesser 1998). In this paper we propose that the availability of several satellite-borne remote sensing instruments for EO allows for the collection of environmental and mine-related data for use in the planning and undertaking of mine restoration work on a frequent and cost-effective basis. The advantage of EO data is that the data are acquired digitally, they can be quickly and easily processed and utilized in various information formats. EO products include thematic, infrastructure, and mine-workings maps, as well as three-dimensional (3D) presentations of the mine site at various points in time and from various perspectives for visualization purposes.

1.1. Test site

Our study is designed to provide a decision support system (DSS) for the miner, LARCO SA, that is partly based on satellite remote sensing information. The system is developed to assist with landscape protection from the disturbances created by open-cast mine works (e.g. Almer et al. 1999, Llorens et al. 2000). LARCO is a leading mining and metallurgical company exploiting nickeliferous ore mines and lignite mines in Greece. The main activity is the extraction of approximately 17 000 tons of Ni per year in the form of FeNi. For this purpose, four rotary kilns, and five electric reduction furnaces are in operation at the metallurgical plant in Larymna, central Greece (figure 1).

The LARCO nickel mines are found on Evia island, about 70 km to the north of Athens (figure 1). Three mining sites have been studied in detail: Pagontas (38°40' N, 23°35'E), Sourtzi (38°39' N, 23°40'E) and Isoma (38°35' N, 23°43'E). The first two sites were used as test sites to construct the DSS, the third site was used as the verification site for the model. The latter site is the only operational mine today (exploitation started in 1983). The relief of the area is rugged with elevations ranging from 0 to 1500 m. All sites have good access through public and private roads by LARCO.

1.2. Geological setting

The LARCO mines are open-cast exploitations of stratiform deposits formed in the Lower Cretaceous, before the Cenomanian transgression. The deposit is a 1–40 m laterite overlying ophiolitic rocks (mainly basaltic lavas and peridotites). Thick, Upper Cretaceous limestones of the Pelagonian isopic zone overlay the laterite. At places, Neogene lacustrine beds cover the limestones unconformably. Scattered Quaternary top soils also occur. Neotectonic faulting has heavily fractured all rocks. Evia has been mapped by the Institute of Geological and Mineral Exploration (IGME), Athens (IGME 1981) at 1:50 000 scale, while LARCO’s geologists have mapped the area at 1:500 to 1:5000 scales.

Total production in Pagontas was 16 000 000 T of ore and 114 000 000 T of steriles (1970–1989), in Sourtzi 2 700 000 T of ore and 16 300 000 T of steriles (1969–1993) and in Isoma 4 800 000 T of ore and 32 700 000 T of steriles, respectively. The ore contains between 0.8–1.2% Ni.
Figure 1. Map showing location of study area in central Greece. Circles indicate the region of the LARCO nickel mines in Evia and Larymna, respectively.
(a) Training sites of 1986 Landsat-5 TM images (outside of the mining area)

(b) Training sites of 1991 Landsat-5 TM images (outside of the mining area)

(c) Training sites of 1997 Landsat-5 TM images (outside of the mining area)
2. EO data

EO data can be applied at different stages in the decision-making process for restoration. We used EO data on the following tasks:

1. to generate digital elevation models (DEM) of mines;
2. to classify for land cover; and
3. to monitor land cover change.

Two aspects of EO data use are of particular importance in restoration: (a) spatial resolution and (b) temporal coverage. For multispectral imagery we used Landsat TM imagery, which satisfies the temporal, but not the spatial, requirement of the end user. This is because the 16-day revisit time is about an order of magnitude more frequent than what is required by LARCO, while the 30-m pixel size is about an order of magnitude larger in order to map land use changes inside the LARCO mines. For panchromatic imagery we used KVR-1000 imagery, which provided adequate spatial resolution but not continuous coverage. For DEM construction we used B/W Système Probatoire de l’Observation de la Terre (SPOT) stereo pairs with 10 m pixel size.

Three cloud-free, spring to summer-time Landsat-5 TM images were processed to derive land use land cover maps. This was done to minimize Sun angle variation effects and keep shadow effects the same across all images. The TM acquisition dates were 22 May 1986, 29 June 1991 and 18 April 1997, all belonging to frame 183/033. All scenes were corrected for atmospheric effects using the ATCOR module (Richter 1996) and meteorological data supplied by the Greek Meteorological Service. All image processing was completed using PCI software on a Silicon Graphics platform. Supervised classification techniques were used to classify the TM imagery after careful selection of training sites in the field. The training sites were most suitable for the 1997 scene; however, they were easily projected back in time as most land cover types were the same. The training sites for classifying surrounding areas are seen in figure 2. Classes included urban types, inland water, vegetation types, pasture and bare rock. For classifying areas inside the mines separate training sets were used. A maximum likelihood classification result for the 1991 scene of the exposed mine surface can be seen in figure 3.

Digital processing involves spatial and thematic errors. Scene co-registration was done by using the image-to-image method where polynomial rectification was employed first on the 1986 image and rms errors were less than a pixel. Classification errors were also small due to (a) similar illumination conditions, (b) minimal anthropogenic activity in the region surrounding the mines, and (c) the radiometric stability of Landsat-5 (Thome et al. 1997). Three change detection maps were also constructed with the following sequence: 1997–1986, 1997–1991 and 1991–1986. In our case the pre-mining cover is forest and bare rock. The post-mining (restored) cover is forest and water (artificial lake). In figure 3 it can be seen that restoration has mostly failed inside both the Pagontas and Sourtzi mines because of the absence of vegetation and the presence of large areas of soil cover.

Figure 2. Location of training sites (colour polygons) used to produce the land cover maps of Pagontas and Sourtzi nickel mines in Evia, central Greece. Letters P and S indicate locations of Pagontas and Sourtzi mines, respectively. The mining areas have been masked out (black patches). Note progressive expansion of the mining activity from 1986 (top) to 1997 (bottom).
Field visits during 1997–1998 showed that slope failure was the main reason for bench collapse.

The KVR-1000 high-resolution camera is well known for its mapping capabilities (e.g. Jensen and Cowen 1999) and was carried aboard the COSMOS series satellites. It has a spatial resolution of 2 m and the scene size is 40 km × 40 km. The COSMOS series originated as a Russian military programme. The satellite flies in a low orbit of approximately 200 km altitude and the TK-350 and KVR-1000 cameras record their high-resolution images on panchromatic film, which is delivered by ejected canisters. The visible wavelength spans the range 0.49–0.59 μm. Due to the finite supply of film and of fuel for counteracting atmospheric drag, the mission duration is limited to about 45 days. On the KVR scene we digitized vector datasets such as roads inside the mines (figure 4(a)), position and width of exploitation benches, various buildings, etc., that were added to the DSS. In particular, the exploitation benches and the deposition sites can be located accurately at metre level. We found that KVR data can be used to map mine activity with great detail; however, no data continuity exists so that they may be used for monitoring.

A comparison with a thematic map derived from TM data can be seen in figure 4(b). The map was the result of maximum likelihood classification of all TM bands of the June 1991 scene. The scene was resampled to 5 m pixel size to enable a comparison with field data and the KVR scene. Three classes were defined that matched the KVR-1000 features satisfactorily. The classes were bedrock, dump sites and benches. No vegetation was detected inside the mine, which confirms what is visible from the KVR image, that is, no restoration had taken place as of the time of the TM scene collection. The statistics of this task are reported in table 1.

For the region outside the exploitation areas of the mine the topographic information was provided in raster form (DEM; figure 5) by automated stereomatching of a SPOT PAN stereo pair. The pair was obtained in winter
Figure 4. (a) High-resolution KVR-1000 panchromatic image of the Isoma nickel mine, Evia (Greece). The image was acquired in nadir view during 17 May 1992. Features such as exploitation benches and deposition sites can be located accurately at metre level. The red overlay is a vector layer showing the exploitation benches extracted with photo interpretation. The deposition sites are seen in the lower right as bright areas with fan geometry (see black arrow). The sites are composed of overburden material, i.e. no restoration has taken place. The dark area to the left indicates a pine forest. (b) Classified TM image of the Isoma mine. Three classes can be seen: dump sites (pink), roads and benches (brown) and bedrock (yellow).
1993 with a high B/H ratio and pixel size of 10 m. Other technical characteristics are given in table 2. Detailed processing including stereomatching is presented in Ganas and Athanassiou (2000). The vertical accuracy of the DEM was calculated using 60 checkpoints and the rms error was found to be 15.74 m. The reference heights originated from a cartographic 10 m DEM of 1990 obtained from the Hellenic Army Geographical Service (HAGS). The model satisfies the LARCO requirements for the surrounding areas; however, we found that inside the mine it was not possible to discriminate earth features and human-made features. The reason is the small size of the mines and the type of excavation.

3. The DSS model

The overall objective is to create an interactive tool based on EO that can be used as a DSS for surface mining restoration. The main restoration options are where to restore and what will be the new land use. We do not provide solutions for maintenance of the restored sites, as those are mostly related to soil chemistry or to microclimate affecting plant growth (e.g. Jim 2001, Ninot et al. 2001). The DSS

<table>
<thead>
<tr>
<th>Class name</th>
<th>Pixels</th>
<th>Area (m²)</th>
<th>Image (%)</th>
<th>Accuracy (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Road and benches</td>
<td>11407</td>
<td>285175</td>
<td>11.53</td>
<td>97.68</td>
</tr>
<tr>
<td>Dump</td>
<td>10085</td>
<td>252125</td>
<td>10.20</td>
<td>92.13</td>
</tr>
<tr>
<td>Bedrock</td>
<td>9655</td>
<td>241375</td>
<td>9.76</td>
<td>97.56</td>
</tr>
<tr>
<td>NULL</td>
<td>67754</td>
<td></td>
<td>68.51</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>98901</td>
<td></td>
<td>100.00</td>
<td></td>
</tr>
</tbody>
</table>

Table 1. Results of the maximum likelihood classification of the Landsat TM image of the Isoma mining area. Scene date is 1991. Null indicates surrounding area.

Figure 5. Intensity image showing the extracted DEM from the 1993 SPOT PAN stereopair. Increasing brightness indicates higher elevations. The box shows a large circular, dark-grey area where open exploitation was taking place and which is now filled with water. P indicates pagontas mine.
makes a comparison between different strategies based on multiple criteria supplied by the user (figure 6). The way to achieve this is the set-up of a framework for analysis (FFA; de Vente and Aerts 2000). The FFA is a framework for analysing and structuring policy issues. It consists of six steps reflecting the line of thoughts of a decision-maker working a decision for the ‘best’ alternative. Within the first step, the decision-maker is supplied with background information on the issues and the accompanying problems. In the second step, the main objective and the criteria necessary to measure the potential alternatives are formulated. In the third step, the decision-maker can select a set of measures (management options or ‘actions’) which together form a strategy. In step 4, a strategy is combined with external influences, i.e. economic developments. Then a strategy combined with a scenario is named a restoration case. In step 5, each case will be analysed against the predefined set of criteria. In this step, models using optimization techniques can be applied in order to find the optimal case. In the last step, all cases are evaluated in a table against the criteria. A similar structure of the DSS has been successfully implemented in hydrological projects (e.g. Aerts et al. 1999).

An important part of step 2 in the DSS is the possibility to apply weights to different criteria, since usually in decision-making not all the criteria are equally important. In step 6 the decision-maker can change the weights of all the criteria and the resulting scores are recalculated for each set of weights. In this way it is possible to determine the optimal strategy given certain criteria.

Table 2. Characteristics of the SPOT stereopair.

<table>
<thead>
<tr>
<th>Item</th>
<th>SPOT 1A 16 January 1993</th>
<th>SPOT 1A 4 February 1993</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scene identification</td>
<td>S2H1930116090905</td>
<td>S2H2930204094347</td>
</tr>
<tr>
<td>Scene centre latitude (°)</td>
<td>38.81528</td>
<td>38.81528</td>
</tr>
<tr>
<td>Scene centre longitude (°)</td>
<td>23.51472</td>
<td>23.83889</td>
</tr>
<tr>
<td>Angle of incidence (°)</td>
<td>R26.9</td>
<td>L28.9</td>
</tr>
<tr>
<td>Sensor</td>
<td>HRV PAN mode</td>
<td>HRV PAN mode</td>
</tr>
<tr>
<td>Scene size</td>
<td>60 km × 60 km</td>
<td>60 km × 60 km</td>
</tr>
<tr>
<td>Resolution (nadir)</td>
<td>10 m</td>
<td>10 m</td>
</tr>
<tr>
<td>Scene orientation angle (°)</td>
<td>008.3</td>
<td>014.4</td>
</tr>
<tr>
<td>Sun angle (azimuth)</td>
<td>157.3</td>
<td>164.2</td>
</tr>
<tr>
<td>Sun angle (elevation (°))</td>
<td>027.0</td>
<td>033.4</td>
</tr>
<tr>
<td>Time (GMT)</td>
<td>09:09:05</td>
<td>09:43:46</td>
</tr>
<tr>
<td>H0 (sensor height)</td>
<td>830297.2</td>
<td>830130.8</td>
</tr>
<tr>
<td>Angular separation R–L look (°)</td>
<td>55.8</td>
<td></td>
</tr>
<tr>
<td>Base/height ratio</td>
<td></td>
<td>1.05936</td>
</tr>
</tbody>
</table>

Figure 6. Chart showing the variety of restoration alternatives for open mining activities.
3.1. Restoration practices at LARCO mines

In open-cast mines two areas are of interest: the area where the exploitation–
excavation takes place (excavation site) and the location where the material is
deposited or dumped (dump site). Before open-mine exploitation starts, the
company acquires the necessary ground near to the ore deposit for depositing the
sterile material of the excavations. This is called the external deposition. The basic
criterion to select a dump site is to overlay a non-economically exploitable ore
deposit or the overburden (i.e. Cretaceous limestone). Other criteria include: (a)
distance from the excavation activity, (b) volume of the sterile material, (c) the
elevation difference between excavation activity and dump site, (d) the nature of
land cover of the proposed dump site (i.e. forest vs bare rock), and (e) the
availability of soil in the vicinity so that it may be used to overlap the proposed
dump site. After the end of exploitation the final slope surface (height 12 m, width
6–8 m) is covered with soil and planted with trees. Sometimes it may be necessary to
level the benches and/or lower the slope angle inside the mine; after the excavation
finishes an alternative restoration is to fill the ‘cavity’ with groundwater discharge
to form an artificial lake.

The critical parameter in creating dump sites is slope stability. The deposited
material is limestone fragments mixed with clay and sand. After reaching a critical
slope angle (\( \approx 45^\circ \)) the ground is converted to a flat surface by terracing. Then the
dump site is levelled every 6 m height to form a series of terraces. Each terrace has a
width of 6 m, as well. The surface is covered by soil of about 40 cm thickness and is
planted with trees. After plantation the restored site is maintained (watering, etc.) at
regular intervals.

3.2. Steps 2 and 3: criteria, features and measures

The criteria for applying measures against restoration plans are:

1. cost of levelling of the dump sites;
2. area of restoration, i.e. hectares of a certain land use. For the LARCO sites,
   there are four available land use types to restore the area. These land use
types are: forest, pasture, lake, bare ground; and
3. the alternatives for recreation potential expressed as (i) the need for national
   park status for the area, (ii) good road access to the neighbouring sites and
   (iii) presence of a lake.

The goal, objectives and criteria can be viewed in a hierarchical ‘decision’ tree
(figure 7). The inputs (including EO) to the model are called features. These are type
of land use, slope, aspect and road network. In our case only two features (land use,
roads) could be defined by using EO, therefore we used a cartographic DEM to
obtain elevation and its derivatives. The measures to change the features are:
levelling and terracing. Other measures to improve the quality of the restored area
in terms of the predefined criteria are: creation of road access, creation of national
park status and improved maintenance.

3.3. Step 4: constraints, strategies, analysis and evaluation

All geographical data obtained in the project are stored in one Geographical
Information System (GIS) database. The data include the external DEM (figure 5),
the land cover (thematic) maps, the geological map, the road map and the drainage
pattern. The database is connected to the DSS and forms the basis of a predictive landscape development model.

A restoration strategy is defined as a combination of different measures. The LARCO model is a raster GIS (ARCVIEW) using a cell size of 5 m² resolution. All chosen strategies selected in step 3 of the FFA are calculated in step 4 and scored on the criteria as formulated in step 2. First, the user has to select the area for restoration by taking into account several ‘constraints’ (figure 7). These are areas that will not be considered for restoration works because of the chosen strategy. For example, in the base strategy scenario those areas are constrained by (a) terrain characteristics such as steep slopes, or areas outside the exploitation area and (b) unfavourable wind direction which in the Evia mine area is north. This operation is a typical GIS processing step comprising sequential overlay procedures.

The constraints for the base strategy are:

C1 Aspect > 270° for dump sites (i.e. north-facing slopes are not for restoration)
C2 Aspect > 270° for exploitation (north-facing slopes)
C3 Aspect < 90° for dump sites (north-facing slopes)
C4 Aspect < 90° for exploitation (north-facing slopes)
C5 Region outside exploitation area (fixed)
C6 Region outside dump area (fixed)
C7 Dump slopes > 45°
C8 Exploitation slopes > 45°
C9 Lake areas

Figure 7. The flow chart of the DSS designed for LARCO SA. The user proceeds from left to right through the various steps before reaching the final decision on mine restoration.
3.4. Steps 5 and 6: base case (strategy) and restoration alternatives

The model starts with calculating the potential land use on the basis of the features of the area just after the exploitation has stopped. The features which determine the potential land use are slope and aspect. The potential land use is summarized in a base case (or base ‘strategy’) where only a minimal number of measures are executed in order to enhance the potential growth of land use. For example, a possible measure is to create a lake inside an excavation area until a user-specified elevation. The user may formulate other strategies which also take into account the economic aspect. Within step 5, all developed strategies will be displayed in one matrix against the criteria. All strategies will be compared to the base strategy. If a strategy is worse than the base strategy on a certain criterion, the cell of the matrix will have the colour red. If the score is better, the colour will be green. Also, by adjusting the weights applied to the different criteria, the user gets an idea on the sensitivity of different alternatives to those criteria.

After all measures are specified in the DSS the predictive landscape development model calculates first the new slopes and aspects and then creates new vegetation maps. The DSS calculates impacts in terms of hectares of new forest, shrubs or other land cover types. In addition, the costs of the different restoration strategies are calculated. The landscape structure can be visualized by 3D presentations.

4. Discussion and conclusions

Our DSS modelling could not be tested thoroughly against ground data because in two of the mines (Pagontas and Sourtzi) most of the terracing work on the dump sites was destroyed due to slope failure well before 1991 (figure 3). However, in the third, active, mine (Isoma) the study showed the strengths of integrating EO and GIS in a management information system (the DSS; figure 7). The EO data were useful to map the environmental structure of the Isoma mine area and its surroundings. The DSS was successful in modelling landscape restoration by (a) selecting dump sites at the same locations as those presented in the KVR scene (figure 4) and (b) applying correct measures such as terrace creation and tree planting, that were confirmed in the field.

The main problem we encountered was the multi-temporal mapping of land use and topography at cartographic scales 1:5000 or larger. LARCO managers need this information in their restoration plans inside the mine. Our EO data could not provide this information; however, we showed that by using KVR data we could provide part of this information for year 1992 (figure 4). The advent of IKONOS and QUICKBIRD sensors is going to fill the gap in this field by supplying good quality orthorectified image maps (e.g. Ganas et al. 2002, Lee et al. 2003). It will be feasible to produce regular maps at an advanced classification level including buildings, conveyor belts, detailed vegetation patterns, etc. Perhaps good quality DEMs (2–4 m pixel size) may also be constructed from IKONOS stereopairs (e.g. Li et al. 2002).

For the areas outside the mines the improvements introduced by the use of digital satellite imagery as opposed to the traditional methods (based on aerial photography and ground surveys) make simpler the analysis of the restoration (planning and monitoring). Furthermore, the use of multispectral imagery can supply very interesting information for restoration monitoring, which now is obtained only by large time-consuming ground surveys.

Our study showed that the integration of satellite imagery in a GIS of the open-cast mine is easy, due to the digital format of data, and facilitates the presentation
of results in two-dimensional (2D) and 3D perspectives. The 3D views of the mine site have special interest because they facilitate the observation of the restoration effects. This aspect is very important not only for restoration stakeholders, but also for environmental organizations. The end users appreciated the friendly environment of DSS methodology. This indicates that such products may soon be incorporated in operational activities of the mining companies.

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