USE OF REMOTE SENSING FOR MAPPING AND EVALUATION OF MINING WASTE ANOMALIES AT NATIONAL TO MULTI-COUNTRY SCALE

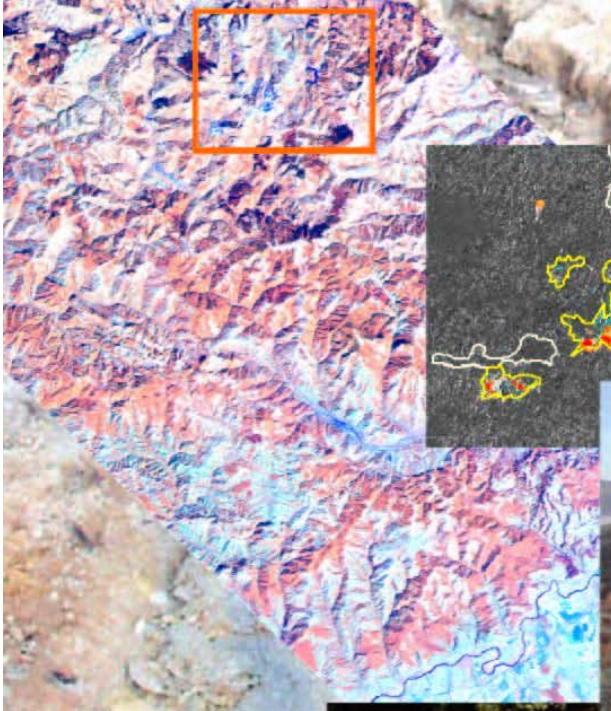
A Case Study to Integrate Remote Sensing Information with Thematic Data Layers and National Inventories on Mining Features in Pre-Accession Countries

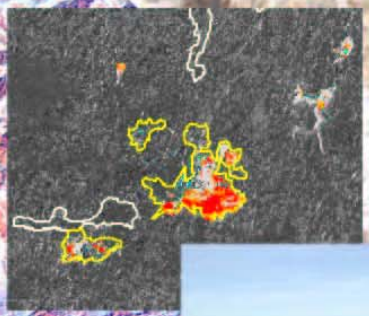
A Report of the JRC Enlargement Project

PECOMINES

INVENTORY, REGULATIONS AND ENVIRONMENTAL IMPACT OF TOXIC MINING WASTES IN PRE-ACCESSION COUNTRIES

A.M. Vîjdea, S.Sommer, W. Mehl





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PECOMINES

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FOREWORD

In the EU, mining waste is known to be amongst the largest waste streams and it ranks first in the relative contribution of wastes in many Central and Eastern European Countries. The European Environment Agency (EEA) reports that mining and quarrying wastes account for more than 20% of the total registered waste in Europe (EEA, 2003). These volumes bear substantial threats to the environment and the health of population, which has been highlighted by recent accidents, such as the Aznacollar spill of tailings sludge (Andalusia, Spain 1998) and the Baia Mare cyanide release (Romania 2000), affecting almost the entire Tisza river and the lower Danube.
Against this background, a new Directive on the management of waste from the extractive industries (COM(2003) 319 final) was proposed by the European Commission. It specifically focuses on the aspects of waste management, prevention of soil and water pollution and the stability of waste management facilities in a long term perspective covering the time span from licensing, to active operation, closure and remediation of mineral extraction sites
Presently no reliable synoptic picture of number, extent, distribution and emissions from mining waste sites exists; neither for EU member states, nor for the Accession and Candidate Countries.
At EU level, this information is needed to assess the large range of environmental impacts caused by mining wastes and their emissions in a coherent way across the different policies addressing the protection and sustainable use of environmental resources. A core task lies in the harmonised collection and standardised compilation and evaluation of existing data and in connecting them to a geographical reference system compatible with other European data sets. Consequently, knowing and being able to regularly up-date fully geo-referenced information on the surface distribution of deposited hazardous mining materials at national or multi-country scale and furthermore, discriminating between less critical materials and more hazardous types, e.g. capable of generating acidification, is considered a pre-requisite for drawing up risk based mining waste inventories.
In the approach proposed by the PECOMINES project, information from national registers of mining wastes is linked to related standardized spatial data layers such as CORINE Land Cover (the classes of mineral extraction sites, dump sites, etc.) or other data sets available in the EUROSTAT GISCO data base, thus adding the spatial dimension at regional scale.
Higher level of spatial detail and distinction between mineral extraction site and waste sites with or without accumulation of potentially hazardous material is added by remote sensing, applying a semi-automated principal component analysis (PCA) to selected spectral channels of geo-referenced Landsat-TM full scenes.
In this report this method is laid out in details and demonstrated on large areas covering approximately 120000 km^2 of Slovakia and Romania. An approach to validate the results of remote sensing data processing against mining-related features from Pan-European and national databases, detailed geological maps, mineral resource maps, as well as by a GIS analysis has been tested, showing the distribution of anomalous pixels in the above-mentioned features and in relation to the main land cover classes.

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The authors of this report would like to acknowledge the contributions of all PECOMINES team members including the Head of the Soil and Waste Unit Giovanni Bidoglio, Marco D'Alessandro, Tamas Hamor, Gyozo Jordan, Marc van Liedekerke and Erik Puura.
The excellent general IT support provided by the Land Management Unit's IT support team led by Michel Amsellem[a] strongly facilitated the extensive processing of large data sets including satellite scenes and European spatial data layers. The valuable ideas of Pierre Soille[a] and Javier Gallego[a] concerning novel image processing techniques and statistical analyses are highly appreciated as well as the data support of the EUSIS (European Soil Information System) team at the Soil and Waste Unit. The part of GIS processing benefited enormously from the advice, consultancy and help given by Alfred de Jager[a] to whom warmest thanks are addressed.

We gratefully acknowledge the contributions of the colleagues who helped in carrying out the validation/verification work described in this report. Special thanks go to Vladimir Sucha[b] for his time dedicated to fruitful thematic discussions, Nada Machova[c] for the Slovakian reference images used in geo-referencing, Monika Lipovska[d], Vlasta Janova[d] and Kamil Vrana[e] for the digital data on mining features of Slovakia, Marcel Suri[a] for information regarding the Slovak territory, Petru Stratulat[f], Seban Veliciu[g] and Iulian Seba[h] for information referring to the mining sites in Romania.

To all the colleagues mentioned above and to all the numerous others that in a way or another were helpful, but might have been unwillingly omitted, the most profound gratitude is expressed.

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a – Joint Research Centre
b – JRC Board of Governors
c – Slovak Environment Agency
d – Ministry of Environment of the Slovak Republic, Brastislava
e – HYDEKO – KV, Bratislava, Slovakia
f – National Agency for Mineral Resources, Bucharest, Romania
g – Geological Institute of Romania, Bucharest
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ABBREVIATIONS

5S	Simulation of Satellite Signal in the Solar Spectrum
AMD	Acid Mine Drainage
AMSS	Airborne Multi Spectral Scanner
ATM	Airborne Thematic Mapper
CCM	Catchments Characterization and Modeling
CLC	Corine Land Cover
CORINE	Co-ordination of Information on the Environment
DEM	Digital Elevation Model
DeMon	Desertification Monitoring
EC	European Commission
EEA	European Environmental Agency
ENVI	Environment for Visualizing Images
ERDAS	Earth Resources Data Analysis System
ETM	Enhanced Thematic Mapper
FPCS	Feature-Oriented Principal Component Selection
GCP	Ground Control Point
GIS	Geographic Information System
IGR	Geological Institute of Romania (Institutul Geologic al Romaniei)
IES	Institute of Environment and Sustainability
JRC	Joint Research Centre
LC	Land Cover
NAMR	National Agency for Mineral Resources
NDVI	Normalized Difference Vegetation Index
PC	Principal Component
PCA	Principal Component Analysis
PECOMINES	Inventory, Regulations and Environmental Risk Assessment in Pre-Accession Countries
RGB	Red Green Blue
SC	Steering Committee
SWIR	Short Wave Infra-Red
TM	Thematic Mapper
USGS	United States Geological Survey

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caused by accidentally deposited material can be solved by verifications with multi-temporal Landsat-Thematic Mapper images in order to determine if the material was left at the site for a short time period or has been accumulated for several years; a) Map of the mining anomaly index for a small inter-basin where temporarily some anomalous material was exposed; b) Landsat – TM image (3,2,1 – RGB); c) Anomaly image (OH-FeOx) image; d) Spectral profiles for two locations within the small dimensions inter-basin (3.1- FeOx-OH anomaly, 3.2 – no anomaly).

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EXECUTIVE SUMMARY

The JRC launched the PECOMINES project to conceptualize and demonstrate, on the territory of the new EU member states and candidate countries in Central-Eastern Europe, a standardized regional inventory of waste sites from mineral mining, taking into account the existing information systems about mining waste issues of the countries, which have been reviewed with the help of national experts (EUR 20868 EN, 2004).

Methods and Data Sets

Within the framework of this project a methodology for regional mapping of wastes from the extractive industry was developed, that was applied and validated on time-series of Landsat-TM satellite data covering large parts of Romania and almost entire Slovakia, two Candidate Countries with a long history in mining. The objective was to obtain a rapid screening of the distribution of mining wastes at country level, differentiating the sites, which have accumulations of material bearing the hazard of acidification due to the presence of mining waste and derived materials.

The method was primarily developed to use multi-temporal Landsat - Thematic Mapper images, which represent with their medium spatial resolution (30 m) a detailed but also a cost-effective mean for obtaining the distribution of mining wastes over large areas of Europe from national up to continental scale. Landsat-TM data have furthermore the advantage of a long time-coverage (since 1983, the launch year of the first Thematic Mapper sensor), making possible the detection of changes that occurred in the mining sites areas and the monitoring of the deposited material.

The independent remote sensing identification of sites, which are characterized by anomalous concentrations of both ferro-oxy-hydroxides (Fe-Ox) and secondary clay minerals (OH-CL) is based on selective principal component analysis (PCA) applied to geo-referenced Landsat-TM reflectance channels. Co-occurrence of both types of anomalies is significantly indicative for most cases of waste material from metal mining or ore processing but also for other types of mineral deposits (e.g. lignite) where pyrite bearing material is frequently associated leading to acidification. This information is linked to existing relevant standardized spatial data layers available at European level, such as CORINE Land Cover, GISCO river networks and catchments, European Soil Database etc., thus extending the spatial dimension to the inventory of mining waste at regional scale.
The linkages between the various data layers and the flow chart of integrating them into a spatially coherent inventory are shown in figure ES-1. The specific rationale and detailed technical aspects of the implementation of the remote sensing approach are outlined in the following sections.

PCA applied to the remote sensing data is the variant “Feature-Oriented Principal Component Selection method – FPCS”, developed by Crosta and McMoore (1989), further modified by Loughlin (1990, 1991), which was adapted to the processing of full Thematic Mapper scenes in vegetated areas specific to the climatic conditions of Central and East European countries.
Its use for mapping mining wastes was inspired due to its applicability to exploration geology. The indicative anomalies obtained in areas of natural hydrothermal alteration

and acidification (acid rock drainage) are in principle reflecting the same mineralogical components than the ones being accumulated in mining wastes. The most relevant groups being iron-oxy-hydroxides (FeOx) and OH-bearing secondary clay minerals and sulfates, frequently associated with pyrite weathering.

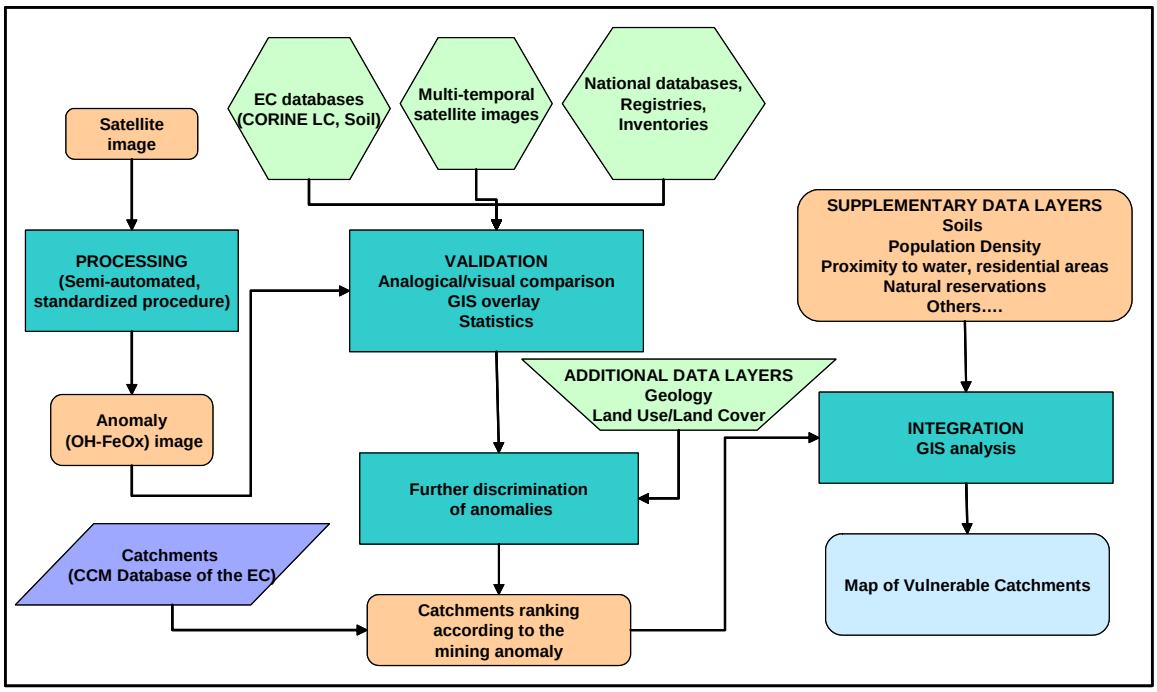

Figure ES-1 PECOMINES methodology for integrating remote sensing derived data with mining-related features

This led to the idea that this procedure can successfully map the areas of rock waste piles, tailing ponds, open-pits, where the exposed material is heavily iron-stained and frequently contains also OH-bearing secondary minerals indicative of processes of alteration and/or acidification. The superficial accumulation of these spectrally distinct minerals in waste materials is typically much bigger than in the case of natural occurrences of alteration minerals, which the exploration geologists are looking for. Therefore, Landsat – Thematic Mapper also has a strong potential to detect even relatively small mining waste deposits.

The chain of processing operations applied to full Landsat-TM scenes consists in:

- Geometric, radiometric and atmospheric corrections as described by Hill and Mehl (2003);
- cloud masking
- application of the FPCS method:
    - input selected bands separately for Fe minerals (TM 1,3,4,5) and OH-bearing secondary minerals (TM 1,4,5,7)
    - compute the principal components
    - examine the magnitude and sign of eigenvectors loadings in the characteristic bands: for Fe-bearing and other metallic cations (TM1 and TM3), for OH-bearing minerals (TM5 and TM7)
    - select the principal component which accounts for the strong blue absorption characteristic to iron oxy-hydroxides. Criterion: high loadings in both TM1 and TM3 and opposite signs.

- select the principal component which maps absorptions in TM7 as opposed to TM5, caused by vibrational processes involving the bond metal-OH. Criterion: high loadings in both TM1 and TM3 and opposite signs.
- level slice the selected components based on their statistics and histogram in four categories:
    - low (class1) represents the lowest brightness values, up to the "mean - 2 standard deviations (StD)";
    - low-medium (class 2) is the next interval containing most of the background values (inclusively the mean, mode and median);
    - medium-high (class 3) is the interval that follows, up to "mean + 2 StD";
    - high (class 4) represents the brightness values greater than "mean + 2StD".
- check the selected components against satellite image and ancillary data
- combine the final OH and Fe classes in an unique anomaly image classified by a matrix overlay of level sliced classes.

- validate by GIS overlaying with other relevant data sets (CORINE Land Cover, mining data of national registries and/or databases).

Generally two components (PC4 and PC3) were necessary for obtaining the final image highlighting iron oxides, including in this generic term also limonite, jarosite and goethite. For OH-bearing secondary minerals indicative of hydrothermal alterations, which are related to the genesis of many metallic ores in sulphides, possible generators of acidification, the single component PC4 was enough. By combining the FeOx-image with the OH-image it was possible to obtain a differentiation of the deposited mined material, the final map containing the areas strongly iron-stained with various amounts in OH-bearing secondary minerals.

The anomaly (FeOx-OH) image obtained by applying the FPCS method contains all combinations of Fe and OH classes. Colours were assigned to the combinations of interest, representing the highest level in iron oxy-hydroxides with all levels of OH (classes 4, 8, 12, 16 and 20, coloured in figure ES-2), as well as the second highest level in FeOx with the highest OH classes (output classes 15 and 19). The further analysis revealed that combinations of the 2 highest FeOx and OH classes are most significantly associated with mining features.

	FeOx class 1	FeOx class 2	FeOx class 3	FeOx class 4
OH class 1	1	2	3	4
OH class 2	5	6	7	8
OH class 3	9	10	11	12
OH class 4	13	14	15	16
OH class 5	17	18	19	20

Figure ES-2 Combinations of FeOx and OH classes

The data sets used for validating remote sensing anomalies against inventory data of mining sites and wastes in the study area consisted in:

- site specific information provided by the national institutions partners in the PECOMINES project, harmonized through means of a specially developed questionnaire (EUR 20868 EN, 2004) and linked with the European standardized CORINE Land Cover database by means of an Access-based application. This refers to all 10 countries participating in the project and includes:
    - mining site identification and location (x, y) in geographic (WGS84) coordinates
    - type of mined commodity, status of the mine (active, temporarily suspended, closed) and production
    - geological characterisation of the mineral deposit (mineralogical composition, type of deposit, age, host rock, geological settings)
    - information/data about mineral processing and waste management
    - information/data about emissions and environmental impacts
    - references and/or metadata

  In some cases this information was supplemented with locations of sites for construction materials and old dumps from closed mines, provided by partner institutions from national databases and registries.

- Landsat-TM scenes covering large parts of Romania and almost entire Slovakia;
- Thematic maps at various scales (mineral resources, metallic minerals and fuels, industrial minerals, building materials, geology, topography etc.);
- Catchments boundaries and river network (CCM – Catchments Characterisation and Modeling Database of the European Commission);
- Other data layers of GISCO database (administrative boundaries, soil type etc.).

The areas in Romania and Slovakia where the remote sensing method was applied correspond to mining site locations for metallic ores, coal and industrial minerals operated in underground or as opencast mines. Some of the sites have a long history in mining, being known since Roman times. The geological setting is very diverse and also the origin of the deposits, from volcanic to metamorphic and sedimentary. The most important ore deposits are located in mountainous areas covered by dense broad-leaved or coniferous forests. The climate is very similar in these two European countries, temperate continental with cold winters and rather hot summers. On the plains and plateaus a varied agriculture is practiced, however open-pits for industrial minerals or coal mines are sometimes found in these areas of predominantly agricultural land use type. Quarries for construction materials are uniformly spread within all forms of terrain, being conditioned not only by the dimension of the reserves, but also by the access roads and facility of operation.

Results and Discussion

The results obtained by applying the method for mapping mining wastes on six Landsat-TM frames covering large areas in Romania and Slovakia were validated in two ways:
- a site specific validation by overlaying and comparing the anomaly images with each site mentioned in CORINE LC and/or in national databases taking into account also thematic data layers such as geology, mineral resource maps etc.
- a global statistical validation, by computing through means of a GIS analysis the statistical distribution of anomalous pixels in the major and most relevant CORINE land cover classes and in mining-related features of available national digital data bases.

Site specific validation in Romania

The selection of a large zone, covered by four Landsat-TM scenes, for applying the methodology in Romania was determined by the variety of the mineral resources existent there (non-ferrous, ferrous, industrial minerals, coal, construction materials) for which underground mines, open-pits and quarries, rock waste dumps, tailing ponds, smelters and plants for processing of ore concentrates are known. Some of the most representative mining sites are considered (Veliciu and Stratulat in *Jordan and D'Alessandro* eds., 2004) as presenting environmental problems due to:

- the equilibrium at the mechanical stability limit of some of their tailings deposits, constituting this way a potential source of pollution
- soil pollution by heavy metals (Cd, Pb, Zn, Cu) – for metal mining
- surface water pollution by mining waters – for metal mining
- gases and suspensions in the air – for coal mining

The problem of acid mining drainage is an important issue in Romania especially for the non-ferrous metal mining sector, as the major deposits have mineralization of Cu, Pb and Zn in the form of sulphides, associated with pyrite and marcasite. Generally these two are in big amounts, not separated by the milling and flotation processes, but deposited with the tailings, representing thus a high environmental risk of acidification and heavy metal contamination. Problems of this type have been reported in the mining zone of Maramures county, as well as for the opencast porphyry copper exploitation at Rosia Poieni in the Apuseni Mountains, two important representative areas for the mining industry of Romania.
The comparison of the FeOx-OH anomalies obtained in the investigated area with all available data and information led to the following observations:

- The applicability of the method for wide area screening of mining wastes was demonstrated by the fact that not only opencast mines and quarries of big dimensions can be pointed out on the remote sensing images, but even waste material deposited in the surroundings of underground mines, if the exposed surface is at least one pixel size (30 m). The cases in the Neogene volcanic area of East Carpathians in the Baia Mare region (Maramures county) for the underground mines of Pb, Zn, Cu ± Au, Ag situated in the Ilba-Baiut metallogenic district proved this by the small clusters of anomalous pixels confirmed by the detailed geological maps as rock waste piles.
- The possibility of differentiating between simple oxidized material and sites where there is a high probability of hazardous material causing acidification was demonstrated by verifications with national data. It can be quoted the

opencast mine for porphyry copper at Rosia Poieni, producing the most intense FeOx-OH anomaly. The environmental conditions of the site were confirmed by the country report of the Romanian partner institutions and numerous other studies carried out there. The FPCS method also pointed out in the region some other areas having the same type of intense anomalies, not included (due to the smaller size, less than 25 ha) in the CORINE database, but representing mining-related features belonging to the mines at Baia-de-Aries.

- In the case where the acidification was not an issue, as for the lignite open-pits in Rovinari coal mining basin from Oltenia (South-West Romania), where the environmental impact consists mainly in dramatic changes of the landscape, geo-mechanical phenomena, qualitative and quantitative modifications of surface and underground water and of air quality due to emissions of gases and suspensions, the results of the processed remote sensing data were again in good agreement with national data. The anomalies showed high content in ferro oxy-hydroxides, but low or moderate content in OH-bearing secondary minerals, inclusively in the areas corresponding to the power plant and its associated ash and slag dump. In a similar way appeared also the steel slag dumps of the smelter at Hunedoara, where furthermore, a large-area anomaly of the same type was located on the CORINE Land Cover polygon indicating the industrial unit and extended beyond its boundaries, pointing out heavy pollution on the 1992-image due to dust and particle emissions from the smelter.
- The applicability of the remote sensing based method for mapping tailing ponds was proved by the cases at Baia Mare (tailings processed for gold extraction) and Aghires (for kaolin sands). The anomalies obtained for the ponds areas are very intense on condition that water is not too deep. Deep water is highly absorbing the electromagnetic radiation and only shallow water mixed with the material in the pond produces anomalies.
- In monitoring the status of a mining site the use of multi-temporal Landsat – Thematic Mapper images in determining the conditions of the site at a certain moment was demonstrated for the sulphur opencast mine at Negoiu Românesc, Calimani Mountains. The anomalies rich both in FeOx and OH-bearing secondary minerals on the image dated 1989 suggested the idea (emphasized by the specific mineralogical composition of the deposit), that at that time there was some acidification at the site. On the image dated 1994 only oxidation could be noticed and after another four years the mine was definitively closed.

Site specific validation in Slovakia

Slovakia has a long history in metal mining. Nowadays, few metal mines are still in operation, but there are numerous active mines producing brown coal, lignite and industrial minerals (magnesite, barite, talc, gypsum, limestone, dolomite, kaolin, ceramic clays, bentonite, zeolites, salt etc.). The validation of the remote sensing method was confirmed by the co-occurrence of anomalous FeOx-OH pixels with mining-related features (mineral extraction sites, dump sites, industrial units representing smelters or ore processing plants) of CORINE Land Cover and/or locations of mines, sites for construction materials and old dumps from closed mines (provided by the Slovak partner institutions). The following observations were drawn:

- Interesting cases of co-occurrence correspond to the magnesite mines, their associated industrial processing plant and adjoining dumps at Jelšava and Lubeník, where there are known environmental problems caused by soil contamination with Mg and heavy metals due to emissions of large amounts of dust from magnesite processing (Jánová and Vrana in *Jordan and D'Alessandro*, eds., 2004);
- Other co-occurrence cases correspond to smelters (Rudňany, Krompachy, Ziar nad Hronom) or mining sites in the region of Spišsko – Gemersky Kras and Volovsk Vrchy, South of Spišská Nová Ves, where there are the mines of Novoveská Huta (Cu, U, talc), Rudňany – Poráč (Fe, barite), Slovenky (Cu), Smolník (Fe, Cu, Sb) and in the region of Stiavnicke Vrchy with the old mine for Au, Ag at Banská Štiavnica and the mines for quartzite, limno-quartzite and bentonite situated North of Stara Kremnička. In some situations there were also noticed other small clusters of pixels outside the boundaries of the CORINE polygons but in the vicinity of mining-related features and, depending on the geology of the zone and the respective land cover type it could be assumed that they represented deposited mining material.
- The type of output FeOx-OH anomaly obtained when using multi-temporal Landsat – Thematic Mapper images can give indications about the changes that occurred in time in the mining or related industrial area. An example of this type was the case of the dump at Rudňany smelter, where it could be observed a modification of the surface properties of the material in the dump between 1985 and 1992 manifested by a reduction of the intensity of the OH anomaly. Another one was the dump of Smolník that in 1992, two years after the mine was closed, was still showing anomalous pixels, but on the image of 2000, when it was remedied and completely covered by vegetation, no remote sensing anomaly could be detected.

Statistical validation

The global statistical validation was implemented for Slovakia. The CORINE Land Cover (CLC) classes used in the analysis consisted in the categories which are related to the features of the extractive industry, i.e. mineral extraction sites (class 131), dump sites (class 132) and industrial units (class 121 – since some of its polygons corresponded to smelters or other plants for mineral ore processing, sometimes having adjacent dump sites). Other land cover classes covering large areas of the Slovakian territory were recoded according to the CORINE nomenclature (CEC, 1993) and introduced in the analysis, being represented by:

- class 111 – continuous urban fabric
- class 112 – discontinuous urban fabric
- class 133 – construction sites
- class 2 - all agricultural areas
- class 31 – forest
- class 32 – shrub and/or herbaceous vegetation associations.

In addition data were used, which have been provided by the Ministry of Environment of Slovakia, representing point locations of active and historical mines, historical dumps and production sites of construction materials. In absence of mining perimeter coordinates the point coordinates were considered associated with a 500-m buffer for mines and open-pits, respectively 100-m buffer for the old dumps. The right selection of the buffer radius was confirmed by the GIS analysis performed between CORINE

and the national database, as well as by visual comparison. The results showed that 73 of 82 CORINE polygons of mineral extraction sites (89%) were intersected by the buffered mines and open-pits and 53% of the total area of this CORINE class was common to the buffered mining features. For the old historical dumps a buffer radius of 100 m was considered acceptable, as these dumps were generally not visible on the satellite images and often the distance between adjoining point coordinates was less than 25 m.

The number of anomalous pixels occurring in the land cover classes and buffered mining features was computed separately for every combination FeOx-OH of interest. The distribution of the anomaly classes for all analyzed features showed that:

- the highest percentage of anomalous pixels (of the total number of pixels in the respective land cover class) occurred in the case of CORINE dump sites and mineral extraction sites, followed by buffered locations of mines and sites for construction materials. The percentage could be even higher if it is taken into consideration the level of generalization in delimiting the CORINE polygons due to the imposed minimum mapping unit of 25 ha. This determined that sometimes, in order not to loose a feature, some other adjoining pixels had been also included in the CLC polygon.
- the anomaly classes 16 and 20 (figure ES-2) representing the combination of the highest FeOx with the highest OH make up together the greatest percentage of the total anomalous pixels for the CORINE dump sites followed by CORINE mineral extraction sites and buffered mining sites (figure ES-3). The next place belongs to buffered sites for construction materials, then buffered historical dumps and CORINE industrial units. Therefore, it can be assumed that these two anomaly classes are most characteristic and of highest significance for the presence of critical mining features.
- the anomalies representing high levels in FeOx and low levels in OH (classes 4 and 8 in figure ES-2) are distributed almost uniformly in all land cover types, except for agriculture and construction sites where they are represented in their highest proportion. This indicates that predominance of iron oxides alone is not a clear indicator since exposed soil may also show a rich content in iron oxides as may be the case for construction sites, artificial surfaces made up of building materials where these minerals are also present.

Comparing the mining-related features of CORINE Land Cover with the sites provided by the Ministry of Environment in Slovakia it was seen that the CORINE mineral extraction sites are represented by open-cast mines for industrial minerals and coal. Metallic mines are mainly located in forests (class 31), or in different types of agricultural land (class 2), the open-pits for construction materials and the historical dumps having the same distribution. A great part of the CORINE mineral extraction sites are represented in Slovakia by open-pits and quarries for construction materials.

Taking this fact into account it was computed the distribution of anomalous pixels inside the buffers of mining locations that were falling in agricultural areas, forests and areas with semi-natural vegetation (class 32). The results showed that of the summed anomalous pixels in classes 16 and 20 found in forest areas or terrain covered by shrubs, grasslands and transitional woodland-pasture, 40% (respectively 22%) are located inside the buffered mining features. As the FPCS-based method was adapted in such a way as to avoid vegetation anomalies, the above observation leads to the conclusion that exposed anomalous pixels of classes 16 or 20 located in these

two land cover types and in a geologic background favorable for mineral resources most probably represent deposited material resulted from mining activity.

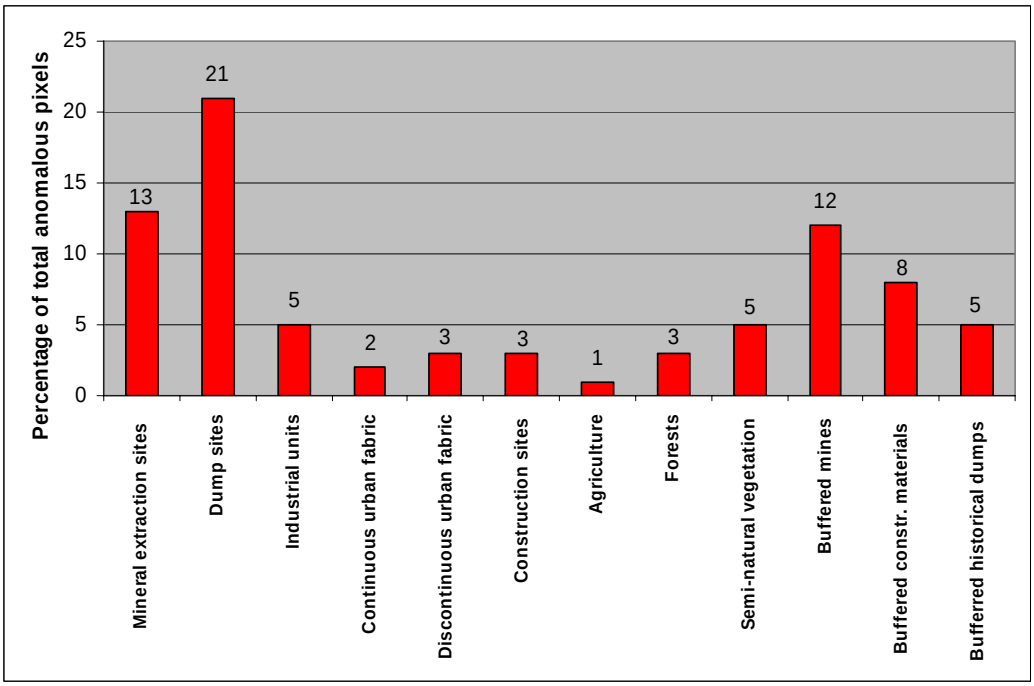

Figure ES-3Distribution of remote sensing FeOx-OH anomalies across various land cover classes and mining-related features

Conclusions and Further Developments

The study demonstrated the possibility of using Landsat – Thematic Mapper scenes processed with the PCA-based method in the FPCS variant for a rapid country-wide screening of location and spatial extent of deposited material from mineral extraction and processing. Extensive validation was performed by comparison with mining-related features from pan-European or national databases. The processing chain is principally independent of any external information about existing mining waste anomalies for calibration purposes. The mining-related features in the validation data set were successfully pointed out by strictly spectrally derived combined FeOx-OH mineral anomalies (i.e. significant mixtures of ferro-oxy-hydroxides and secondary layer silicates). This implies that the way in which the accumulated material in dumps or tailing ponds appears on the FeOx-OH image, depends on the mineralogical composition of its surface layer.

Test cases in the Neogene volcanic area around Baia Mare (East Carpathians) and at Rosia Poieni (Apuseni Mts.), proved the ability of the method to distinguish between simple oxidized inert material appearing also in open-pits and quarries of unaltered rocks (e.g. construction material production) and metal sulfide bearing materials imposing clearly higher potential of acidification and mobilization of toxic quantities of heavy metals. Also mixed pixels with substantial vegetation influence but having sufficiently strong FeOx spectral features are detected, which allowed identifying small waste rock piles associated to underground mining in mountainous areas of North-western Romania.

The statistical validation performed for Slovakia by equally confirmed the suitability of the method for mapping and differentiating the deposited mined material. The

mining features showed not only the highest percent match with total anomalous pixels, but also the greatest proportion in the anomaly classes indicative of potential hazard (16 and 20, rich in both FeOx and OH).
Based on the tested methodology a standardized GIS based procedure is proposed for further classifying the remote sensing anomalies according to risk assessment criteria, making use of all available mining-related data, land cover, geology, land use and multi-temporal satellite data (figure ES-4). The goal is the definition of a validated mining waste hazard index, enabling the estimation of the source potential to be used as input together with other data (soil type, proximity to urban areas and critical land uses etc.) in further vulnerability studies at river basement level.

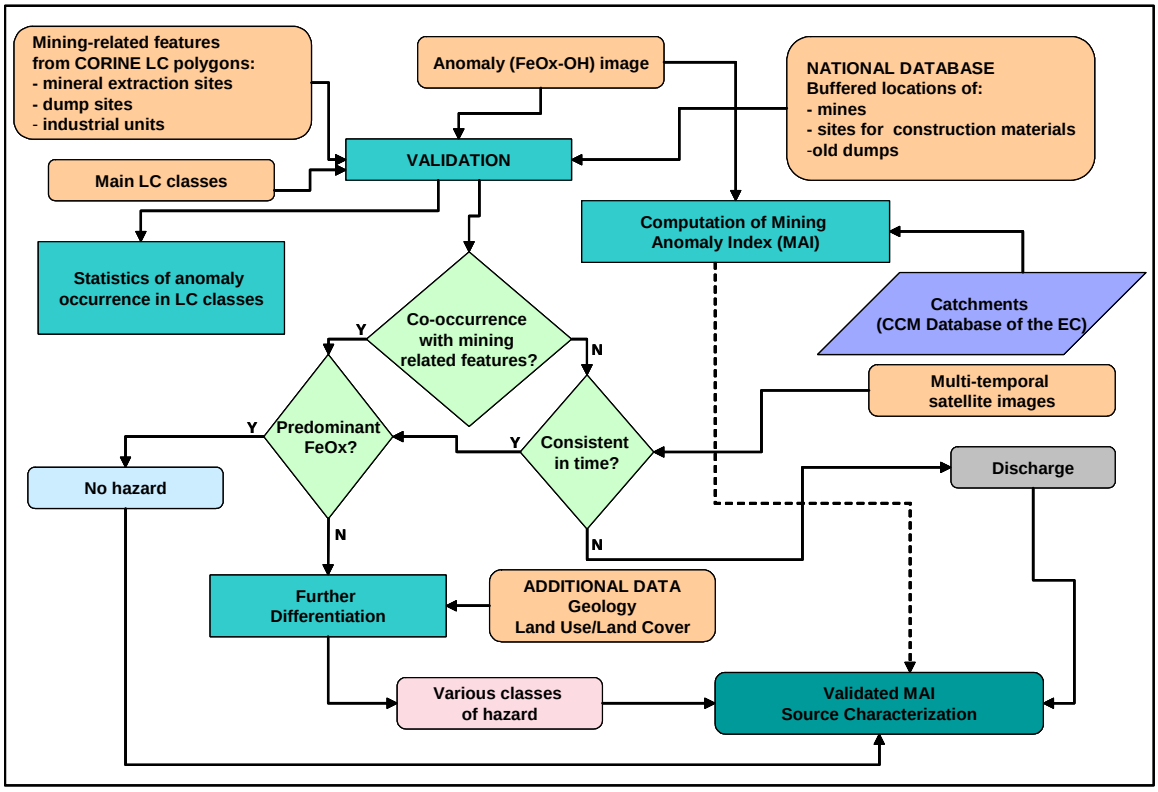

Figure ES-4 Processing chain for standardized validation and further differentiation of remote sensing FeOx-OH anomalies

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1. INTRODUCTION

The amount of waste produced world wide by hundreds of years of mining and quarrying operations is huge and it has massive impacts on the surrounding soil, surface and underground waters, air, influencing also species habitats and degrading the landscape. During the last 30 to 40 years, the increasing public concerns about the loss of environmental quality and its impact on human well being, increasingly raised awareness that the socio-economic need for mineral resources and the environmental problems posed by extracting and processing non-renewable resources need to be reconciled by applying sustainable management principles. This implies that the long-term effects of remaining waste deposits on the environment and human health has to be taken into account, both during mining operation and for long time after the end of mining activities.

Many of these historical waste sites have to be considered "orphan" sites, for which no liability can be assigned to former operators or any legal successor. Moreover, it is known from existing records but also from recent research projects, that this "burden of the past" in numerous cases may constitute a serious threat to the environment and human health (EUR 200661 EN, 2003).
Consequently, not only active mining, but also historical mining regions need to be reviewed carefully.

1.1. Objectives

According to the figures provided by EEA (Total waste generated by sector – EEA Countries, 1992-1997), mining and quarrying waste represents almost one third of the total waste (29%). In the most recent summary report of the Agency "Europe's environment: the third assessment" (EEA, 2003) it is stated, that for this type of waste in Europe the data "indicate a general decrease, which is in line with a reduction in mining and quarrying activity". However, closed but un-remedied mines can pose problems to the surrounding water and soil not by an increased amount of waste but by its specific nature. For instance acid mine drainage (AMD) caused by pyrite oxidation, by which iron sulfate and oxide minerals and in particular sulphuric acid are formed and set free in the water and soil and the mobilization of associated heavy metals represent a significant source of pollution. These effects do not only occur in metals mining but may even be significant where pyrite is just associated as minor mineralogical constituent, which is frequently the case for a wide range of deposits of technical and energy minerals. It is therefore crucial to know the location and spatial extent of the accumulations of hazardous materials related both to active mines and quarries, as well as to the closed ones.
This type of geo-referenced information would be needed in order to assess the large range of environmental impacts caused by mining wastes and their emissions in a coherent way across the different EU policies addressing for instance the protection of inland water (EU Water Framework Directive) and soil resources (EU Soil Thematic Strategy).
Hence, the core task lies in the harmonized collection and standardized compilation and evaluation of existing data and in connecting them to a geographical reference system compatible with other relevant European spatial data sets.
In this context remote sensing has an important role to play as independent source of information about extent, distribution and nature of mining waste, which allows for repeated up-dating and immediate integration with data from other sources for further

risk and impact analysis from the catchment to country level and across national borders.

1.2. The role of remote sensing within the PECOMINES project

The PECOMINES project has used operational remote sensing data (Landsat-TM) in its inventory and impact assessment work packages due to the following advantages:

- continuous coverage of large areas (one Landsat-TM satellite scene 180 x 180 km), allowing down-linking to and up-scaling from discrete point measurements. The Image 2000 mosaic of satellite images from the period 1999-2001 already exists for the entire European continent.
- digital geo-referenced output, facilitating in this way the combination with other thematic data in a GIS for validation and further analysis;
- multi-temporal dimension (high repetition rate), allowing change detection and site monitoring.

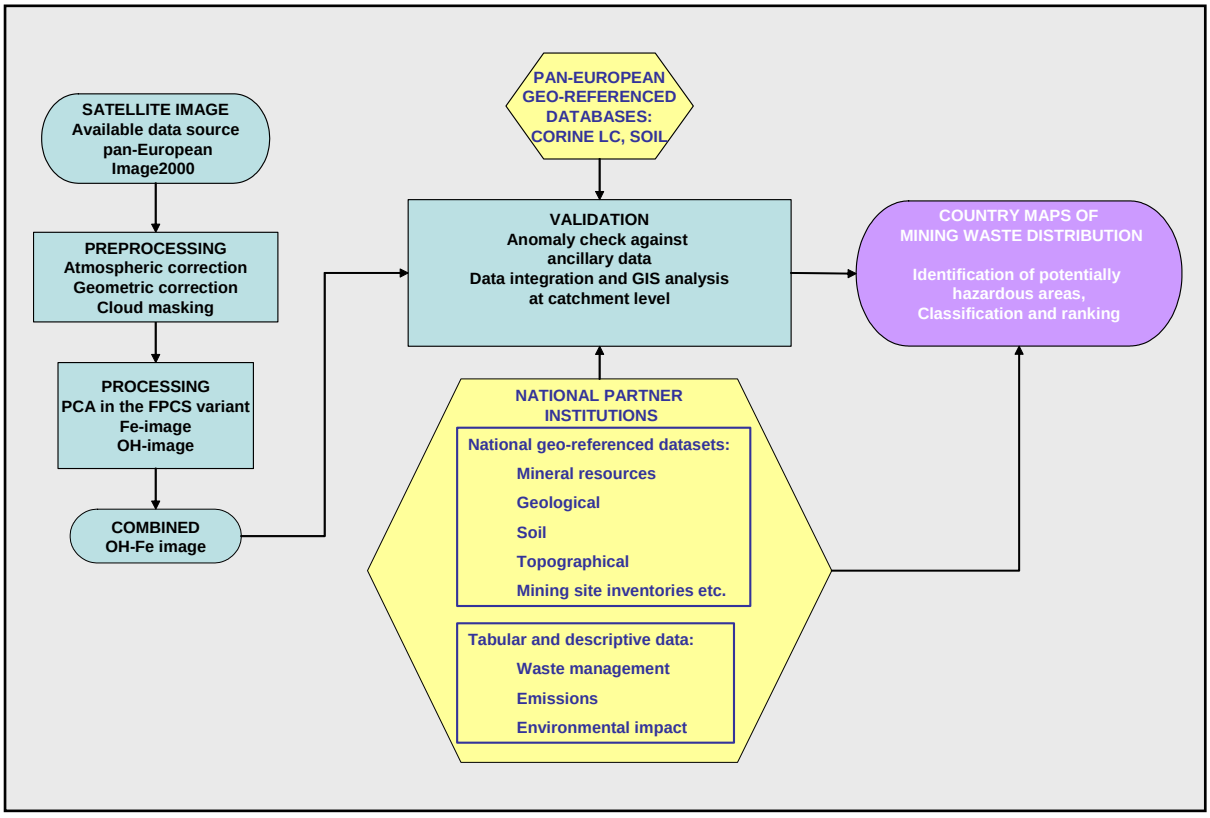


Fig. 1.1 Overview of PECOMINES methodology for remote sensing based large scale mapping of mining wastes

An overview of the operational processing chain of Landsat – Thematic Mapper images is presented in figure 1.1. The developed methodology resulted in fully geo-referenced identification and mapping of superficial mining waste deposits at local and national scale, based on spectral discrimination of key mineralogical components. It was possible to differentiate between accumulations of simple weathered material (enriched in iron oxides and hydroxides) and others where high concentration of secondary OH-bearing minerals co-occurred. These sites rich both in FeOx and OH minerals are significantly indicative for most cases of waste material from metal mining or ore processing, but also for other types of mineral deposits (e.g. lignite,

quartzite) where pyritic material is frequently associated, thus leading to acidification problems.

The preprocessing of the Landsat TM images consists of radiometric and atmospheric correction, geometric correction and geo-referencing and cloud masking. The thematic data processing is based Principal Components Analysis in the "Feature-Oriented Principal Component Selection" variant (FPCS) for obtaining the final FeOx-image and OH-image that lead to a combined OH-FeOx image.

This output anomaly (OH-FeOx) image offers geo-referenced spatial information on the distribution and type of accumulated waste material (simple common oxidation or co-occurrence of OH-bearing secondary minerals indicative of potential hazard, such as acidification). Its content is validated by cross-checking with site specific information from continental databases such as CORINE Land Cover, Soil, CCM (Catchments Characterization and Modeling Database of the European Commission), etc. or from existent databases in the Candidate Countries. Within the framework of the PECOMINES project the above mentioned information was provided by the national partner institutions in these countries by means of a filled in questionnaire and publications. Integration of all available data is needed in order to perform a statistical and GIS analysis at catchment level.

The final deliverables consist in country maps of mining waste distribution, which point out the potentially hazardous areas. Supplementary data regarding emissions, waste management practices and studies of environmental impact support these maps for a further classification and ranking of hazardous areas, as it is needed for the implementation of the proposed Mining Waste Directive.

2. PRINCIPLES OF THE METHODOLOGY

The methodology for regional screening of mining wastes takes advantage of the spectral characteristics of the minerals that are frequently found in the waste rocks and tailing ponds. Numerous spectroscopy studies have been made along time and the first big collection of minerals and rocks spectra in visible and infrared was due to the work done by Hunt and his collaborators in the seventies (1970, 1971, 1972, 1973, 1974). They explained the origin of the spectral features which are diagnostic for different classes of minerals, as well as their possible variations related to grain size, contamination with other components etc.

In the visible and near infrared range of the electromagnetic spectrum which coincides with that in which operates also the Landsat – Thematic Mapper sensor, the most common features in the spectra of minerals are due to: the electronic processes of metallic ions (the most frequently occurring being the ferrous and ferric ions) and to the vibrational processes of the anions (OH^-, CO_3^{2-}). These features characterize almost all mineral deposits and their associated facilities (waste rock dumps, tailing ponds etc.) and generally appear in different parts of the spectrum:

- in the visible, corresponding to Landsat – Thematic Mapper bands TM1, TM2, TM3, for the electronic processes;
- in the near infrared, corresponding to Landsat – Thematic Mapper bands TM4, TM5, TM7, for the vibrational processes.

The methodology of processing Landsat – Thematic Mapper images for rapid screening of mining wastes uses the Principal Component Analysis in a variant that points out the areas where the materials on the Earth surface exhibit these two specific types of spectral features.

2.1. Spectral features of mining-related materials

The main characteristic of the mining sites is the weathering of the surface of the exposed mineral material and the formation of iron oxides and hydroxides. This is a general phenomenon and is met almost everywhere in nature, as iron not only enters into the composition of many minerals, but it can also substitute for other cations in the crystalline lattice. The spectral features produced by the electronic processes involving the iron ions (Hunt in Siegal and Gillespie, 1980) can be summarized as:

- large absorption minima centered between 0.8 μm and 1.1 μm for Fe^{2+} due to the crystal field effects. The location (wavelength) and appearance of this feature varies among various minerals depending upon the crystalline field in which the ion is situated;
- absorption minima centered around 0.7 - 0.87 μm for Fe^{3+} due to the crystal field effects;
- other absorptions in the range 0.4 – 0.55 μm caused by the transitions of the ferrous and ferric ions in different crystal fields;
- steep falloff of the reflectance intensity (steep slope) towards the blue region of the electromagnetic spectrum due to the charge transfer absorptions. A very commonly observed feature, especially in the spectra of many weathered minerals and typical for the iron oxides and hydroxides (hematite, goethite, limonite), where it is responsible for their red colour.

These features are illustrated in the spectra presented in figure 2.1, where the position in the electromagnetic spectrum of Thematic Mapper bands TM1 and TM3 is also indicated.

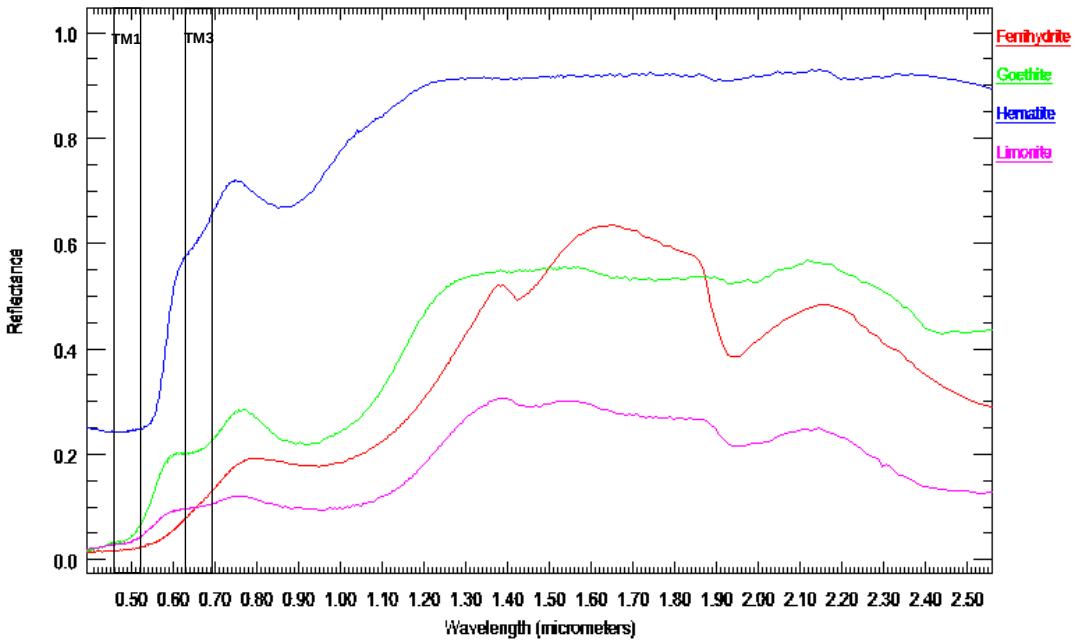


Figure 2.1 Diagnostic features in the spectra of iron oxides and hydroxides (source: ENVI spectral library - USGS). The difference in reflectance intensity in the wavelength range corresponding to Thematic Mapper bands TM1 and TM3 can be easily noted.

The other group of spectral features related to the mining materials identifiable on Thematic Mapper images are the absorptions caused by the vibrational processes involving the anion OH^-, present in the structure of very many minerals. In figure 2.2 there are shown for some minerals formed in different stages of hydrothermal alteration the spectral features produced by the vibration of the metal-OH bond.

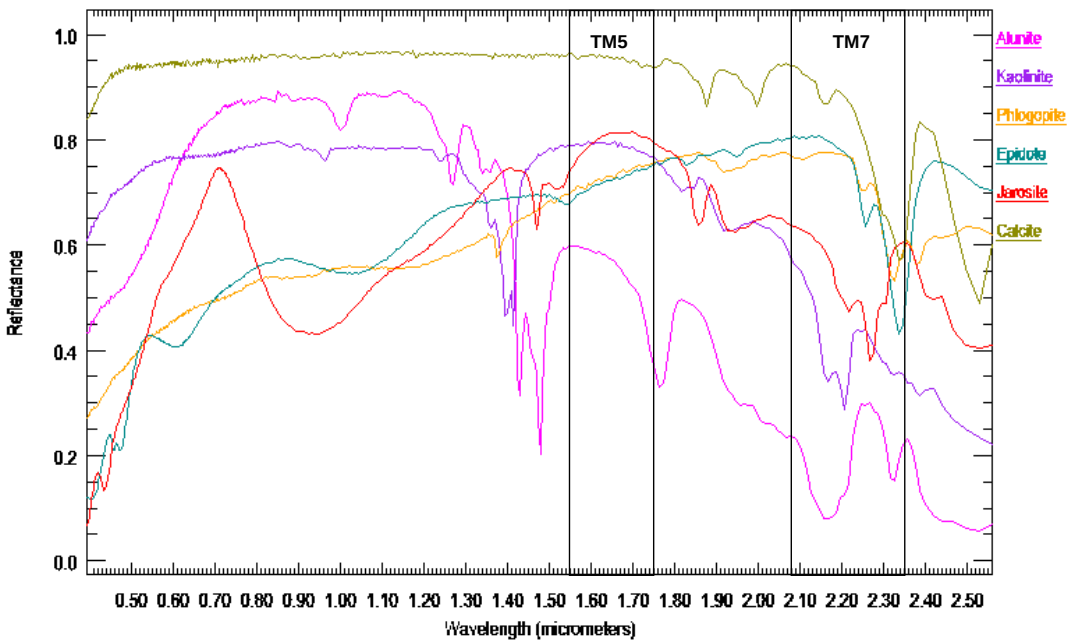


Figure 2.2 Diagnostic features in the spectra of secondary minerals formed by hydrothermal alteration (source: ENVI spectral library - USGS). Easily observable the lack of absorption features in the spectral window of TM5, while in the range of TM7 the respective minerals exhibit various absorption minima.

The absorption features that occur at different wavelengths in band 7 of the Thematic Mapper (2.08 – 2.35 μm) are caused by the vibrations of the bond Al-OH (for alunite, kaolinite), Mg-OH (for phlogopite), Fe-OH (for epidote, jarosite). Only few from the variety of OH-bearing minerals that possess spectral features in TM7 are presented in figure 2.2, but a rich literature exists for this field and numerous collections of spectra have been published or/and included in commercial image processing software packages (ERDAS Imagine, ENVI etc.). Further references on this topic can be found in the works of Hunt et al. mentioned above, Clark (in Rencz, 1999), to mention just a few.

In figure 2.2 it was included also the spectrum of calcite which presents absorptions in TM7 produced by the vibration of the anion CO_3^{2-}, due to the fact that:

- carbonates can also result from processes of hydrothermal alteration;
- limestones and dolomites extracted in quarries to be used as construction materials, ornamental rocks or for industrial purpose are ubiquitously spread and present in almost any country mineral resource inventories.

Generally the mining wastes (rock dumps or tailing ponds) are characterized by the presence of secondary minerals having vibrational absorption features and being also heavily iron-stained. Therefore, the methodology proposed for regional screening of accumulated mining material by use of medium resolution satellite images (Landsat – TM or ETM) employs these specific bands of the sensor where the objects of interest display distinctive spectral properties.

2.2. The Principal Component Analysis

The processing of the satellite images for large scale mapping of mining wastes uses the Principal Component Analysis (PCA), well known in image processing literature and also largely used for statistics studies. A variant of applying this method, namely the "Feature-Oriented Principal Component Selection" (FPCS), created by Crosta and McMoore (1989) and further developed by Loughlin (1990, 1991) takes into account only the bands of Thematic Mapper sensor that exhibit spectral features caused by Fe and OH bearing minerals. This method is described in chapter 2.3, herein a brief summary of the classical PCA processing method being done.

An important advantage of the PCA consists in the fact that the new principal component images are often more interpretable than the original data (Kaneko in Jensen, 1986). Another one is the fact that the informational content can be compressed in a fewer number of bands, thus reducing storage necessities and increasing processing speed.

Basically, PCA implies performing a linear transformation of the original coordinate axes of the data (multispectral vector space), into a new vector space where the axes are uncorrelated. Mathematically, this means that the covariance matrix in the new system is diagonal, having all elements equal to zero, except the first diagonal, where the elements (i.e. the variances of the data in the transformed coordinates) are in decreasing order. These variances λ_{ii} of the data in the transformed multispectral vector space (or principal components) are the *eigenvalues* of the covariance matrix. The covariance matrix E of n bands of data projected in the new vector space can be represented as:

$$\begin{bmatrix} \lambda_{11} & 0 & \dots & 0 \\ 0 & \lambda_{22} & \dots & 0 \\ 0 & 0 & \dots. & 0 \\ 0 & 0 & 0 & \lambda_{nn} \end{bmatrix}$$

where $\lambda_{11} > \lambda_{22} > \dots\dots\dots > \lambda_{nn}$

For obtaining this new matrix a special transformation should be applied to the original data, starting with the computation of the covariance matrix *Cov*:

$$\begin{bmatrix} \mathrm{var}_{11} & \mathrm{var}_{12} & \dots & \dots & \mathrm{var}_{1n} \\ \mathrm{var}_{21} & \mathrm{var}_{22} & \dots & \dots & \mathrm{var}_{2n} \\ \dots & \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots & \dots \\ \mathrm{var}_{n1} & \mathrm{var}_{n2} & \dots & \dots & \mathrm{var}_{nn} \end{bmatrix}$$

Similarly, the correlation matrix can be used. This is related to the covariance matrix by the relation (Richards and Jia, 1999):

$$\rho_{ij} = \frac{\mathrm{var}_{ij}}{\sqrt{\mathrm{var}_{ii}\,\mathrm{var}_{jj}}}$$

Where ρij – an element of the correlation matrix
var_{ij} – an element of the covariance matrix , i.e the variance between band *i* and band *j*.
var_{ii}, var_{jj} – variances in band *i*, respectively *j* (named also co-variances).

The eigenvalues and eigenvectors (that define the transformation to be applied to the data) are computed from the covariance matrix according to the following equation (Jensen, 1986):

$$EV\ Cov\ EV^T = E$$
$$[n \times n]\,[n \times n]\,[n \times n] = [n \times n]$$

where:
EV - the eigenvectors matrix
EV^T - the transpose of the eigenvector matrix
Cov – the covariance matrix of the original *n* bands of the satellite image
E – the new covariance matrix of the transformed *n* bands, a diagonal matrix meeting the condition stated above ($\lambda_{11} > \lambda_{22} > \dots\dots\dots > \lambda_{nn}$).

The first eigenvalue corresponds to the length of the major axis of the new ellipsoid in the vector spectral space (the new coordinate axis or the first principal component PC1), accounting for the largest variance in the data. Its direction is determined by the eigenvectors for the respective component. The second eigenvalue corresponds to the maximum length axis perpendicular (orthogonal) to the first component axis and

which accounts for the greatest variance in the data not already considered by the first principal component. The successive principal components are orthogonal to the previous ones and account for lesser and lesser variance in the data.

The percentage of total variance contained in each of the principal components can be computed as the ratio between the eigenvalue for the respective component and the sum of eigenvalues for all principal components:

$$percentage\ \nu_p = \frac{\lambda_p \times 100}{\sum_{p=1}^{n} \lambda_p}$$

The output data values in the new multispectral vector space (the new principal component images, sometimes called eigenimages) are obtained by applying to the initial data the principal components transformation matrix, which is the transposed matrix of the eigenvectors of the covariance matrix *Cov*. For a pixel at row *i*, column *j*, its value for component *p* can be calculated (Jensen, 1986) from the respective original values at the same row and column in band *k* (*k* = 1 to *n*) according to the formula:

$$Value_{ijp} = \sum_{k=1}^{n} eigenvector_{kp} Value_{ijk}$$

In some applications it is important to reduce the dimensionality of the data, therefore the first three principal components are preserved, since they usually contain over 98 % of the data variance. However, the higher order components can emphasize subtle spectral features that were not initially detected due to the high contrast of the original image (Faust, 1989).
The methodology for regional fast screening of mining wastes is based on these high order, low variance principal components, furthermore enhanced by a preliminary selection of the spectral bands where the materials of interest exhibit distinctive features.

2.3. The Feature-Oriented Principal Component Selection Method (FPCS)

This method was created by Crosta and McMoore (1989) with the purpose of using remote sensing satellite images for geologic exploration in an environment lacking bedrock exposure. The idea was to take advantage of the residual soils enriched in iron oxides as a result of the weathering of the sulphide ore body in a region in South-West Minas Gerais, Brazil. The authors tested several methods of image enhancement techniques (band composite combinations, ratios, differences, Principal Component Analysis) in order to assess which was more applicable for ore body mapping. When processing the data with the mentioned methods there were always taken into account the spectral bands of the Thematic Mapper sensor where the iron oxides showed specific features, capable of separating them from the spectral response of vegetation.
In the visible range of the electromagnetic spectrum, these bands were TM1 and TM3, since in TM3 the iron oxides have a raise in reflectance while the green vegetation has a chlorophyll absorption feature. Also the pair TM2 and TM3 can be used, but not TM1 and TM2, because there is a weak raise in reflectance of the iron oxy-hydroxides

in TM2 and also an apparent increase of reflectance of green vegetation caused by the two chlorophyll absorption minima (in the blue – TM1, respectively in the red region of the electromagnetic spectrum – TM3).
The eigenvectors expressed as percentages of loading from the original bands were analyzed in order to determine the principal components (PCs) in which the spectral features of iron oxy-hydroxides were manifested. This meant looking for high loadings in TM1, TM3 (or TM2, TM3) and TM5, TM7 from the short-wave infrared (SWIR). In these last two bands the iron-rich minerals can also be separated from vegetation due to their generally high and almost equal reflectance, while the vegetation has lower reflectance values in TM7 compared with TM5.
The signs of the eigenvectors in these bands helped to determine if the areas with high concentration in ferrous and/or ferric minerals appear on the images of the selected components (PC images) as bright or dark pixels. Image composites were made using three "iron oxides" PCs and the checking with ground data proved very good correlation.
From all methods tested and mentioned above, the PCA offered the best results and the method, called "Feature-Oriented Principal Component Selection" (FPCS), was took over by Loughlin (1990, 1991), who modified and developed it further. For the geologist that made exploration works in hydrothermally altered areas more important were the zones of subtle argillic alteration (with OH-bearing minerals) within large known areas, overlooked by former prospects. The zones with iron-staining occur almost on every outcrop, inclusively on sands and pebbles and on some disturbed soils. Therefore, the zones enriched in iron oxides associated with argillic alteration are those of interest for exploration, since they can reveal the presence of a prospective outcrop.
The modification introduced by Loughlin consisted in separating from the beginning the bands where different minerals (FeOx and OH-bearing) exhibit distinctive features in order to make the process of selecting the principal components easier and more straightforward. The examination of the eigenvectors for six bands of the Thematic Mapper sensor (in visible and infrared) leads always to several high-order principal components where FeOx and OH can be negative (or positive) or can have different signs. This renders the interpretation of PC images laborious, therefore the desire was to obtain only one image for FeOx and one for OH-bearing minerals. The solution to this problem consists in selecting as input for PCA from the beginning the bands where the minerals of interest (OH-bearing) show diagnostic features and excluding the bands where there were present spectral features of the other type of minerals (FeOx), in order not to map them too. This way there were used two sets of Thematic Mapper bands:

- for OH-bearing minerals: (TM1, TM4, TM5, TM7) or (TM2, TM4, TM5, TM7) or (TM3, TM4, TM5, TM7). Only one band from the visible region was used, anyone between TM1, TM2 and TM3.
- for FeOx minerals: (TM1, TM3, TM4, TM5) or (TM1, TM3, TM4, TM7). Only one band from short-wave infrared was used, anyone between TM5 and TM7. Band TM2 can be used in combination with TM3, especially if the objective is the mapping of hematite. However, TM2 is usually more noisy, therefore it was preferred TM1 together with TM3.

The method proposed by Loughlin examined the eigenvectors in the pair TM1-TM3 looking for the medium to high values and opposite sign. The PC for FeOx was the component with the highest magnitude satisfying this relationship. The sign of the respective eigenvector loading in TM3 determined if the FeOx image showed the

iron-stained pixels in dark or bright tones. If the sign was positive, the PC image was left as it was, because it was in accordance with the increase of the reflectance in these bands. If, on the contrary, it was negative, the corresponding principal component was also negated, as the zones of interest are more easily seen by the human eye if they are bright.
For the PC image of OH-bearing minerals the criterion consisted in examining the pair TM5-TM7 and looking for the highest values and opposite sign. If the eigenvector loading in TM7 was negative, the image was left unchanged, as OH-bearing minerals have strong absorption minima in this band, therefore will appear on the image as bright pixels. If it was positive, the image was negated for the same reason as stated above.
This way usually a single high order PC-image was obtained for FeOx and another one for OH-bearing minerals. In rare cases when two images were obtained (PC3 and PC4) it was recommended to perform firstly a Gaussian stretch of the data so that they had the same mean and standard deviation and then a pairwise PCA using these two stretched components as input. The final unique PC image for FeOx or OH was the component having positive loadings for both input bands.
The development introduced by Loughlin consisted also in obtaining a combined OH-FeOx image by performing a pairwise PCA of the Fe-image and OH-image and then displaying all of them together as RGB. The variant used by Loughlin and renamed by him the "Crosta method", was tested on both satellite (Landsat – Thematic Mapper) and airborne imagery (Daedalus AADS 1268 - ATM, Geoscan AMSS) on gold known and prospective areas from Nevada and Oregon, United States. It was confirmed by correct identification of known mineralized areas and it showed also other areas of subtle alteration in the vicinity of the known ones. Every anomalous pixel on a processed Thematic Mapper image was confirmed by several anomalous pixels on the airborne image.
The method was "fast, robust and reliable" and required only basic knowledge of mineral spectral properties and standard PCA software. It was tested using satellite TM images on other areas in the western U.S., southern Spain, the eastern Mediterranean, the Middle East and South America, demonstrating its wide application in arid and semi-arid terrain.

2.4. Application of FPCS for regional mapping of mining wastes

The method used successfully for exploration purposes was took over in order to be used for mapping mining waste on regional scale by means of the same medium spatial and spectral resolution satellite imagery (Landsat – Thematic Mapper). Due to the fact that the open pits, rock dumps and tailing ponds resulted from the mining industry occupy a much bigger area at the surface comparatively to outcrops used in mineral prospecting, their identification is easier on satellite images.
Generally, all the areas related to the extracted industry are characterized by the presence of iron oxides and hydroxides, which, as it was shown above, occur also as a thin rind on almost every outcrop, pebbles and sands deposits and on some disturbed soils. It is therefore necessary to discriminate between these universal occurrences and those which can be hazardous.
The acid mining drainage issue (AMD), an important environmental problem posed by the mining activity, is caused by the oxidation-weathering of sulphides containing heavy metals (Pb, Zn, As, Cd, Ag), a process which produces low-pH water mobilizing the heavy metals and transporting them by runoff into the neighbouring

streams and rivers. Pyrite is almost always found associated with other sulphides used as a metal source (Cu, Pb, Zn, etc.) and by oxidation in the presence of water and oxygen gives birth to secondary minerals (oxides, hydroxides, hydrated sulphates etc.), all containing ions of Fe and some of them also OH-bearing. Another source for their origin can be direct precipitation from the water transporting the soluble metallic ions. These secondary minerals (copiapite, jarosite, ferrihydrite, goethite, hematite) that characterize the sulphides waste rock piles are presented in an idealized model in figure 2.3 (Swayze et al., 1996). They can precipitate when the pH of water increases (due to a supplement of stream water) forming a streambed coating. The heavy metals precipitate together with the secondary minerals due to the capacity of substituting for Fe and can enter into their structures as constituents or can be adsorbed at their surface as contaminants. Later on, if there is a new reaction between unoxidized sulphides and water, the pH decreases again due to the newly-formed sulphuric acid and the secondary minerals are dissolved, remobilizing the heavy metals and transporting them further away into the catchment.

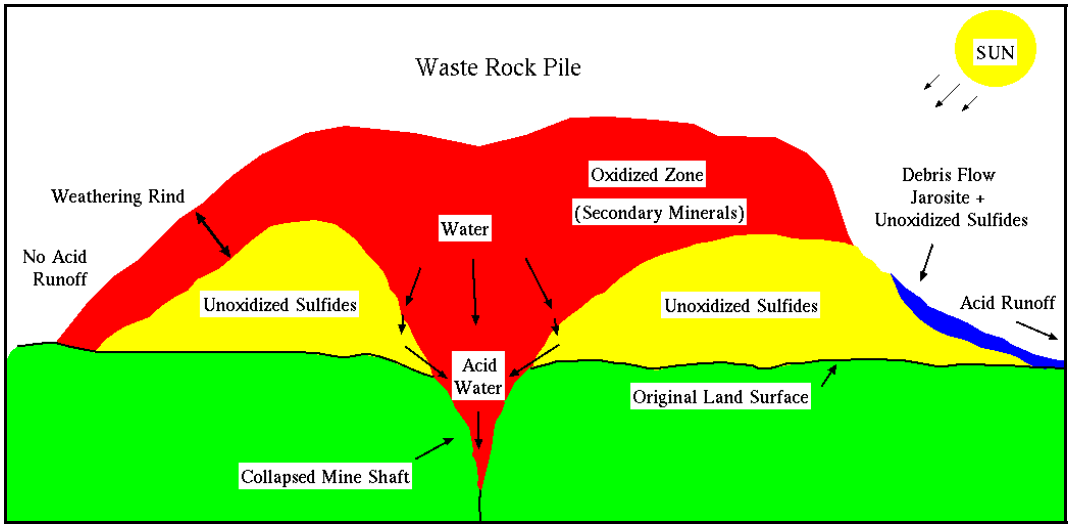


Fig. 2.3 General model of a sulphide waste rock pile (Swayze et al., 1996). Exposed sulphides are weathered/oxidized, forming acid water and secondary minerals that are transported on slopes. In favorable conditions the reactions start again, spreading out the low-pH water and heavy metals.

Sulphides oxidation, with pyrite (FeS_2) the major source of sulphuric acid is, as shown above, a complex cyclic chemical process, biologically driven by the presence of specific bacteria and where the pH of the environment plays a major part. Generally, the secondary minerals containing ferrous/ferric ions and sometimes also hydroxyl, formed in this complex chain of chemical reactions, can be mapped by satellite remote sensing due to the specific spectral features.
The methodology for regional mapping of mining wastes and separating amongst them those more hazardous (prone to acidification) consists therefore in:

- identifying the areas with high content in iron minerals (oxides, hydroxides, sulphates) by their spectral features in the visible range of the electromagnetic spectrum (using the different spectral response in TM1 - TM3, or TM2 - TM3);
- discriminating within these areas those with spectral features produced by the metal-OH bond in the infrared range of the spectrum (TM7). This type of

features are known to occur in jarosite, which is one of the minerals formed by pyrite oxidation and which is indicative for an environment with low pH (acidic), favorable to the solubility and mobilization of heavy metals.

The method takes over the development introduced by Loughlin to the method of "Feature-Oriented Principal Components Selection" created by Crosta and McMoore, that is the processing of satellite images has the purpose of obtaining one single PC-image for FeOx and one PC-image for OH-bearing minerals. One combined FeOx-OH image is afterwards produced, representing the final output.

The methodology was developed to be applied for entire satellite scenes (Landsat – Thematic Mapper) and the steps of the processing chain are summarized in figure 2.4.

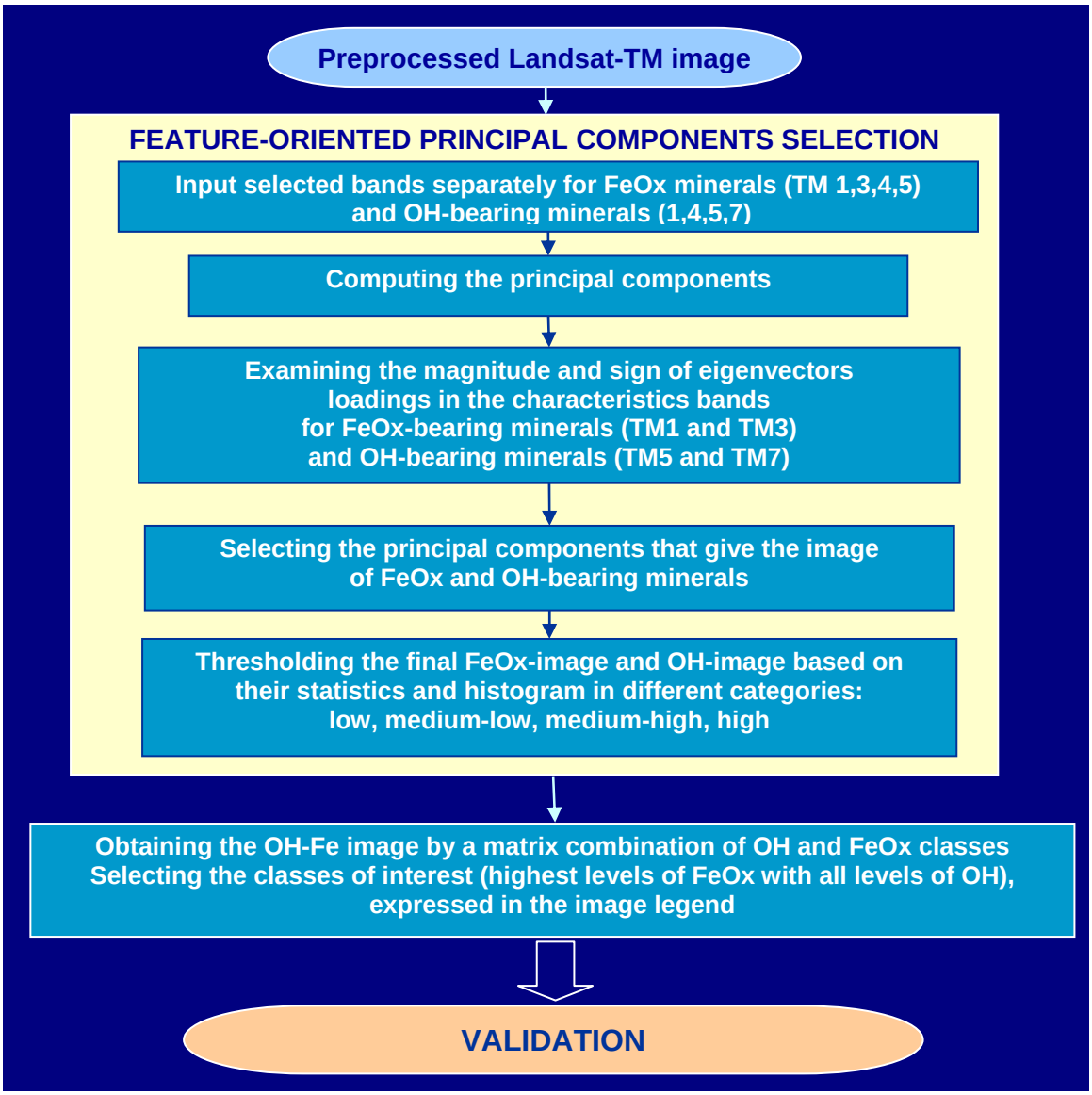


Figure 2.4 Remote sensing processing chain

An important pre-requisite of the Landsat - Thematic Mapper images to be employed for regional mapping of mining wastes is the preprocessing phase, imposed not by the FPCS method itself, but by the intended use of the images, inclusively the necessity of validating the results.

2.4.1. Preprocessing of Landsat – Thematic Mapper images

Prior to applying the FPCS method the Landsat - TM images should be radiometrically and geometrically corrected. Then, if necessary, a cloud mask needs to be applied in order to remove from the image statistics these zones.

2.4.1.1. Radiometric corrections

As a rule, the FPCS method does not require atmospheric or radiometric corrections (Loughlin, 1991) and this is applicable in the case of airborne scanner images too. However, for mapping on large areas, at country level or even entire continent, the wastes resulted from the mining activity, the processing has to be done on entire Thematic Mapper scenes, recorded at different dates and on different illumination conditions. It might happen also that a mining region falls in the overlapping area of two or more satellite scenes. Moreover, in order to monitor the mining waste sites and to detect the changes occurred in time, multi-temporal satellite images need to be used. A comparison for a site at different dates requires that the signal is corrected:

- for the different response of the satellite sensor (at-satellite radiance) during its lifetime due to the variability in the sensitivity of the detectors. These calibration corrections apply a series of coefficients (offsets and gains) to the digital numbers output from the detectors for each spectral band. The coefficients are available from experimental works performed in various remote sensing laboratories (Hill and Hostert, 1996).
- for the atmosphere characteristics that influence the propagation of the incident electromagnetic radiation and, after having interacted with the materials on the Earth surface, of the reflected radiation reaching the sensor.

Very many methods of compensating for the atmosphere-induced effects were developed along time by the remote sensing research community, each one having its own advantages and disadvantages. Within the framework of the PECOMINES project it was used a program previously developed at JRC and University of Trier (Germany) and successfully applied in the DeMon I and II projects. The program incorporates both types of corrections and uses a function of radiative transfer calculation based on a modified 5S model “Simulation of Satellite Signal in the Solar Spectrum” created by Tanré et al. (1990) with later improvements (Hill, 1993; Lacaze et al., 1996; Hill and Mehl, 2003).

Ideally it would be desired to compensate in the estimated ground reflectances for the topographic effects too. These represent variations of the reflectance of the same material on the Earth surface depending on the orientation (sun-lighted or not) and steepness of the slopes. This type of corrections is necessary especially in hilly and mountainous areas with high relief and requires a fine resolution Digital Elevation Model (DEM). The program described above incorporates also a module for taking into account the topographic effects using a method described by Radeloff et al. (1997). However, misregistration between DEM and imagery may introduce significant radiometric errors. Therefore it is preferable to refrain from use of DEMs of doubtful geometric quality.

For the PECOMINES project it was not possible to find a DEM of 25 m resolution covering such a big area as that used for testing and applying the methodology, therefore the radiometric preprocessing of the data was limited to data calibration and atmospheric correction, described in great detail in the quoted works and in a couple of remote sensing EUR publications. The importance of performing these corrections

prior of applying the FPCS method for mapping mining wastes resides in the possibility of comparing the detected anomalous zones on time-series Thematic Mapper images. There is no need to perform the PCA in the standardized variant (i.e. employing the correlation matrix) and it can be used, as usually, the covariance matrix.

2.4.1.2. Geometric corrections

As in the case of radiometric corrections, neither the geometric corrections are imposed by the FPCS method itself. Applying them to the Landsat – Thematic Mapper images is required by:

- the necessity to verify the results against existent digital databases, some of them already GIS-integrated at pan-European level, as CORINE Land Cover. Several categories from the latter (mineral extraction sites, dump sites, industrial units, bare rocks) were extremely useful for checking and validating the results, despite the fact that there are some limitations of the CORINE database (25 ha the minimum size of the mapping unit; inclusion in the same category of waste originated from various sources: mining, industrial, urban).
- comparing the results with other data at national level, more detailed (geological, topographical, maps of mineral resources etc.), available in digital form or not. Depending on the situation, the material made available by the members of the Steering Committee was scanned and geo-referenced (or simply re-projected) in order to facilitate the cross-checking and implicitly, the validation of the remote sensing anomalies.
- performing a GIS analysis at catchement level taking into account all available data in order to find, on statistical basis, the relationship between the obtained anomalies and the areas with accumulations of mining material.

Basically, applying the geometrical corrections to the satellite data means performing a linear (or polynomial) transformation of the image such that all the distortions present in it due to irregularities in the satellite platform motion are compensated and the data recorded become conform to a map projection. Each pixel in the new corrected image is characterized not only by its row and column, but map coordinates (meters, feet etc.) are assigned to it, according to the specific map projection used for referencing.

The procedure is described in numerous remote sensing books, inclusively in previous EUR reports, being already implemented in almost all commercial image processing software packages (ERDAS Imagine, ENVI, EASI/PACE, ER Mapper etc.). It is based on selecting some points in the image (named *ground control points*) easily recognizable (intersections of roads, rivers etc.) for which the exact map coordinates can be obtained from a map or other geo-referenced image. The input and output coordinates of all these points serve for computing the coefficients of the transformation to be applied to the image. This way every pixel is relocated from its original position to a new position, where the distortions mentioned above are corrected. The brightness values of the pixels in the new locations are then computed based on values in the corresponding adjacent pixels from the initial image, using from the standard methods of interpolation the one considered most suitable for the pursued objective.

In the PECOMINES project, for geometrically correcting the Landsat – Thematic Mapper images it was used a program developed at JRC (Hill and Mehl, 2003), which employs a procedure for selecting in a semi-automated manner the ground control

points, based on three initial GCPs and the cross-correlation computed between the image to be corrected (source) and a reference image (target) at selected roughly estimated coordinates. The program, called FINDGCP, has the advantage of speeding very much (almost six times) the tedious routine work of ground point recognition and selection.
In order to facilitate the cross-checking of the remote sensing anomalies obtained by FPCS method with the available data from national databases the geo-referencing of the images was done in the national projection of the country. The final output of each satellite scene can be mosaicked with its neighbours and/or re-projected for integrating the results at continental level.

2.4.1.3. Cloud masking

As the FPCS method is a statistically based technique, the eigenvectors loadings in the principal components can be considerably influenced by the presence of large areas (up to one quarter – one third) of clouds within the scene. This does not mean that the method cannot be applied or that the areas with high concentration in FeOx or OH-bearing minerals cannot be anymore pointed out on the principal components images. But the process of selecting the components based on the magnitude and sign of eigenvectors loadings in certain bands are not so straightforward, following the criteria described in chapter 2.3. It might happen also that the extension of the remote sensing anomalies to be reduced. It is a situation similar somehow to the case of applying the method in the field of exploration geology for detecting extensions of known mineralization. “The analyses are much more sensitive when the area for the determination of image statistics is carefully selected to avoid areas of well exposed alteration” (Loughlin, 1991).
Due to their spectral characteristics (difference in reflectance in the pairs TM1-TM3 and TM5-TM7) the clouds can be also mapped in the respective principal components and appear as anomalies. In order that time is saved in checking the output images against the original satellite data (and also ancillary data, when they are small and very similar to bright white areas of mineral extraction sites), the clouds should be masked as no-data values and excluded from the image statistics, prior of running the FPCS method.
Although cloud masking is an important issue for other applications too, for example vegetation estimation using NDVI, the problem was not yet entirely solved. Basically, a cloud mask can be made using a combination of NDVI and TM6 and this procedure was already tested for one Thematic Mapper scene within the PECOMINES project. The method was simple and the results were good for dense clouds.
It was also tested a cloud mask from a principal component image (using the bands 1,4,5,7 for mapping the hydroxyl features), selected by its highest loading in TM1. As with the previous method, the image to be used as a mask was thresholded for the areas corresponding to the clouds on a trial-and-error basis till all cloudy areas were covered. Care should be taken in both cases not to include also other areas that are not clouds but due to their spectral properties come close to those of very thin clouds. In this situation it is preferable to preserve the zones of interest, which can be just some of the mining related features, letting the thin clouds unmasked, but keeping this in mind in the interpretation process.
There are also more sophisticated approaches, as the method developed by Logar et al. (1998), with a neural network classifier. However, difficulties were also met when detecting very thin and transparent clouds. An algorithm capable of perfectly masking

all types of clouds, inclusively smoke and smog from industrial activity is not yet known in the remote sensing literature. It is therefore up to the user to decide when a cloud mask is necessary, what method to apply and how much time is worthy to be spent for further refining it.

2.4.2. Selection of FeOx and OH components for regional mapping of mining wastes

The possibility of using the FPCS method for regional mapping of mining wastes was inspired by the results obtained when the method was applied for exploration geology. The anomalies obtained in areas of mining activity led to the idea that this procedure can successfully map the areas of rock waste piles, tailing ponds, open-pits, where the exposed material was heavily iron-stained and sometimes contained also OH-bearing secondary minerals indicative of processes of alteration and/or acidification. The area covered by these accumulated waste materials is generally much bigger than in the case of outcrops and hydrothermal alteration features which the exploration geologists are looking for. For this reason they can be detected more easily on Landsat – Thematic Mapper images of 30 m pixel resolution.

When the method was applied for mapping subtle hydrothermal alterations in the Neogene volcanic region of Gurghiu-Harghita Mts. (East Carpathians, Romania) the limitations in areas with dense forest vegetation cover became evident. The satellite images have proved instead to be very efficient in identifying the mining activities. All the open-pits, waste dumps and tailing ponds were correctly identified on the Landsat-TM images processed with this method and it was possible to discriminate between extraction sites in hydrotermally altered andesites and quarries for unaltered volcanic rocks (andesites, dacites) used as construction materials (Vîjdea, 2000).

For the objectives of the PECOMINES project, the method was tested first for the purpose of detecting anomalous areas enriched in iron oxides and OH-bearing minerals related to the extractive industry on a scene covering North-West part of Romania (figure 2.5), path 185, row 27, available at multiple dates: 13.08.1988, 16.08.1989, 25.09.1992, 09.08.1998 and 22.08.2000. This scene will be used for exemplifying the way in which the Feature-Oriented Principal Component Selection method can be applied at regional scale for mapping the distribution and extent of waste sites from the mining industry.

In the area covered by the scene (approximately 32400 sq km) the relief is very diverse, from the Pannonic plain in the West with altitudes around 100 – 200 m, where the land use is agriculture (crops but also pastures) to the hills that make up a sort of link between the Eastern Carpathians in the NE of the image with altitudes up to 2300 m and the Northern part of the Western Carpathians where the heights are less than 1800 m. The vegetation consists mainly in deciduous forest and grassland, the higher mountains being covered by coniferous forests with alpine pastures and scarce vegetation on the most elevated peaks. The South-Eastern part of the satellite scene comprises almost a quarter of the Transilvania Plateau, the average height being around 500 meters. A diverse agriculture is being practiced there, crops but also vineyards and orchards. Within the scene there are also present several water bodies and the traces of human activity in the field of mineral exploration and extraction: waste dumps, tailing ponds and quarries.

The method was then applied on another three scenes in Romania (184/27, 185/28 and 184/29) and two scenes in Slovak Republic (187/26, 188/26) and the results were all similar. Comparatively to the case when the FPCS method was applied for

exploration geology, on image subsets of 512 X 512 pixels and in tropical and subtropical (Crosta and McMoore, 1989) or arid and sub-arid (Loughlin, 1991) climate conditions, mapping mining wastes at regional scale in this areas of Europe implied:

- use of entire satellite scenes (generally more than 8500 pixels on 9500 pixels after performing the georeferecing with 25 m pixel size – for compatibility with other data sources);
- existence of different land cover categories due to other types of climatic conditions for this part of the European continent.

All these factors are reflected in the statistics of the image, which determined the way of selecting the principal components for the FeOx and OH images.

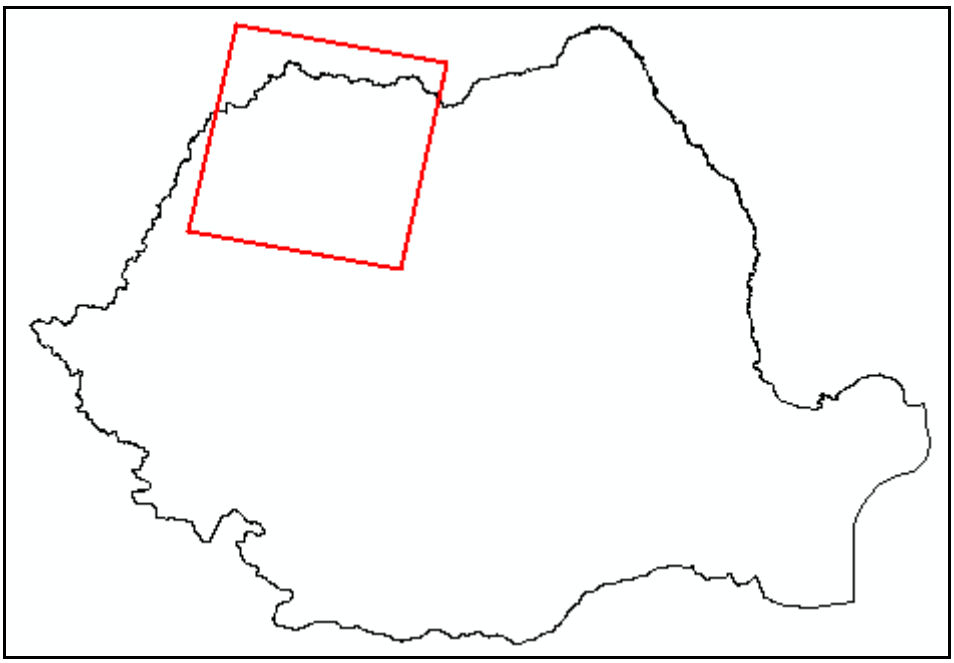


Figure 2.5 - Coverage of Landsat – TM scene in NW Romania used for describing and exemplifying the proposed methodology

The exemplification of the results obtained by applying FPCS method to the time series Landsat-TM scenes covering the area shown in figure 2.5 is done for the image dated 09-08-1998, after it was firstly atmospherically and geometrically corrected. The covariance eigenvectors for bands 1,3,4,5 (used as input for iron oxides) are shown in table 2.1a and the eigenvalues used for computing the respective variances in table 2.1b.

Table 2.1a - Eigenvectors matrix for TM bands 1, 3, 4, 5

	TM1	**TM3**	**TM4**	**TM5**
PC1	0.131	0.149	0.816	0.543
PC2	0.307	0.454	-0.551	0.630
PC3	-0.670	-0.487	-0.161	0.537
PC4	0.663	-0.732	-0.068	0.143

Table 2.1b - Principal components eigenvalues for TM bands 1, 3, 4, 5

	Eigenvalue	Variance (%)
PC1	4004.41	93.34
PC2	238.96	5.57
PC3	41.57	0.97
PC4	5.32	0.12
	4290.26	100.00

According to the criterion introduced by Loughlin (1990; 1991), the principal component having high or moderate magnitudes (in both TM 3 and TM1 and opposite sign) will show the areas enriched in iron oxides. If the contribution in TM3 is negative these areas will appear as the darkest pixels in the image. As the reflectance of iron oxides is higher in TM3 than in TM1, in order to have these areas shown in bright pixels (facilitating thus the visual inspection, image interpretation and correlation with other data sets) the image should be negated.

For the mentioned Landsat – TM image PC4 in table 2.1a meets these conditions and needs to be negated. The comparison of the image of this PC4 component with the sites of mineral extraction and dumps from the CORINE Land Cover database and with other data showing the locations of galleries, waste dumps and tailing ponds for metal minerals, open-pits and quarries for industrial minerals or construction materials (published geological maps of the Geological Institute of Romania, etc.) indicated that all these sites can be recognized on the image as bright pixels. For a better visualization the image of PC4, after negation, was stretched to 0-255 and level sliced into 4 categories: low, low-medium, medium-high, high. The level slicing was performed taking into account the histograms and the statistics of the PC4 image:

- low and high represent the mean minus, respectively plus 2 standard deviations (classes 1 and 4 in the legend presented in figure 2.6);
- low-medium is the next interval containing most of the background values (inclusively the mean, mode and median), corresponding to class 2;
- medium-high is the interval that follows, up to $\mu + 2\sigma$ (class 3). This scheme was kept for all time series images in order to be able to compare them.

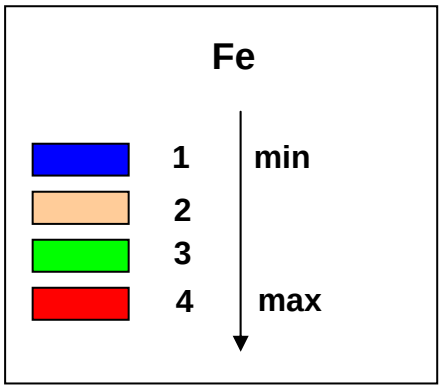


Figure 2.6 Legend of FeOx classes

Examining the satellite scene in its whole it was noted that all the above mentioned sites related to the extractive industry are indeed shown as the brightest pixels of the image, but unfortunately, in this way (red colour on the pseudo colour image) there

are represented also almost all agricultural parcels with bare soil (intense cyan color on 4,5,3 – RGB composites) that also have a rise in reflectance in TM3 compared to TM1. This is shown in figure 2.7a, the corresponding portion of the satellite scene being presented beside (figure 2.7b). Furthermore, pixels located in areas covered by alpine pastures at altitudes higher than 1400 m, where there are andosols and brown ferriiluvial podzols also exhibit high content in iron oxides (figure 2.8a). These soil types are described (Florea et al., 1971 in the Geologic Atlas of Romania, 1:1.000.000) as having the *Bfe* horizon (in which the mineral grain are covered by organic matter and iron oxides) with the upper horizon *A2* missing or very thin.

Component PC4 has the greatest loading in TM3 and also a big one in TM1 (of opposite sign) and it depicts correctly all the pixels in the scene having this increase in reflectance in band TM3 compared to TM1, but not all of these areas are of interest when the objective is detecting the zones with high amounts of iron oxides related to the accumulations of waste materials from the extractive industry. The latter categories (located in agricultural areas or on the top of the mountains) need to be eliminated from the inventory of the detected anomalous zones.

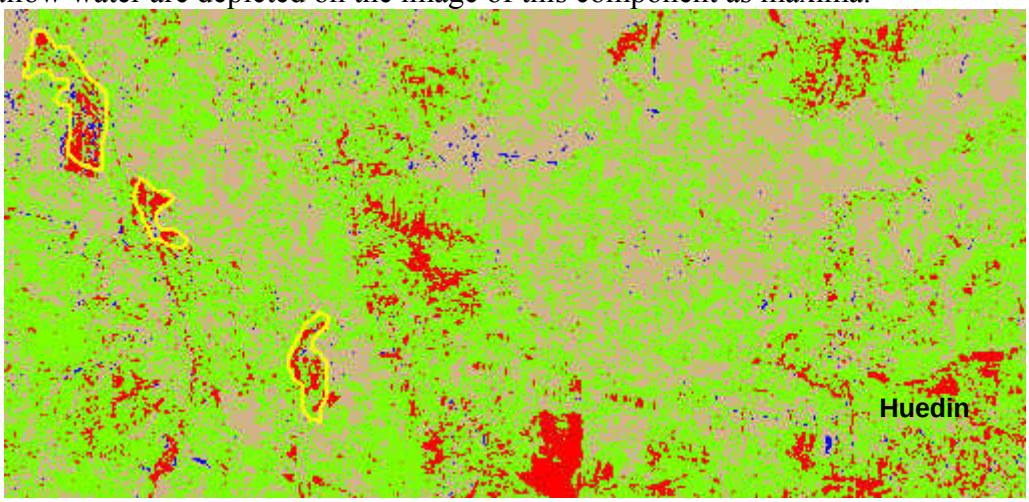
This thing was achieved by examining again the matrix of covariance eigenvectors (table 2.1a) and selecting from it another principal component (PC3), which had a loading of -0.670 in TM1, -0.487 in TM3 and 0.537 in TM5, being also capable of showing the areas enriched in iron oxides. This PC3 component was also negated in order to have the most reflective pixels in TM3 as bright pixels (similar to PC4) and its level sliced image (after stretching to 0-255) is presented in figure 2.7c and 2.8c.

In figure 2.7 it can be noted that PC4 shows as the most brightest pixels (in red) not only the quarries for extraction of dacites, but also the bare fields, whilst PC3 shows in red only the mineral extraction sites and some pixels in the Huedin locality (bottom right corner of the image), explicable by the metallic roofs of houses and concrete/asphalt surfaces. These materials have also the reflectance higher in TM3 than in TM1, being highlighted by PC4 too. Some other red pixels in the bottom left part of the PC3 image resemble in hue (on the 4,5,3 RGB image) the dacites deposits and it is very probable that they are smaller quarries that were not included in the CORINE databases as such because of their size smaller than the minimum mapping unit (25 ha). In the region many quarries have been opened along time depending on the necessities and closed when the reserves were exhausted (Pârvu et al., 1977).

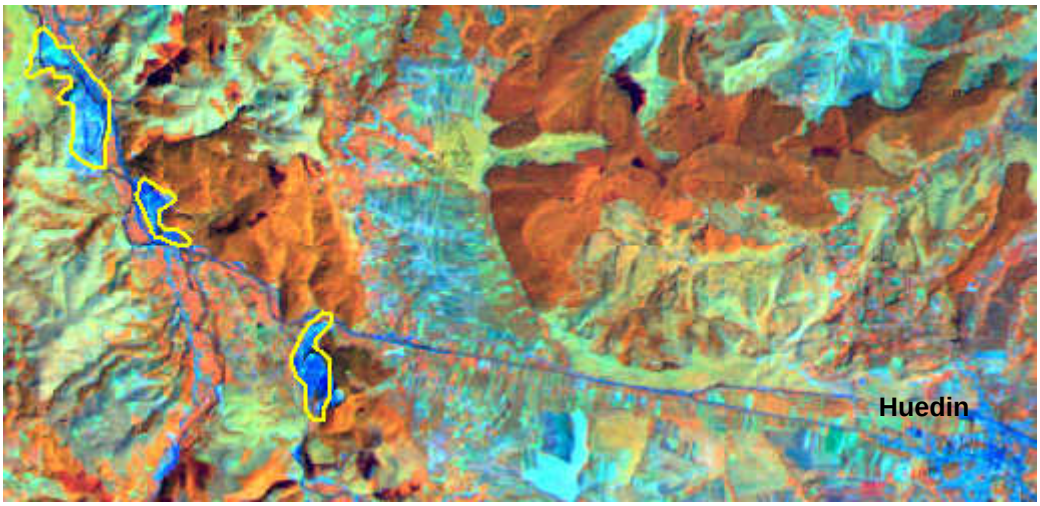
Another exemplification of the behaviour of PC4 component for the above mentioned scene is shown in figure 2.8 and it refers to the mining region of Baia Borsa. Comparing this image with the mineral resource map (Borcos et al., 1983) it was seen that PC4 component highlights the tailing ponds at Baia Borsa and other iron-enriched areas related to the mining industry as the brightest in the image (red colour), but also the alpine pastures around Toroiaga Peak in the upper right part of the image and the grasslands in its left bottom portion. The contribution of TM1 in PC4 is 0.663 and after negation water bodies, which have the highest reflectance in TM1 are shown now as dark pixels (blue colour). This fact explains the blue pixels corresponding to water on the surface of the tailing ponds in Baia Borsa and near Novat, as well as along the valleys Secu and Colbu.

Component PC3 highlights in red the exposed rock areas and it is fairly reasonable to assume that in this region where pyrite is present in all the deposits shown on the mineral resource map (Explanatory Notes; Representative Areas), being sometimes the main mined mineral, the iron oxides that were formed are transported on the valleys. The contribution of TM1 in PC3 is -0.670 and after negation water bodies are

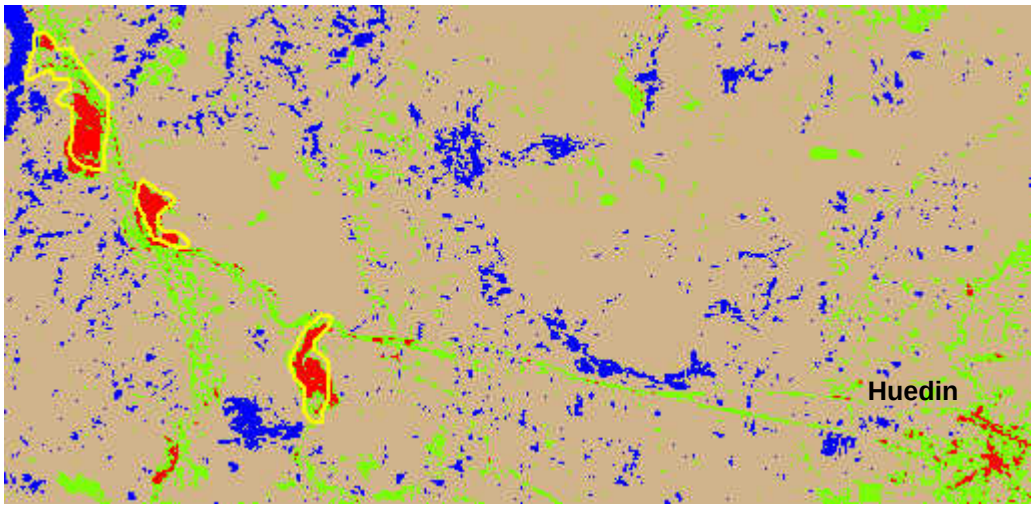
also shown in red. This determines that generally the water bodies and streams with shallow water are depicted on the image of this component as maxima.



a) PC4 image of TM bands 1,3,4,5

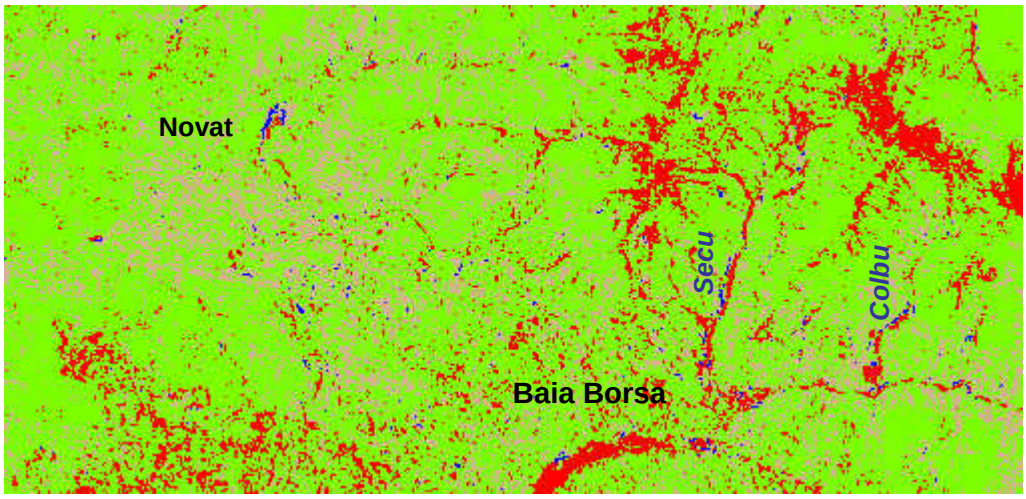


b) Landsat – TM image (4,5,3 – RGB)

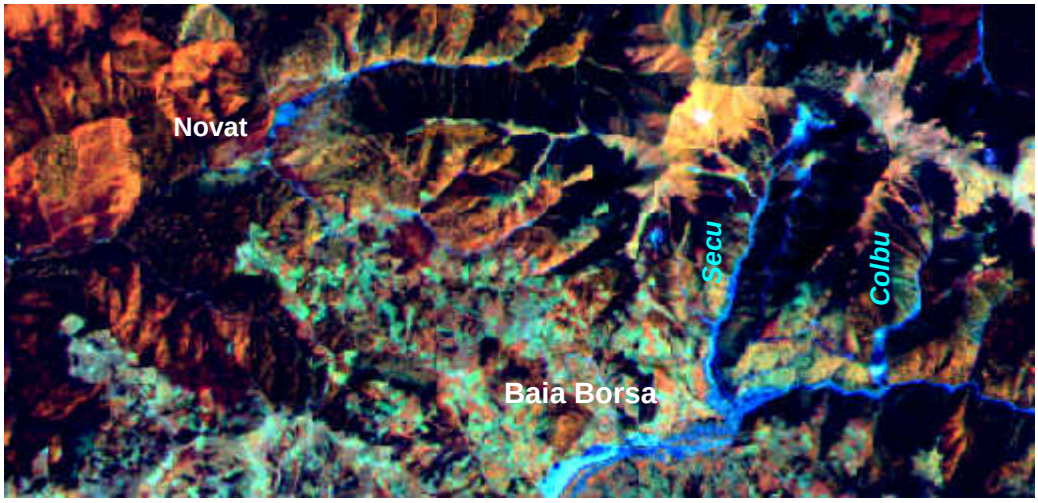


c) PC3 image of TM bands 1,3,4,5

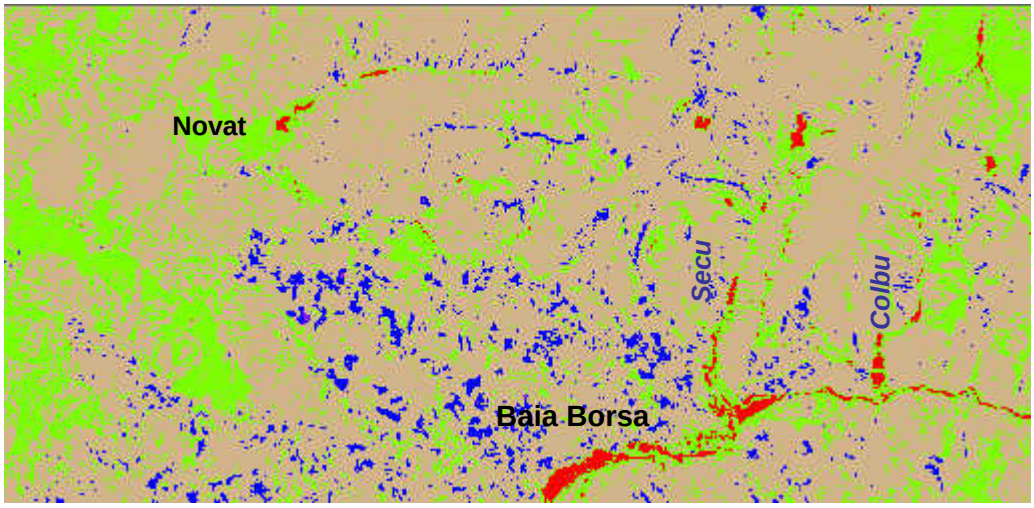
Figure 2.7 Three mineral extraction sites (dacites) at Poieni, Apuseni Mts., Romania, existent in the CORINE land Cover database, used as construction materials and ornamental rocks; a) PC4 image; b) TM 4,5,3 – RGB image; c) PC3 image.



a) PC4 image of TM bands 1,3,4,5



b) Landsat – TM image (4,5,3 – RGB)



c) PC3 image of TM bands 1,3,4,5

Figure 2.8 Baia Borsa mining region in the Maramures Mts., Romania, covered with coniferous forests, grasslands and alpine pastures, where several hydrothermal deposits for Cu, Pb, Zn, pyrite ±Au, Ag are known; a) PC4 image; b) TM 4,5,3 – RGB; c) PC3 image.

As it was shown, neither PC4 or PC3 alone was best in showing as anomalies only the areas with high concentration in iron oxides related to the extractive industry. Both components show indeed these areas of interest as anomalies (and they were both stretched and level sliced in the same way) and both present high loadings from TM1 and TM3, in different ways. PC4 showed as brightest pixels also the mixed pixels on grasslands and alpine pasture located on andosols, as well as almost every parcel of bare arable field (which indeed have a raise in reflectance in TM3 compared to TM1). PC3 showed as maxima all shallow water courses and bodies, as well as the clouds (which have a very high reflectance in TM1). Both components showed as maxima the areas with metallic roofs and concrete/asphalt in urban areas or industrial units.

For the purpose of identifying the areas with high concentrations of iron oxides related to the extractive industry it was necessary to perform a combination of the two components PC3 and PC4 which eliminated the undesired anomalies located on bare soils, scarce vegetation on alpine volcanic soils and water, while keeping all the detected zones of interest. The easiest way to do this was by a GIS overlay of the two pseudo-colour images, selecting as criterion in the output the minimum from the two. In this way the anomalous areas of iron oxides representing (compared against CORINE Land Cover database or national geologic maps, mineral resource map etc.) open-pits, quarries, rock waste dumps at the entrance of galleries, tailing ponds (all these represented as maxima in both components) were preserved and the undesired categories mentioned above were mutually compensated. Water was not anymore depicted as maxima, except shallow turbid water with sediments, which also presented a raised in reflectance in band TM3 compared to TM1. Zones of dense urban fabric and industrial areas (source - CORINE Land Cover database) still show up as maxima as these surfaces also have spectral features of this type.

Another representative example of applying the methodology described above is presented in the figures 2.9, 2.10, 2.11, 2.12, 2.14 and 2.16, which render a zone from the same Landsat – TM scene corresponding to the Neogene volcanic area near Baia Mare. The results are validated by verification with mining-related categories from CORINE Land Cover pan-European database and/or national thematic maps at more detailed scales. In this area there are numerous hydrothermal accumulations for base metal minerals, gold, industrial minerals, as well as quarries for unaltered volcanic rocks which, due to their physical-mechanical properties, are used as construction materials, ornamental rocks, etc. It was possible to obtain a separation between waste rocks and tailings from metallic minerals in deposits of hydrothermal origin and the quarries for unaltered rocks. This was achieved by making use of the final unique FeOx image computed from PC3 and PC4 as it was previously shown and the image highlighting the zones with high content in OH-bearing minerals, in a way going to be discussed herein.

The image shown in figure 2.9 comprises a large part of the Baia Mare city and its industrial zones, the Firiza lake to the North, the dumps at Tautii de Sus (a suburb of Baia Mare), and the mining site of Baia Sprie (Pb, Zn, Cu, Au, Ag in Pontian hydrothermally altered pyroxene andesites). At Tautii de Sus it can be seen at the left

the old dump (now vegetated), at the right the new one, which represents the central flotation where ore from the whole region is brought, deposited and processed. It is located nearby the industrial unit marked in the CORINE database. This zone was selected for presentation due to the variety of different categories present on a rather reduced areal extent (approx. 14 X 14 km), thus enabling the exemplification of these features in the computed PC images.

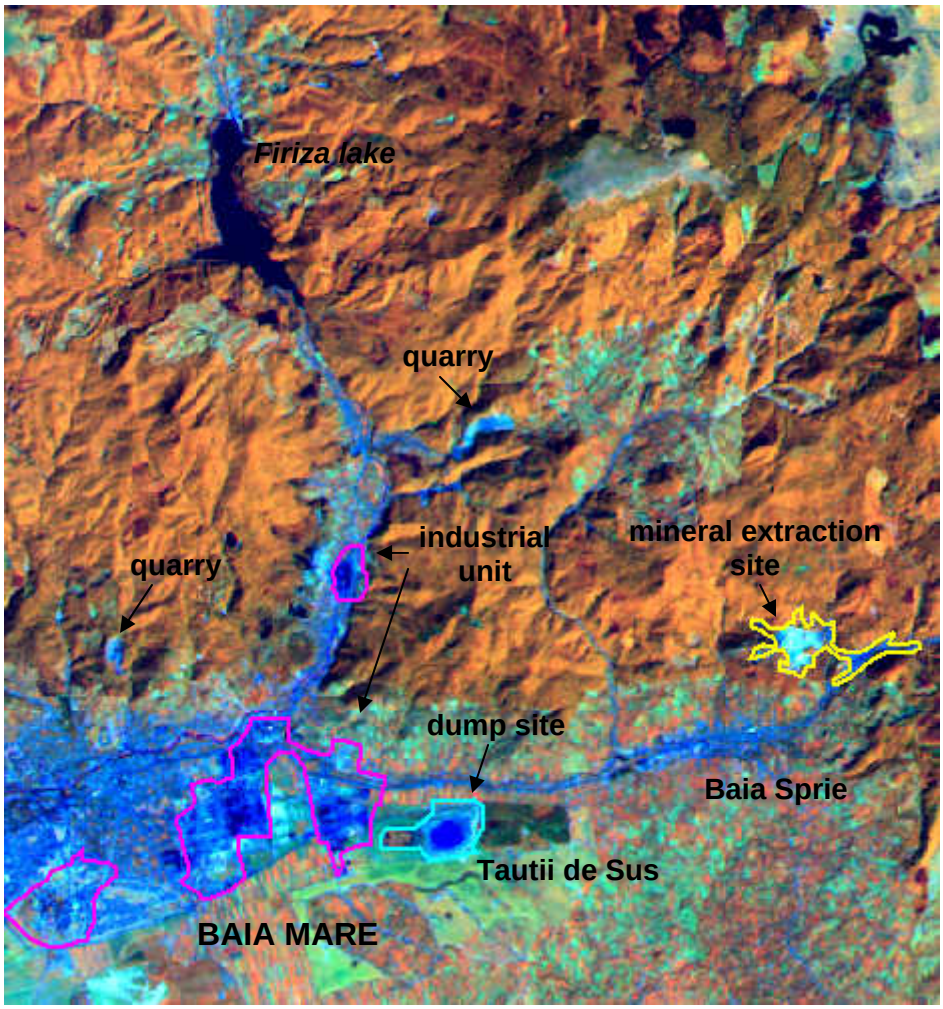


Figure 2.9 Landsat – TM image (4,5,3 – RGB) in Baia mare region, Romania. The following colours were assigned to the CORINE Land Cover categories overlaid as vectors: magenta – industrial or commercial unit (class 121), yellow – mineral extraction sites (class 131), cyan – dump sites (class 132).

The PC3 and PC4 images for pointing out iron-staining areas are shown in figures 2.10 and 2.11 and their similarities in highlighting the sites related to the extractive industry is evident. It can be seen also how some other categories (water bodies, pastures, grasslands etc.) are mapped as bright pixels due to their spectral features and the way in which the Thematic Mapper bands where they are manifested distribute their loadings for the PCA transformation.

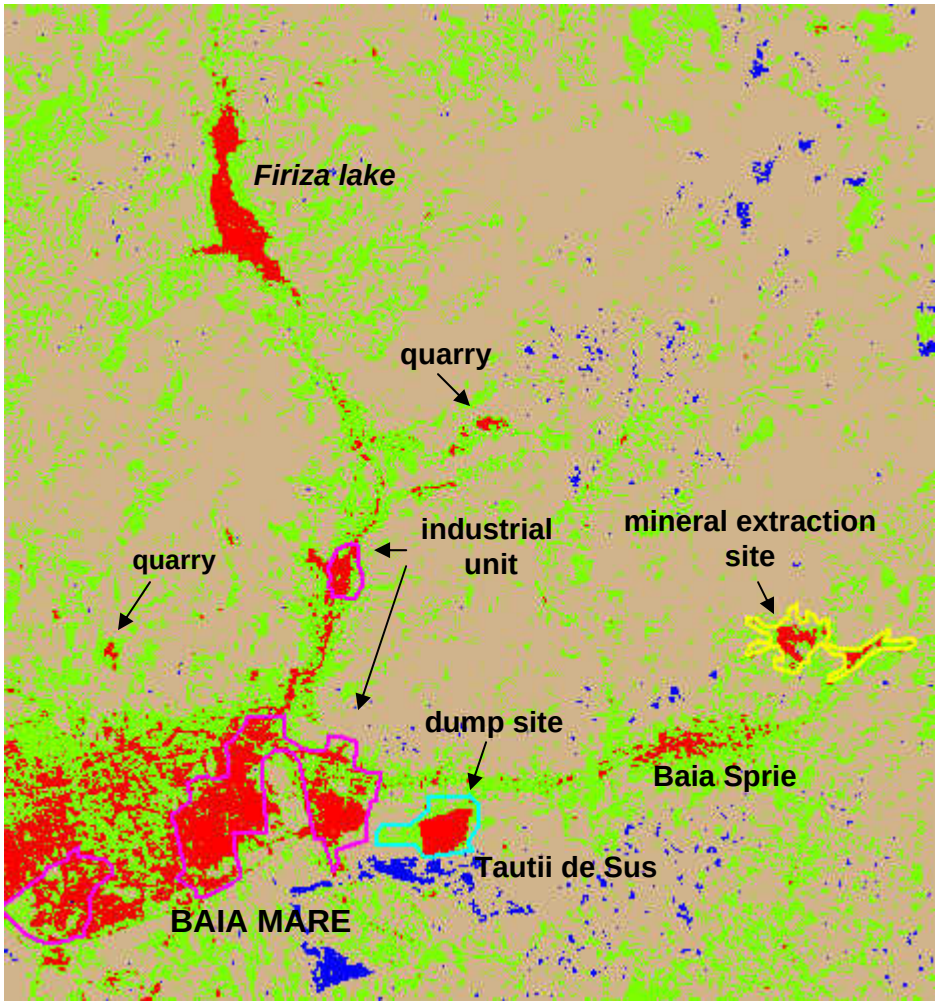


Figure 2.10 Image of PC3 component for FeOx. The brightest pixels (coded red) correspond to: mining area at Baia Sprie, Baia Sprie locality, the dump site at Tautii de Sus, the city of Baia Mare (inclusively the industrial units in the city and immediately North to it, related to ore processing) and the Firiza lake. Some other red pixels correspond to exposed rocks and after comparison with the 1:50.000 scale geological map (Borcos et al., 1981) it was seen that the largest areas represent quarries for andesites. The region has been intensely explored and there are many mining facilities. Plants for ore processing (one for Pb, Zn, Cu and the other for Au) exist in Baia Mare, giving out gaseous and dust emissions.

The fact that the image of component PC4 for FeOx in figure 2.11 shows less bright pixels in the urban and especially in the industrial areas can be explained by the fact that to the radiation coming from these surfaces sometimes it is added the signal from smoke and haze in the air above. As these have the highest reflectance in TM1, by examining the loadings in table 2.1a it can be seen that after negation (necessary for both PC3 and PC4) they will show as bright pixels in PC3 and dark in PC4. Therefore, in PC4 they will have a subtractive contribution, while in PC3 an additive one. This observation was checked against the clouds (present in some parts of the scene), that have similar spectral features and which appear indeed as bright pixels (red) on PC3 and dark pixels (blue) on PC4 images computed for iron oxides.

The result of combining the two FeOx images is presented in figure 2.12, which highlights as bright pixels those mentioned before as being related to the extractive industry (mining area at Baia Sprie, dump site at Tautii de Sus, other small areas representing quarries for andesites). The other remaining anomalous pixels correspond to urban and industrial units and sometimes to bare soils where the content in iron oxides is so high that it is manifested in both components. Such pixels can be found in the left bottom part of the image.

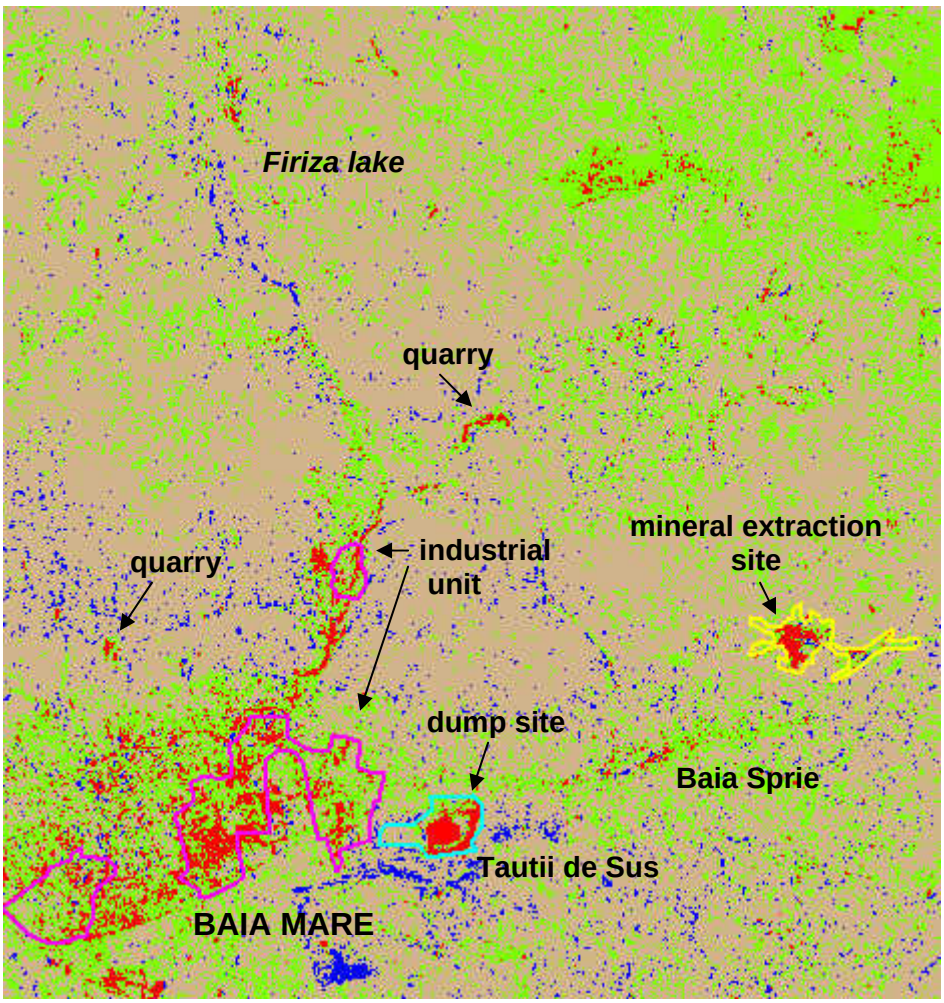


Figure 2.11 Image of PC4 for FeOx. The brightest pixels correspond to the mining area at Baia Sprie, smaller exposed rocks (as the image of PC3), as well as the dump site at Tautii de Sus. The Firiza lake does not present anymore high values, instead there are highlighted some other anomalous pixels in the upper right part of the image (corresponding to pasture) and near the lower left corner (bare soil). The urban and industrial areas are also visible, but the extension of the anomalies is smaller.

A further differentiation between the anomalous zones identified this way is possible by combining them with the areas determined by applying FPCS to the input TM bands 1,4,5,7 for the purpose of highlighting the minerals having absorption features in TM7, respectively OH-bearing secondary minerals or carbonates. For this type of PCA the criterion of selecting the principal component giving the image of OH-bearing minerals consists in looking for the highest (moderate) loading in both TM5

and TM7 (having opposite signs). If the loading in TM7 is negative the component is to be left as it is, since it shows the absorption in TM7 compared to TM5 and the materials having this greater reflectance in TM5 will appear on the image as bright pixels. If the contribution of TM7 is positive, then the image should be negated (Loughlin, 1990; 1991) in order to have these pixels as the brightest in the image.

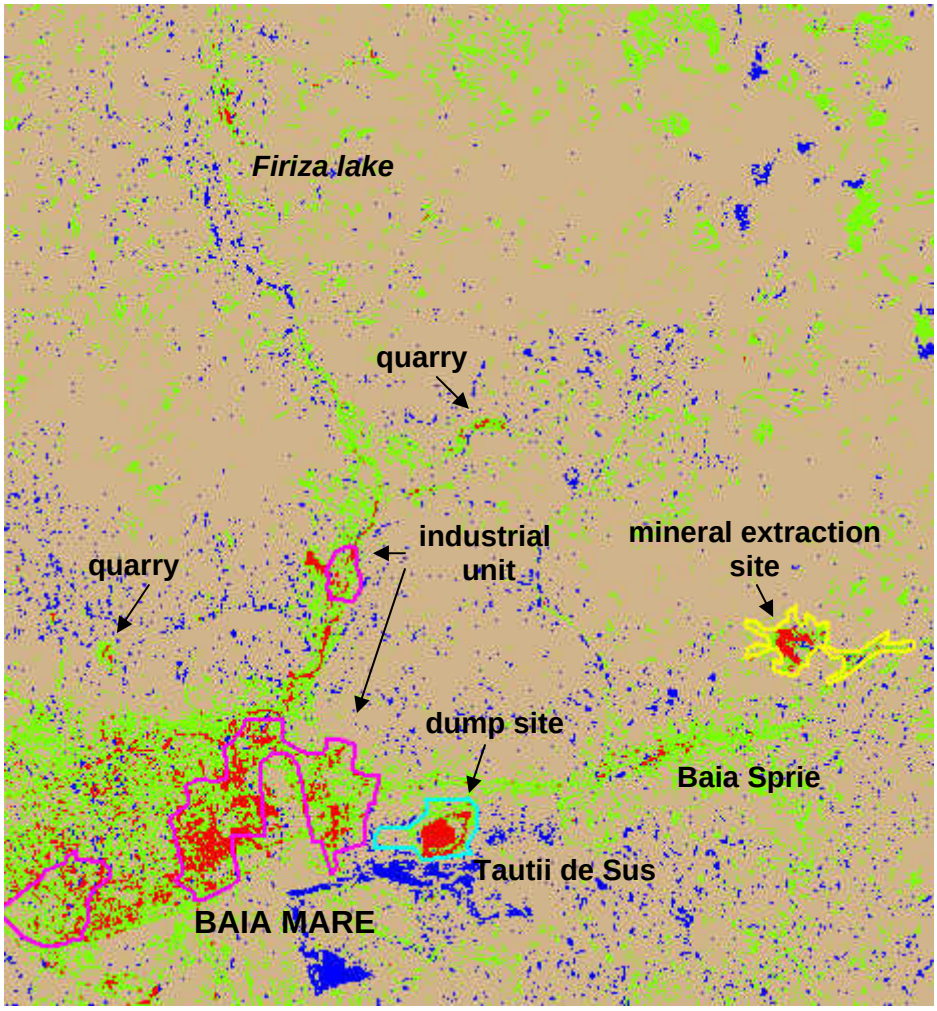


Figure 2.12 Final image of FeOx obtained by combining PC3 and PC4. The undesired anomalies present in both PC3 and PC4 were almost completely compensated, while keeping the areas of interest related to the extractive industry.

The eigenvectors of the covariance matrix for bands 1,4,5,7 are presented in table 2.2a and it can be seen that the component that fulfils this criterion is PC4, which, according to what was stated above, needs to be negated. The contribution of TM7 in component PC3 is too low, and this component, in which TM1 has a contribution of -0.911 has the variance of 0.70% (table 2.2b) given by clouds, characterized by the highest reflectance in TM1 and a lower reflectance in TM7 compared to TM5. PC1 represents the overall albedo, accounting for 93.46% of the data variance and PC2 has contributions in different proportions from all input bands (5.71% of the variance). The image of PC4, which contains 0.13% of the data variance can highlight "subtle differences in TM7 against TM5" (Loughlin, 1990) and its brightest pixels correspond well with known mining-related artifacts, as resulted from the comparison with CORINE Land Cover, geological and/or mineral resource maps. However, this

difference in reflectance between TM5 and TM7 is related also to the moisture content of plants. By combining the OH-image with the FeOx image, this type of anomalies can be eliminated or at least minimized and for this purpose the image of PC4 from table 2.2a was negated, stretched and level sliced (pseudo-coloured). Five levels were preferred for this type of images, the legend of the colour codes being shown in figure 2.13. The first three levels are identical with those used for the images of the principal components computed for emphasizing iron-staining (classes 1, 2, 3). The last two levels represent a further differentiation of the brightest pixels into:

- a first group consisting of pixels with the same value(s) and high frequency distributed nearby the mean + 2 σ, depicted in magenta colour (class 4);
- the rest of the pixels with higher brightness values but lower frequencies, more largely distributed up to the value of 255 and which are represented in red colour (class 5).

Table 2.2a - Eigenvectors matrix for TM bands 1, 4, 5, 7

	TM1	**TM4**	**TM5**	**TM7**
PC1	0.130	0.807	0.539	0.205
PC2	-0.267	0.573	-0.613	-0.474
PC3	-0.911	-0.088	0.390	-0.098
PC4	-0.285	0.115	-0.426	0.851

Table 2.2b - Principal components eigenvalues for TM bands 1, 4, 5, 7

	Eigenvalue	**Variance (%)**
PC1	4085.19	93.46
PC2	249.65	5.71
PC3	30.42	0.70
PC4	5.72	0.13
	4370.98	100.00

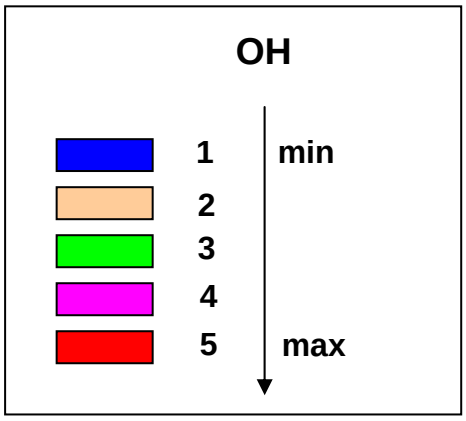


Figure 2.13 Legend of OH classes

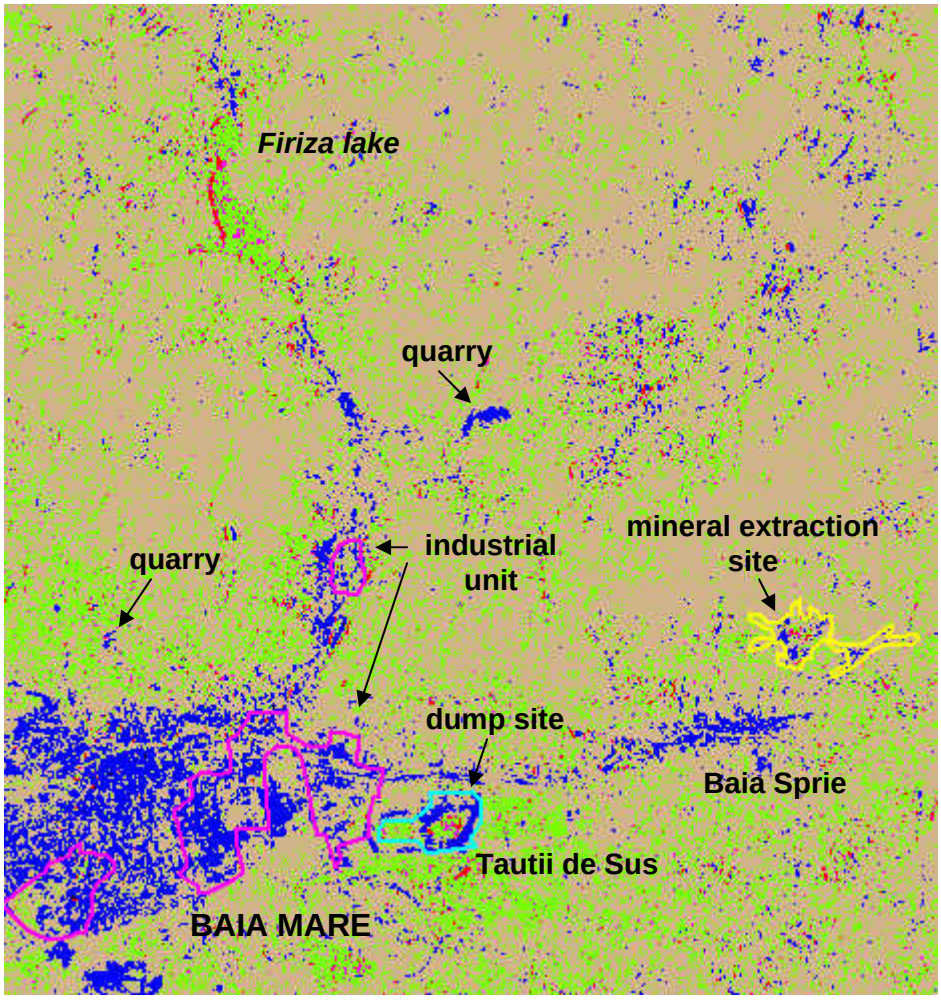


Figure 2.14 OH-image (component PC4 from table 2.2a). Used alone, without the FeOx image, the areas of exposed rocks with high content in OH-bearing secondary minerals (the mineral extraction site at Baia Sprie with hydrothermal alterations, the dump at Tautii de Sus) cannot be separated from some types of vegetation. Unaltered rocks are shown as dark pixels (blue colour).

The image for OH-bearing minerals is presented in figure 2.14 and it can be seen that the brightest pixels correspond to the mineral extraction site at Baia Sprie and to the dump at Tautii de Sus. However, as it was mentioned before, some types of vegetation show also a strong decrease of reflectance in TM7 against TM5 related to their moisture content. On the OH-image alone it is difficult to discriminate between the anomalous areas with exposed rocks and the pastures in the central, upper right or the heterogeneous agricultural areas in the bottom right (see figure 2.9).The forest present moderate or moderate-high values, posing no problems. Localities are shown as dark pixels (blue colour) and in the same way it is depicted an area corresponding on the satellite image (figure 2.9) to exposed rocks (center of image). On the 1:50.000 scale geological map (Borcos et al., 1981) this is indicated as a quarry (East of Chiuzbaia locality) for pyroxene andesites of Jereapan type (used as construction materials), located outside the halo of hydrothermal alterations where many galleries have been dug during time.

2.4.3. Computing the final FeOx-OH image

The combination of OH-image with FeOx-image can be done by performing a pairwise PCA of these two images (Loughlin, 1990; 1991) and selecting the component in which both input images have positive loadings. A colour composite with OH-image in red, OH-FeOx in green and FeOx in blue was recommended by the same author as being the most suitable for geological interpretation. For the purpose of obtaining by rapid screening of Landsat-TM images the anomalous areas with high concentration in iron oxides and OH-bearing secondary minerals related to the extractive industry the PECOMINES project proposed a different approach. The final product output by processing the remote sensing satellite scenes consists in a thematic layer on which only the above mentioned zones are emphasized, the background being shown in different shades of gray and retaining some of the informational content of the satellite scene necessary for location. This type of map is more directly related to the usual mode of perception of the common user (inclusively the decision maker), having furthermore the advantage that the areas of interest (enriched in iron-oxides) are separated into several categories, depending on their content in OH-bearing secondary minerals, indicative of materials originated from alteration processes.

A simple procedure was used for obtaining this final combined OH-FeOx map, i.e. the PC images of the respective materials (one final image for OH and one final image for FeOx), both showing the highest concentration in these minerals as bright pixels, pseudo-coloured and converted into thematic layers, were overlaid in a matrix analysis, which created a separate class for each combination of classes of the input images. The rows of the matrix were represented by the 5 levels of OH content, while the columns were the 4 levels of content in iron oxides. It resulted thus a matrix of 5 rows and 4 columns, having 20 output categories.

From these, colours were assigned only to the interesting combinations, the others were left as they were, depicted in various shades of gray, from dark to light. These combinations of OH and FeOx that were highlighted by colours represent the coincidence of the highest content in iron oxides (class 4) with all levels of OH (classes 1 to 5), the output categories and corresponding colours on the map being shown in the legend presented in figure 2.15. The colours follow the old classification scheme for individual FeOx or OH images, except cyan, which replaced tan for the purpose of better visualization of isolated pixels on a background with different shades of gray.

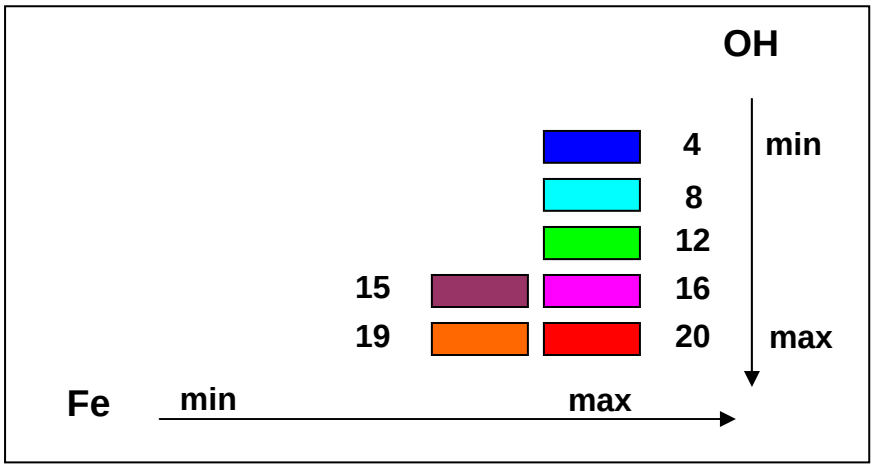


Figure 2.15 Legend of OH-FeOx classes

It was considered important to identify also the areas corresponding to the coincidence of the next category of FeOx content (class 3) with the categories of highest OH content (class 4 and 5), the output classes being assigned as 15 (maroon) and 19 (orange).

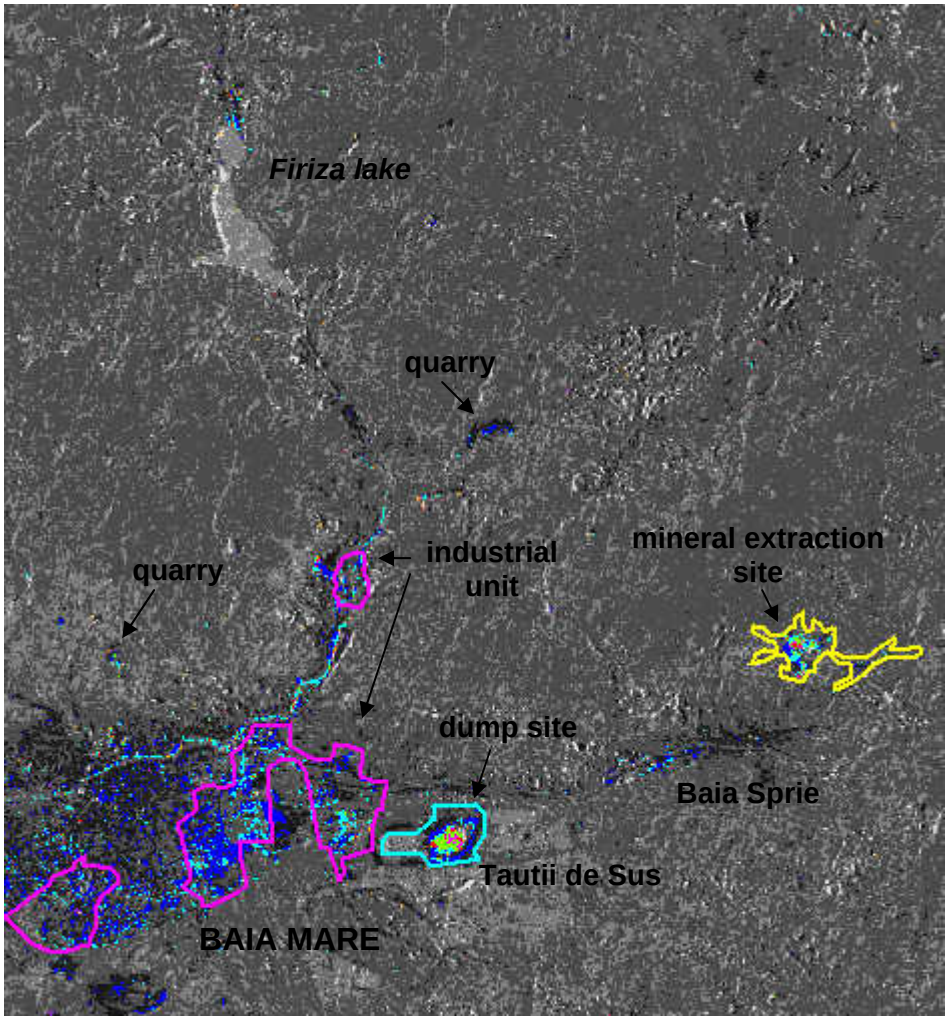


Figure 2.16 Combined OH-FeOx map. This way the anomalous pixels (coloured) can be easily detected on the background of gray values.

The combination of OH-image with the FeOx image (both components PC3 and PC4) produced the final image presented in figure 2.16. The most striking areas are those where a big amount of material having strong absorption features in TM7 and high iron-staining was deposited. These are two: the mineral extraction site at Baia Sprie and the dump site (central flotation) at Tautii de Sus. They appear as a mixture of moderate-high and high values for OH-bearing secondary minerals being also strongly iron-stained. The quarry of pyroxene andesites is also highlighted as a maximum in ferric and/or ferrous minerals but without showing the spectral feature characteristic for alteration processes. On the background of various gray shades made up by the combination of OH classes with FeOx classes some other coloured pixels (meaning that they have different levels of OH-bearing minerals and high amounts of Fe) can be easily distinguished now. An example of this type can be given for the quarry located approximately 1 km North of Baia Mare, in the western part of

Crucea hill, for extracting pyroxene andesites of Jereapan type. The quarry, named "23 August", is marked on the corresponding 1:50.000 geological map (Borcos et al., 1981) and its andesites are described (Pârvu et al., 1977; Mihailescu et al., 1981) as being partly hydrotermally altered. On the output image (figure 2.16) this quarry is highlighted as a group of pixels of different colours (blue, cyan, chartreuse, orange, maroon), indicating moderate-high and high values in OH-bearing secondary minerals.

Besides the described quarries, on the image there are also pointed out some other small clusters of anomalous pixels which, compared to ancillary information (especially detailed geological maps produced by the Geological Institute of Romania) were found to correspond to deposition of material nearby the mining galleries entrance. On the satellite image (4,5,3 – RGB) shown in figure 2.9 they represent non-vegetated areas. Many example of such good correlation between the anomalous pixels and the geological maps can be given for all the Neogene volcanic area contained in the processed satellite scene. They are a good illustration of the validity of the method which can bring results regarding the distribution of deposited material originated from the mining activity even using medium spatial and spectral resolution remote sensing data (Landsat – Thematic Mapper). It is also possible to discriminate between commonly oxidized material and other that had suffered alteration processes leading to formation of secondary minerals, most of the time associated to acidification.

3. APPLYING THE METHODOLOGY ON LARGE AREAS IN CANDIDATE COUNTRIES

The method developed within the framework of the PECOMINES project for regional mapping of mining wastes was applied on time-series satellite scenes covering the territory of Romania and Slovak Republic, two countries with historical tradition in mining, where this type of activity was known from Roman times. The validity of the method was confirmed by checking the outputs against available data sets from pan-European databases or obtained through the Steering Committee of the project.

3.1. Romania

The methodology for rapid screening of mining wastes (in detail described in chapter 2) was firstly tested on a satellite scene covering the North-West part of Romania and then extended on three adjacent scenes in order to have a bigger area to be used for validation. The selection of this large zone was determined by the variety of the mineral resources existent there (non-ferrous, ferrous, industrial minerals, coal) for which underground mines, open-pits and quarries, rock waste dumps, tailing ponds, smelters and plants for processing of ore concentrates are known.

3.1.1. Description of the area

The area selected from the Romanian territory for applying the methodology is covered by four Landsat – Thematic Mapper scenes: 184/27, 185/27, 185/28 and 184/29, their spatial extent being shown in figure 3.1.

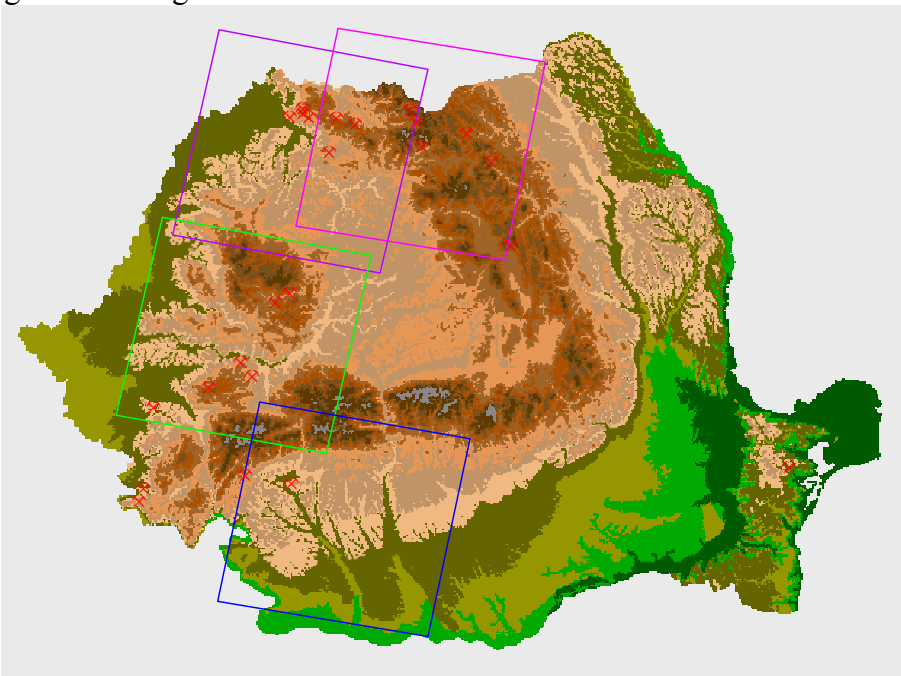


Figure 3.1 Coverage of Landsat – Thematic Mapper satellite scenes used for validation of the methodology in Romania. The location of some of the most important mining sites (questionnaire filled-in by the national partners in the PECOMINES projects) is indicated.

This zone corresponds to well-known mining districts in Romania (Geological Atlas of Romania 1:1.000.000, Map of Mineral Resources):

- Ilba-Baiut metallogenetic district (base metal sulphides: Cu, Pb, Zn ±Au, Ag)

- Baia Borsa district (base metal sulphides and pyrite)
- Rodna Mountains (Pb-Zn, Cu, Fe)
- Bistrita Mountains (Fe, Mn, Pb-Zn-Cu, barite)
- Balan district (Pb-Zn ± Au, Ag, Sb, Cu)
- Poiana Rusca Mountains (Mn, Pb-Zn, Cu, talc, muscovite)
- Western Metalliferous Mountains (Pb-Zn ± Au, Ag, Sb, Cu, Mn, Ni, Fe-Ti-V, Mo, pyrite)
- Brad – Sacaramb metallogenetic district (Au ± Ag, Te, Cu, Pb-Zn, Mo)
- Zlatna – Stanija metallogenetic district (Au ± Ag, Cu, Pb-Zn, Fe-Ti-V)
- Rosia Montana – Bucium – Baia de Aries metallogenetic district (Au ± Ag, Cu, Pb-Zn)
- Baisoara - Lita metallogenetic area (Mn, Cu, Au ± Ag)
- Brusturi – Halmagiu – Poiana metallogenetic district (Mg, barite, Mn, Pb-Zn ± Au, Ag, Sb, Cu)
- Padurea Craiului Mountains (bauxite)
- Valea Jiului Basin (bituminous coal)
- Dacic Basin of Oltenia – Getic zone (lignite)
- Pannonian Basin (bituminous sands)

Some of the most representative mining sites belonging to these mining districts are indicated in figure 3.1, most of them being considered (filled-in questionnaire and Country Report of the national Steering Committee) as environmental "hot spots" due to:

- the equilibrium at the mechanical stability limit of some of their tailings deposits, constituting this way a potential source of pollution
- soil pollution by heavy metals (Cd, Pb, Zn, Cu) – for metal mining
- surface water pollution by mining waters – for metal mining
- gases and suspensions in the air – for coal mining

In Romania the problem of acid mining drainage is an important issue especially for the non-ferrous metal mining sector, as the major deposits have mineralization of Cu, Pb and Zn in the form of sulphides, associated with pyrite and marcasite. Generally these two are in big amounts, not separated by the milling and flotation processes, but deposited with the tailings, representing thus a high environmental risk of acidification and heavy metal contamination. Problems of this type have been reported in the mining zone of Maramures county, as well as for the opencast porphyry copper exploitation at Rosia Poieni in the Apuseni Mountains, two important representative areas for the mining industry of Romania.

An exemplification of applying the remote sensing methodology for rapid screening of mining wastes in these zones is presented herein, together with some other cases for industrial minerals and coal mining in adjacent areas. The validation of the remote sensing OH-FeOx anomalies took into account all data made available for the project from various sources.

3.1.2. Available data sets

The data sets that were available to be used for validating the outputs of the remote sensing methodology consisted in:

- CORINE Land Cover database in digital format
- Map of Mineral Resources of Romania (Borcos et al., 1983), Explanatory Notes, Representative Areas (*Geological Atlas of Romania 1:1.000.000* second edition, 1984)

- Geological maps at different scales (1:200.000 - 1:50.000) edited by the Geological Institute of Romania (IGR)
- Topographic maps
- Soil map (Cernescu et al., 1971 in the *Geological Atlas of Romania 1:1.000.000*)
- Metallogenetic map (Radulescu et al., 1969 in the *Geological Atlas of Romania 1:1.000.000*)
- Questionnaire and Country Report produced by the national partners from the Steering Committee (SC) for the inventory component of the PECOMINES project (Veliciu and Stratulat, 2004 in *Jordan and D'Alessandro*, eds.)
- Published literature regarding industrial minerals and mineral resources for construction materials in Romania.

Due to its availability in digital format and already geo-referenced, the CORINE Land Cover data served as the first checking of the remote sensing OH-FeOx anomalies against the classes representing features related to the extractive industry, i.e.: class 131 (mineral extraction sites), class 132 (dump sites) and class 121 (industrial or commercial units – for ore processing plants). There were cases when the minimum mapping unit of 25 ha of the CORINE database hampered the checking of smaller size groups of anomalous pixels which could represent rock waste dumps or tailings. In these situations, for a rigorous comparison it was necessary to scan and geo-reference other thematic maps, where these features were pointed out.

3.1.3. Validation

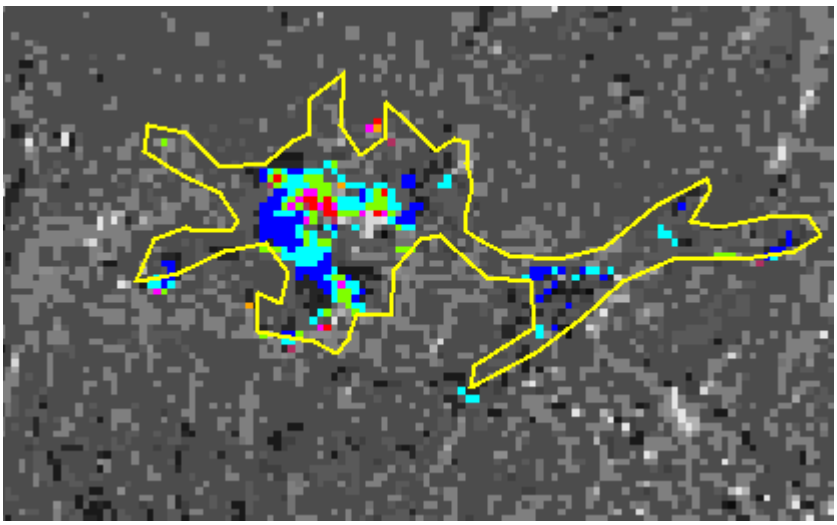
The validation of the methodology for regional mapping of mining wastes was performed by applying it on a large surface, covered by four Landsat – Thematic Mapper scenes, summing altogether approximately 130,000 km^2. The comparison of the remote sensing anomalies with the above-mentioned available data sets has demonstrated the validity of the method in detecting areas with iron oxidations associated with various amounts of OH-bearing secondary minerals, corresponding to rock waste dumps, open-pits, tailing ponds, smelters and plants for ore processing. From the variety of co-occurrence cases representative examples were selected for illustrating the most interesting and important sites.

3.1.3.1. Open-pits and underground mining

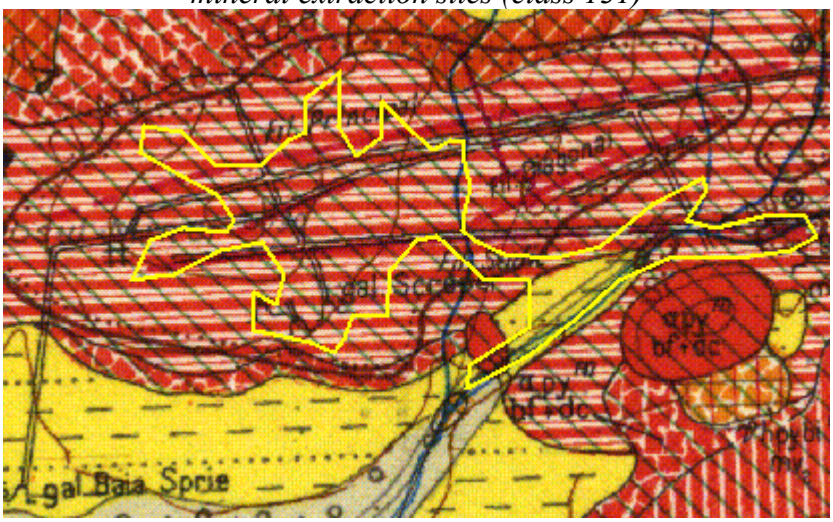
The exposed material within an open-pit is generally oxidized, therefore can be identified on the processed images without difficulty if the exposed size of the mining site is at least one pixel (30 m). Further differentiation between sites based on the amount of OH-bearing secondary minerals allows the identification of zones that could be hazardous (prone to acidification). Generally the open-pits and quarries for building materials are characterized only by iron-staining, while the sites with base metal sulphide deposits are pointed out as zones with various amounts (from low to high) of OH-bearing secondary minerals.
In the case of underground mining it is possible to locate the material deposited at the surface after being excavated from the mine if the same criterion of size (at least one exposed pixel) is met. An exemplification of the anomalies obtained by applying the remote sensing based methodology for the mining sites operated both at the surface and in the underground is presented for three Neogene volcanic areas of the Romanian territory.

Neogene volcanic area in East Carpathains (Maramures county)

A first example in this region refers to the Baia Sprie mining site, located at North-East of Baia Mare, illustrated also on the Landsat – Thematic Mapper image in figure 2.9. The deposit for Pb, Zn, Cu, Au, Ag of hydrothermal origin in Pontian pyroxene andesites propylitized, chloritized, adularized, sericitized, carbonated, argillized, silicified has been mined out since Dacs times (b.C.), the first evidence for smelting installations dating from the eighteen century. Between 1970 and 1990 it was also operated at the surface, but presently only underground mining activity is still going on. The main vein represents the longest one known in Romania (almost 2000 m – Petrulian, 1973) and six minerals have been determined here for the first time (andorite, semseyite, felsöbanyite, monsmedite, klebersbergite and szmikite). The remote sensing anomaly pointed out in figures 2.10, 2.11, 2.12, 2.14, 2.16 and at a greater scale in figure 3.2a was confirmed not only by the CORINE Land Cover class (131 – mineral extraction sites), but also by the 1:50.000 scale geological map presented in figure 3.2b.



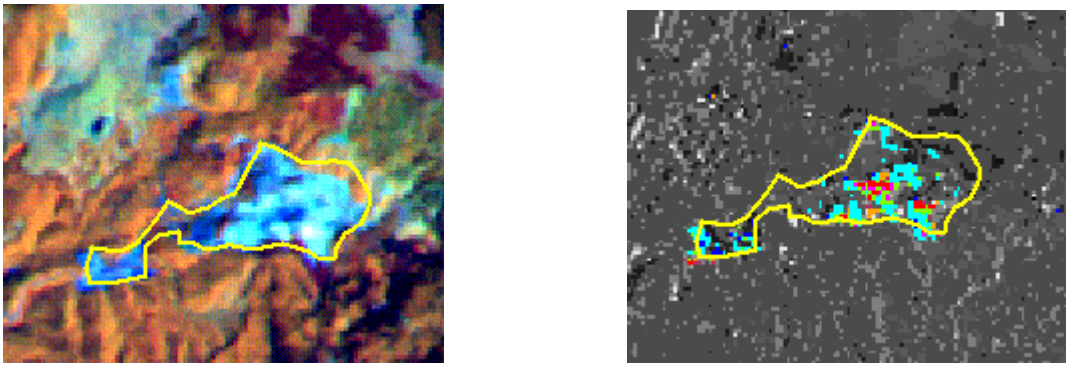
a) Anomaly image (OH-FeOx) showing co-occurrence with CORINE Land Cover data for mineral extraction sites (class 131)



b) Geological map (Borcos et al., 1981) indicating the galleries, shafts, veins and haloes of hydrothermal alteration (legend in figure 3.4c)

Figure 3.2 Baia Sprie mining site. The remote sensing anomaly was confirmed by the CORINE LC mineral extraction site and the detailed geological map.

Another example in the Neogene volcanic region of Maramures county refers to the mining area of Suior (figure 3.3), only some kilometers North-East of Baia Sprie. The mining works for the hydrothermal mineralization of Au, Ag, Pb, Zn (in polygenous breccia body formed of pyroxene andesites and Pannonian sedimentary rocks adularized, silicified and argillized) were also performed both at the surface and in the underground. The site was included as a mineral extraction site in the CORINE Land Cover database and specified in the questionnaire of the PECOMINES project as an environmental "hot spot".



a) Landsat – TM image (4,5,3 – RGB) *b) Anomaly image (OH-FeOx)*

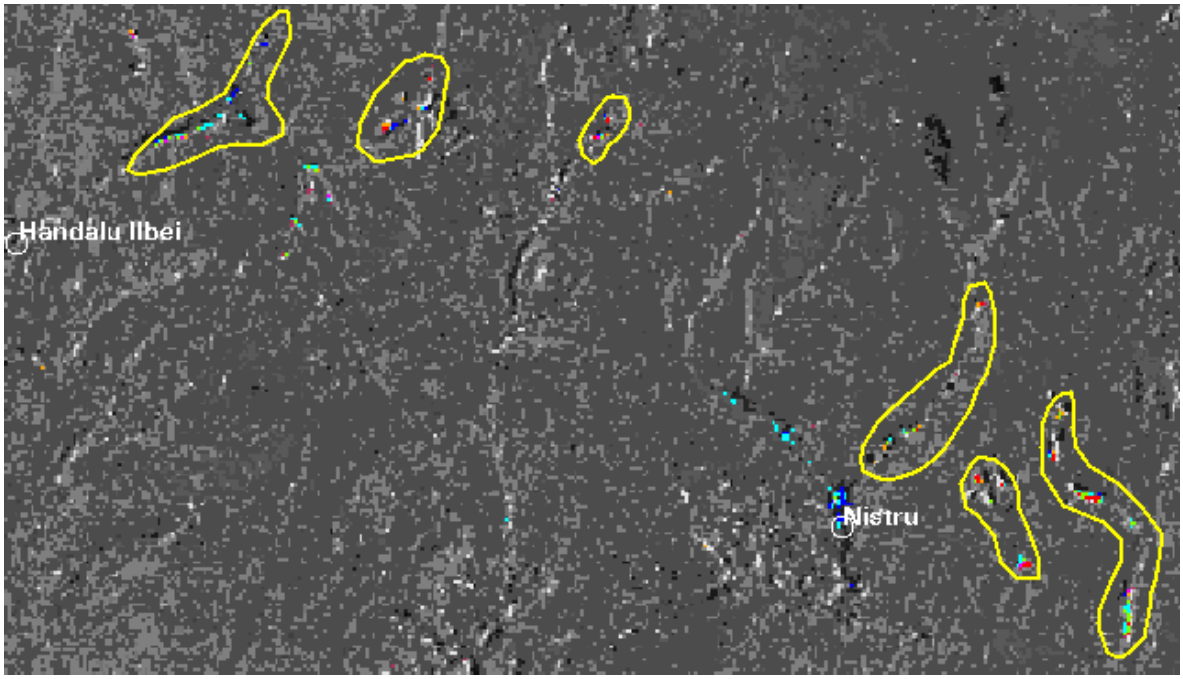
Figure 3.3 Suior mining site. The remote sensing anomaly was confirmed by the CORINE LC mineral extraction site and the SC questionnaire.

The last example for the Neogene volcanic area of Maramures county represents exclusively mining material deposited in the vicinity of underground mines from the Ilba – Baiut metallogenetic district. In the area shown in figure 3.4a small groups of anomalous pixels nearby the mining sites of Ilba-Handal and Nistru correspond to waste rock piles from these underground mines operated for extracting Pb, Zn, Cu ± Au, Ag in Sarmatian pyroxene andesites, rhyodacites with intercalations of Badenian sedimentary deposits propylitized, chloritized, adularized, sericitized, silicified, pyritized. The confirmation is given by the 1:50.000 scale geologic maps (figure 3.4b) pointing out the location of dump sites, shafts and gallery entrances. These mines have been indicated as "hot spots" in the SC questionnaire due to the 18 (Ilba-Handal), respectively 19 waste dumps (Nistru) that affect the environment.

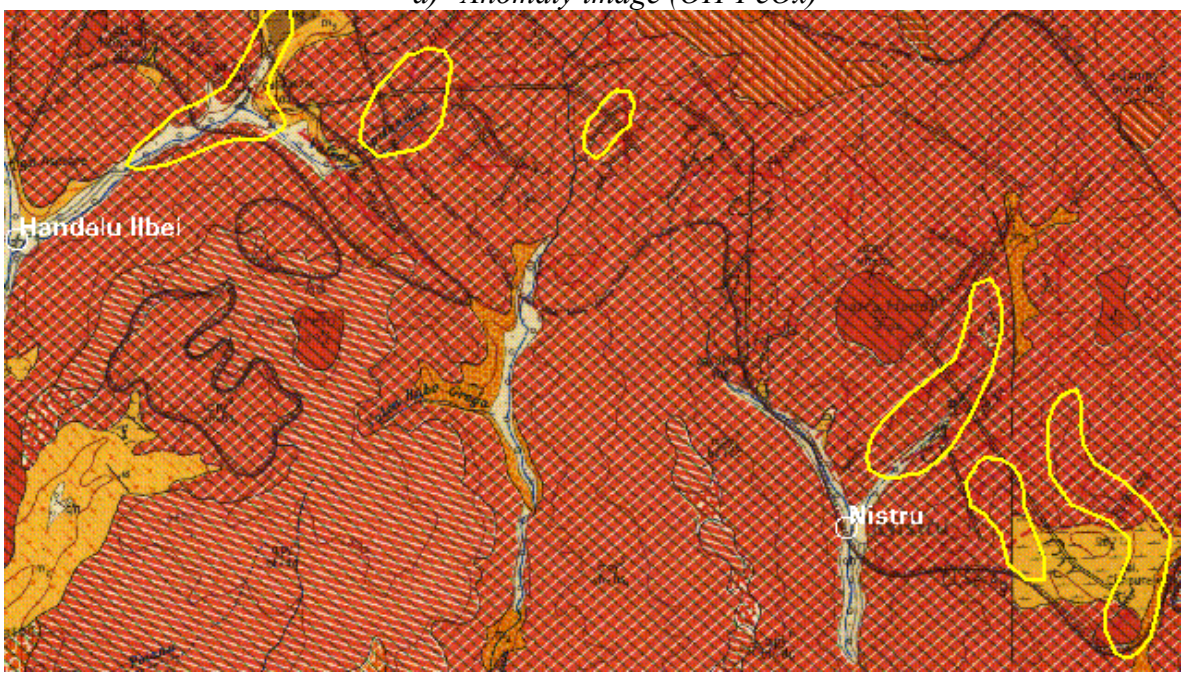
Between the geological map (Borcos et al., 1980) and the processed Landsat – Thematic Mapper image (dated 1998) there is a time difference of 18 years. Therefore, it seems reasonable to assume that other isolated anomalous pixels outside the haloes of confirmation with the geologic map represent also mining waste dumps of small size which have been deposited in the area as the mining activity went on in time.

Neogene volcanic area of Apuseni Mountains (Western Carpathians)

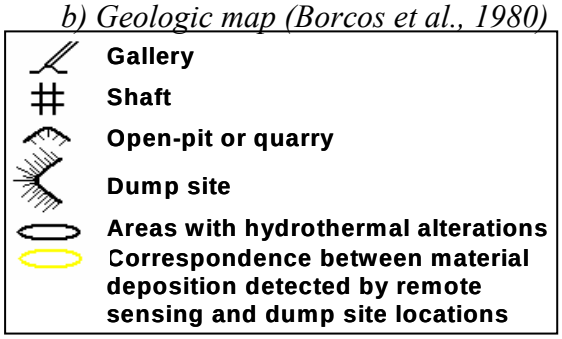
The list of validation examples presented herein includes the opencast porphyry copper mine at Rosia Poieni (figure 3.5), the biggest exploitation of this type in Romania and in East Europe. The site is a known "hot spot" due to the acidification problems and several geo-technical, hydro-technical studies and topo-fotogrammetrical measurements regarding the waste dumps stability, leaching channels and acid water neutralization have been carried out by different research institutes in Romania.



a) Anomaly image (OH-FeOx)



b) Geologic map (Borcos et al., 1980)

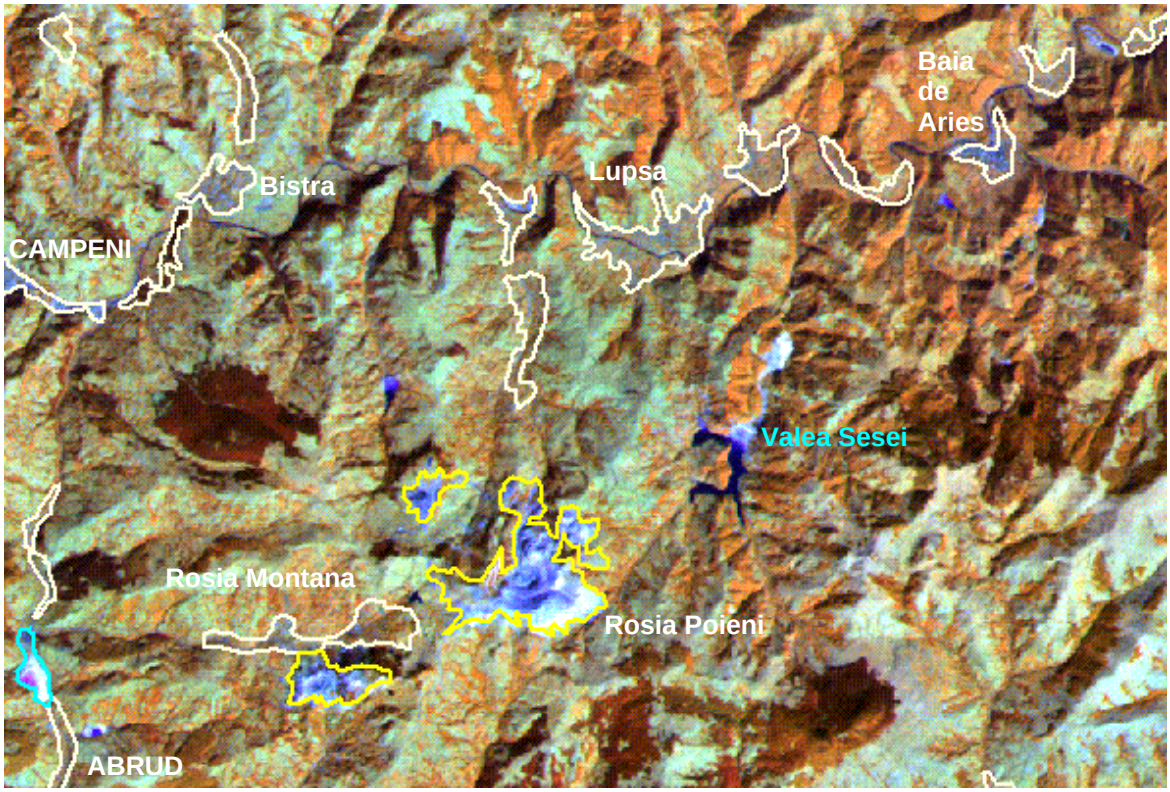


c) Legend of the geologic map. Same geologic and mining related features as in figure 3.2b
Figure 3.4 Waste rock piles in the vicinity of Ilba-Handal and Nistru underground mines. The correspondence between anomalous pixels and features related to the mining industry indicated by the geologic map is shown as yellow haloes.

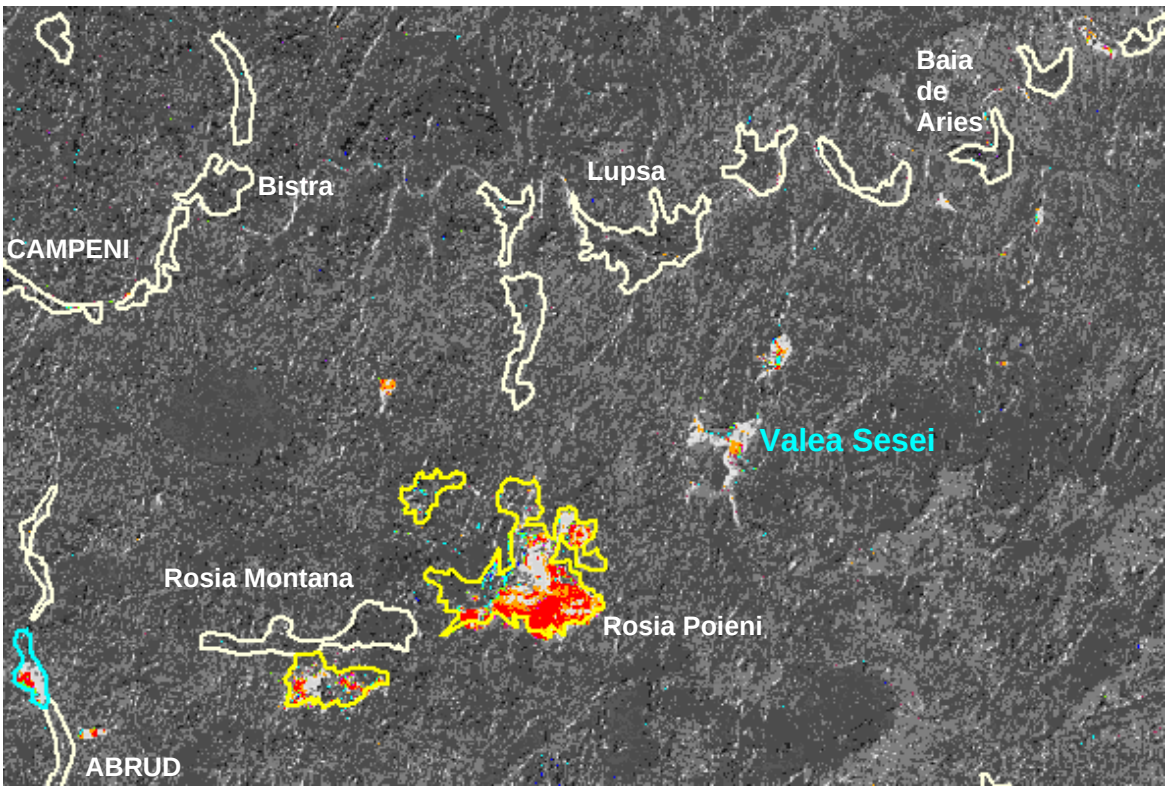
The deposit with a morphology of stockwork and impregnations was discovered rather recently, the mining operations starting in 1978. The mineralogical composition includes alkali feldspar, biotite, pyrite, chalcopyrite, bornite, sericite, clay minerals, chlorite hosted in Sarmatian amphibolic andesites in subvolcanic facies, felspathized, biotitized, argillized, propylitized.
In the satellite image presented in figure 3.6a it can be seen not only the opencast mine of Rosia Poieni, but also numerous other features related to the mining industry in this part of the Apuseni Mountains, south of Aries valley: two dump sites near Abrud (only one included in the CORINE Land Cover database), the open-pit of Rosia Montana (Au, Ag), another extraction site near Rosia Poieni and a dump site a little North to it (not included in the CORINE Land Cover database), the Valea Sesei pond where the flotation tailings accumulate, as well as the small waste dumps from the underground mines of Baia de Aries (Au, Ag ± Pb, Zn, Cu).

Figure 3.5 Rosia Poieni porphyry-copper opencast mine (detail), pointing out the reddish colour of the oxidized minerals on the bleach altered andesites (courtesy of INFOMIN, Deva, Romania)

All the above-mentioned features are highlighted on the processed remote sensing image (figure 3.6b) as anomalies and the high amount of OH-bearing secondary minerals is striking in this area. The biggest anomaly corresponds to the Rosia Poieni opencast mine where acidification is intense and known, the mine being specified in the SC questionnaire as a “hot spot”. In the same way is considered the mining district of Baia de Aries where the waste dumps, of much smaller dimensions, are pointed out as isolated couples of anomalous pixels.



a) Landsat – TM image (4,5,3 –RGB)



b) Anomaly image (OH-FeOx)

Figure 3.6 Mining area in the Apuseni Mountains, south of Aries valley, Abrud – Baia de Aries zone. Some other anomalous areas (not included in pan-European or national databases) are pointed out as a potential hazard.

However, not all the anomalous areas have already been included in a database (pan-European as CORINE Land Cover or national) as representing a mining-related feature, or, when included, their potential hazard was indicated. Examples refers to the intense anomalies (high co-occurrence of both FeOx and OH-bearing secondary minerals) for the two dumps sites at Abrud, the small one North of Rosia Poieni, the open-pit of Rosia Montana and Valea Sesei pond. In this respect the methodology developed and applied within the framework of the PECOMINES project proves its usefulness by its general potential in regional mapping mining wastes and furthermore, pointing out the areas which could pose problems to the environment.

Neogene volcanic area in East Carpathians (Calimani Mountains)

The example selected in this zone emphasizes once more the potential of the remote sensing method in discriminating between the general phenomenon of oxidation (common to all mining waste sites) and the areas where acidification and alteration leading to formation of secondary minerals are occurring. For this purpose it was chosen the deposit of native sulphur operated in opencast mine in Negoiu Românesc, Calimani Mountains.

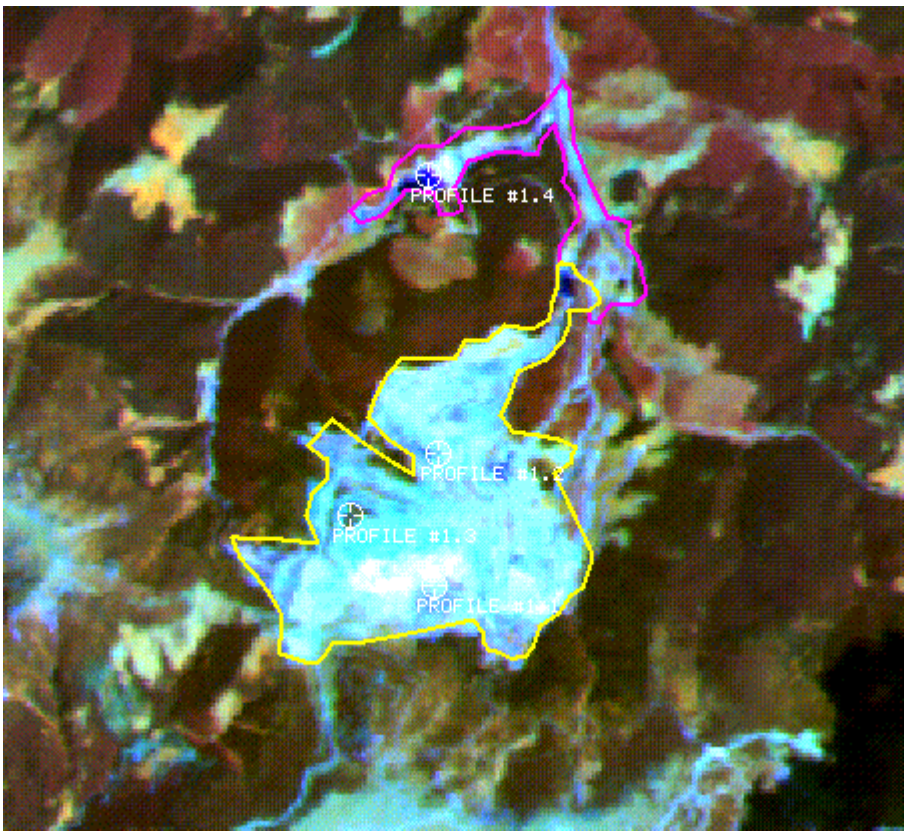


Figure 3.7 Landsat – TM image (4,5,3 – RGB) showing the open-pit for native sulphur at Negoiu Românesc, Calimani Mts.

The deposit was discovered at the end of 1960's and is of solphatarian origin, the sulphur mineralization (as impregnation and sublimation) being hosted in the Pliocene pyroxene andesites and their pyroclastics and in biotite-hornblende-quartz andesites, argillized, silicified. Besides native sulphur there were pyrite (and other minerals produced by its oxidation: limonite, goethite, hydrogoethite), silica, alunite and argillic minerals. The whole mountain was excavated by the mining operations, however nowadays the

exploitation is ceased, since it was not economically feasible. The landscape was degraded by a negative visual appearance and the dimensions of the site, easily visible on satellite images, allowed its inclusion into the CORINE Land Cover database, as shown in figure 3.7. By processing the Landsat – TM image (available from the date of 08.07.1989), it can be seen that inside the open-pit some areas with high amounts of OH-bearing secondary minerals are present on the background of general iron-staining (figure 3.8). Taking into account the mineralogical constituents of the mined deposit it can be assumed that at the time some hazard (acidification) existed at this site.
The spectral profiles built for some locations (figure 3.9) allow an explanation of the detected anomalies. The spectrum at location 1.1 shows a steep raise in reflectance from TM bands 1 to TM band 3, being very similar to the classical spectrum of sulphur, which exhibits this feature caused by the conduction band (Hunt in Siegal and Gillespie, 1980). However, the deep decrease of reflectance in TM7 leads to the conclusion that the mineral mixture in the field of view of the sensor includes also OH-bearing secondary minerals, pointed out by the respective anomalous zone (red colour on the processed image in figure 3.8).

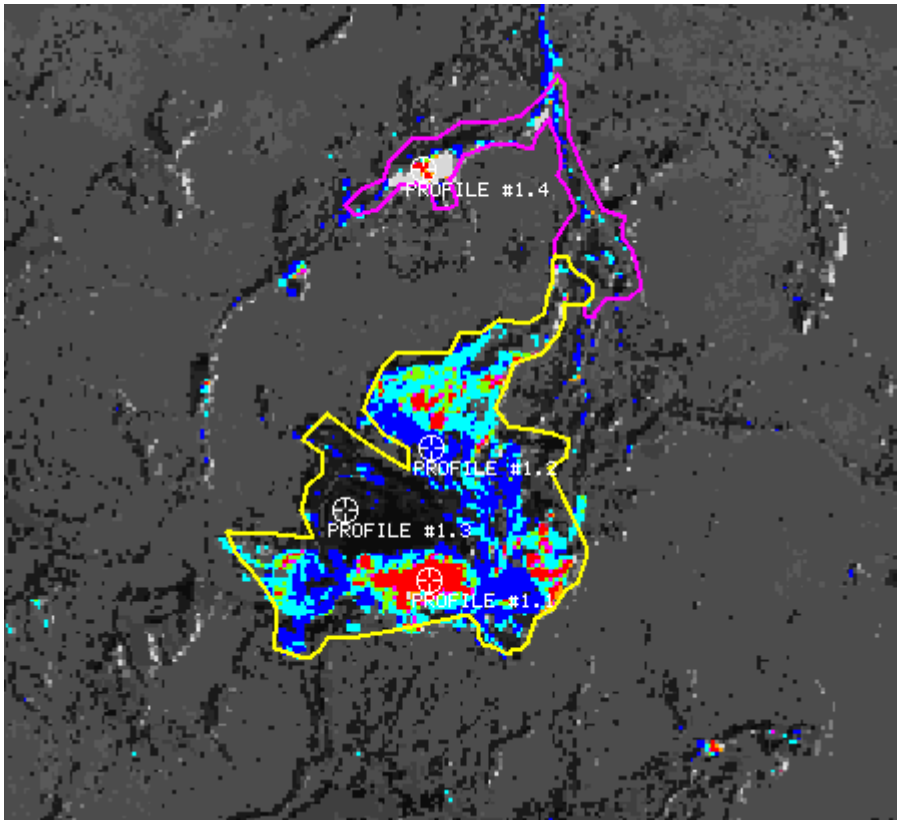


Figure 3.8 Anomaly image (OH-FeOx) for area of native sulphur open-pit at Negoiu Românesc, Calimani Mts.

Location 1.2 is characterized only by oxidation and the associated spectrum presents the raise in reflectance between TM1 and TM3 that is typical for iron oxides due to the charge transfer band, as described in chapter 2. The zone lacking remote sensing anomalies situated inside the CORINE polygon corresponds by its spectrum to mixed vegetated pixels (location 1.3), producing no FeOx anomalies. A small but intense anomaly at location 1.4 inside the industrial site (class 121 of the CORINE Land Cover database) nearby the opencast mine represents a tiny pond with water and mined material.

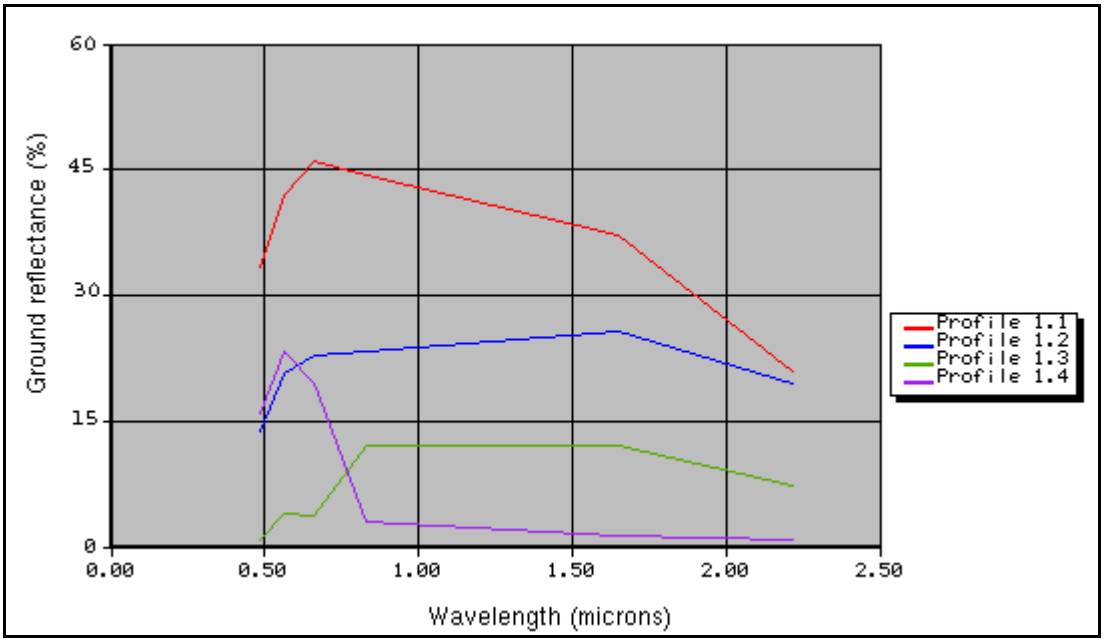
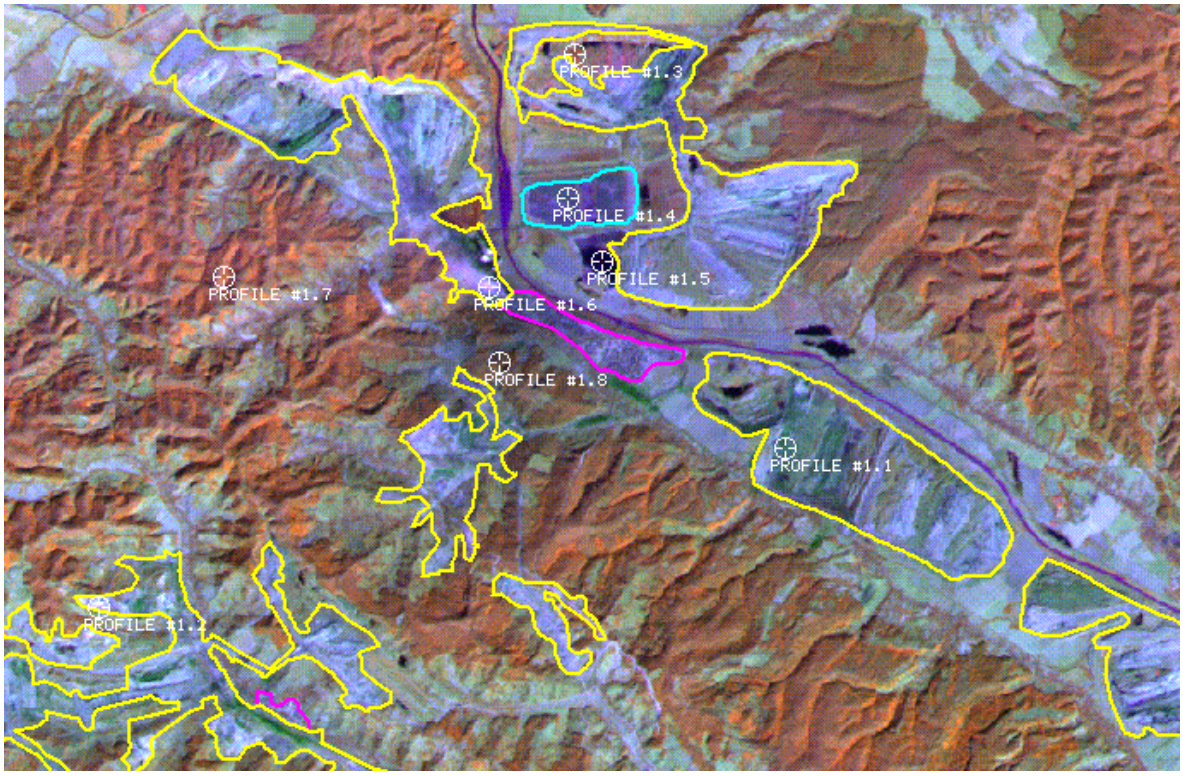


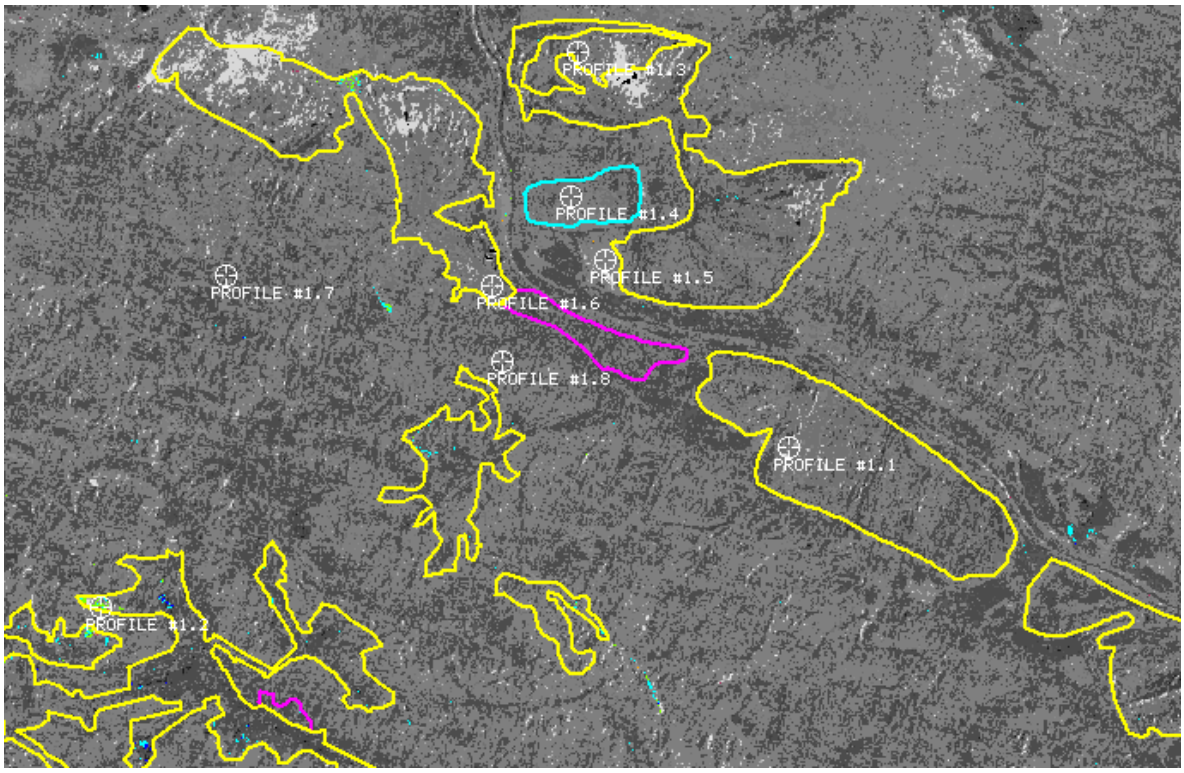
Figure 3.9 Spectral profiles in the area of the mineral extraction site and associated industrial unit at Negoiu Românesc, Calimani Mountains

Rovinari coal mining basin (Getic zone) in Oltenia

The succession of examples presented as validation of the remote sensing methodology in the case of open-pits and underground mines in Romania includes also a case for solid mineral fuels, which enter into the categories of mineral commodities studied within the framework of the PECOMINES project. For this purpose it was selected the zone of Rovinari coal mining basin in Oltenia, where there are big open-pits for lignite exploitation, operated since middle 1960s. The soft brown coal makes up beds with thickness up to 10 meters situated above and under the hydrostatic level, hosted in an alternation of sands, sandy clays, clays and carbonaceous clays of Pliocene age.
On the Landsat – Thematic Mapper image (available from 15.10.1990) presented in figure 3.10a there are overlaid the CORINE LC polygons representing operating facilities for lignite: the extraction sites (class 131), the termo-electrical power plant where lignite is burnt (class 121) and the associated dump site for depositing the slag and ashes (class 132). In this zone lignite exploitation determined dramatic changes of the landscape, accompanied by geo-mechanical phenomena, sinks, landslides, qualitative and quantitative modifications of surface and underground water and of air quality. Due to the emissions of gases and suspensions in the air the site is considered an environmental hot spot (SC questionnaire) while due to the absence of pyritic material acidification is not an issue. The barren gangue (waste) that was extracted and reloaded on dumps has a medium content in phosphorous, medium to high in potassium and a high pH, being appropriate for rehabilitation of the lands freed from the mining operations. The chemical properties of the waste materials in the old unused dump sites are favorable for a rapid grow of spontaneous vegetation (Fodor et al., 2003). Moreover, from the beginning of lignite exploitation (1967 in Rovinari zone) the state policy was to re-introduce as much as possible into the agricultural or forestry circuit the lands where the extraction activity had ceased. Different types of crops, vines and trees were tested in order to select the best suited vegetation type for the soil that had been recovered from the conservation silos and re-deposited on the waste dumps, then fertilized.



a) Landsat – TM image (4,5,3 – RGB)



b) Anomaly image (OH-FeOx)

Figure 3.10 Rovinari mining area. The petrography of the deposit (absence of pyritic material) and the specific properties of the overburden (favourable for rapid growth of spontaneous vegetation) determine the lack of remote sensing anomalies for this area, where the environmental hazards consist mainly of geo-mechanical phenomena, gaseous and dust emissions in the air.

Exemplifications can be given for Cicani waste dump site where an experimental agricultural station has been doing researches in this field since 1969 (Tomescu, 2003) and for Poiana waste dump with acacia plantations. The latter is visible on the satellite image in figure 3.10a (location 1.3) and an examination of old topographical map showed agricultural fields in this area that changed into mineral extraction site (class 131) and forest (class 311), as indicated by the CORINE Land Cover polygons.
Examining the anomaly OH-FeOx image (figure 3.10b) it can be noted that except some small clusters of anomalous pixels related to mineralogical components present in the undisturbed overburden, located inside the mineral extraction sites (e.g. location 1.2) or not mapped in the CORINE due to their small area, the zone lacks anomalies. This is in accordance with the petrography of this deposit where the coal lenses alternate with sand and sedimentary clays, and also with the type of mining operations performed. The lignite exploitation at Rovinari is done by reloading the excavated overburden by means of the conveyor belts, so the mixed pixels generally do not present a raise of reflectance between TM1 and TM3 bands (in figure 3.11 spectrum 1.1 located inside the open-pit). The same characteristics (difference in the above-mentioned visible bands too small to cause anomalies) are presented by other representative spectra for the area: 1.3 (the acacia plantation for ecological rehabilitation of the dump), 1.4 inside the dump for slag and ashes deposition and 1.6 (smoke from the power plant). Spectrum 1.5 corresponds to turbid water and spectra 1.7 and 1.8 are forest vegetation outside the open-pits.

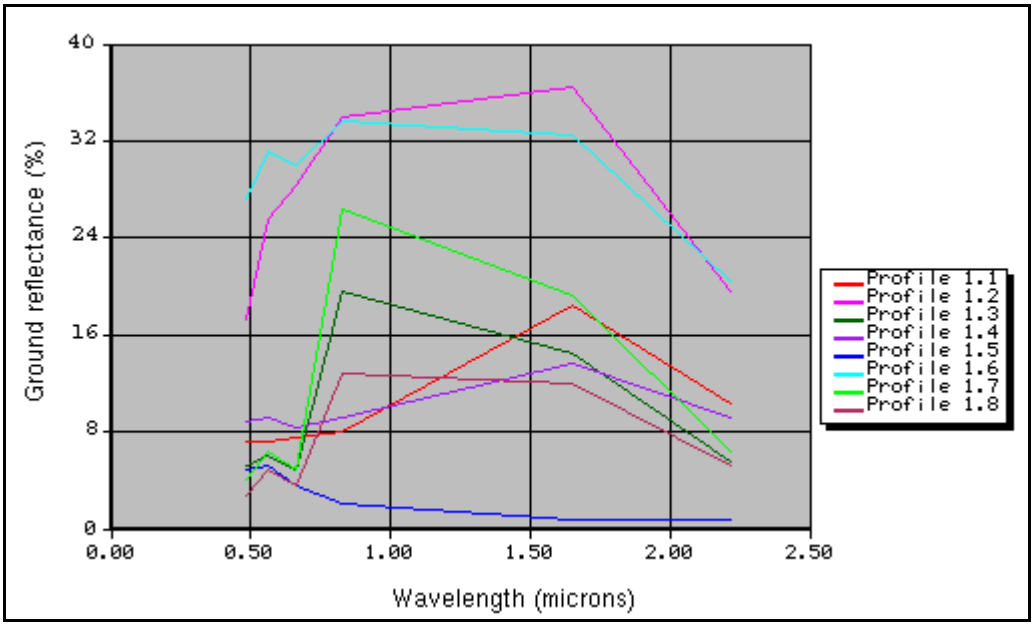
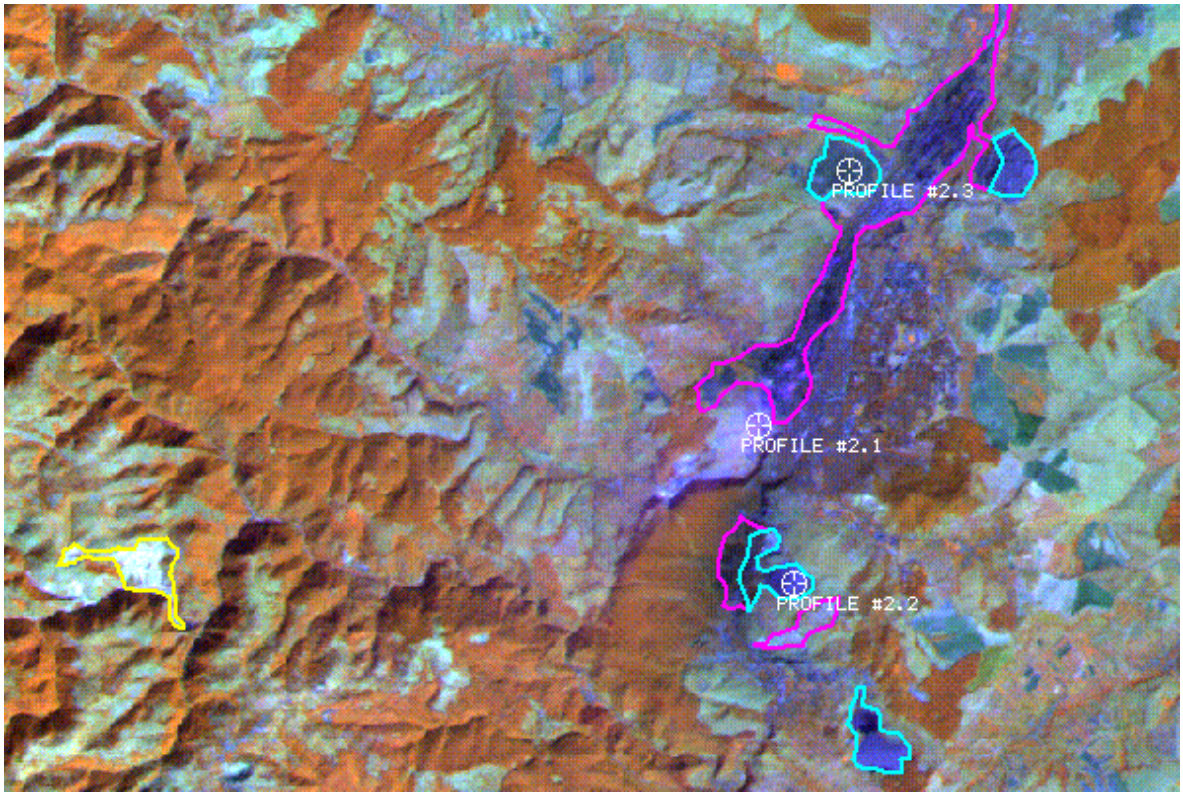


Figure 3.11 Spectral profiles in Rovinari coal mining basin, inside the operation facilities, rehabilitated waste dump and surrounding forests

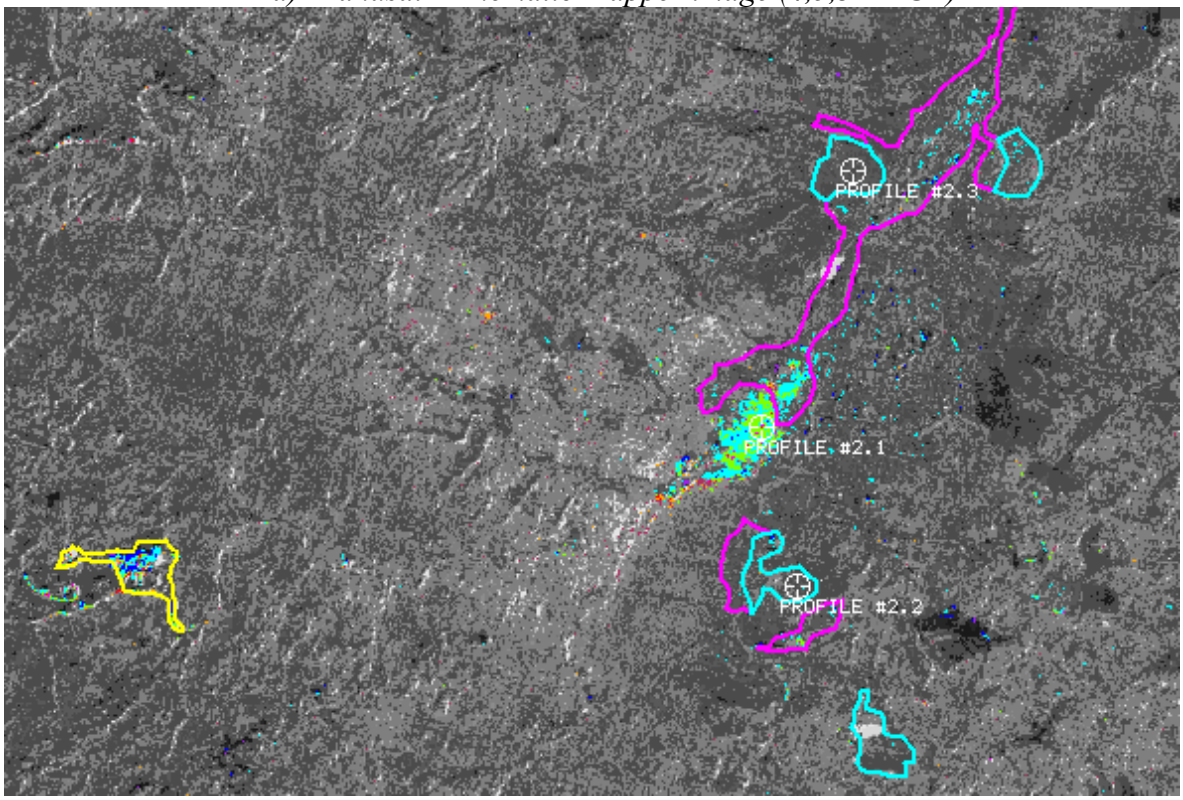
It should be noted the difference in reflectance intensity between the three vegetation spectra: dense forest (1.7), acacia plantation in an intermediate stage (1.3) and dust-covered forest (location 1.8). In this case the FPCS method did not produce anomalies, being in accordance with:

- the principles of the method (destined for mapping exposed mining waste materials, not vegetation);
- the petrography of the deposit (absence of pyritic material, therefore of acidification);

- the nature of environmental hazard produced (geo-mechanical phenomena, gaseous and dust emissions).



a) Landsat – Thematic Mapper image (4,5,3 – RGB)



b) Anomaly image (OH-FeOx)

Figure 3.12 Steel smelter industrial unit at Hunedoara. The anomaly (high amounts in iron oxy-hydroxides) extends beyond the limits of the CORINE LC polygon.

In the case when the particle emissions originate from smelters for metal extraction the affected areas are highlighted by remote sensing anomalies due to the great amount of iron oxides produced. As an exemplification it is presented the case of steel smelter at Hunedoara, one of the biggest of this type in Romania.
On the satellite image (dated 25.09.1992 - figure 3.12a) the CORINE LC polygons point out the steel smelter area with the adjoining dumps at Hunedoara, as well as the smaller industrial unit for iron ore concentrates and its dump at Teliuc (in the bottom part). The processed remote sensing image in figure 3.12b shows a big anomalous zone extending beyond the limits of the industrial site, representing deposition of particle emissions from the smelter, rich in iron oxides and with various (mainly moderately high) levels in OH-bearing secondary minerals. The dumps containing the slag, which is a calcium-aluminum-silicate glassy matrix with other opaque metallic oxides, do not produce anomalies, as the difference in reflectance between TM1 and TM3 is not great enough.
The spectra built for two of the dumps (2.2 and 2.3 in figure 3.13) show the spectral properties of the slag resulted from steel production in contrast with spectrum 2.1 corresponding to the area affected by particle emissions from the smelter. The mineral extraction site in the South-West part of the image is highlighted also as anomalous pixels, proving the presence of iron-staining.

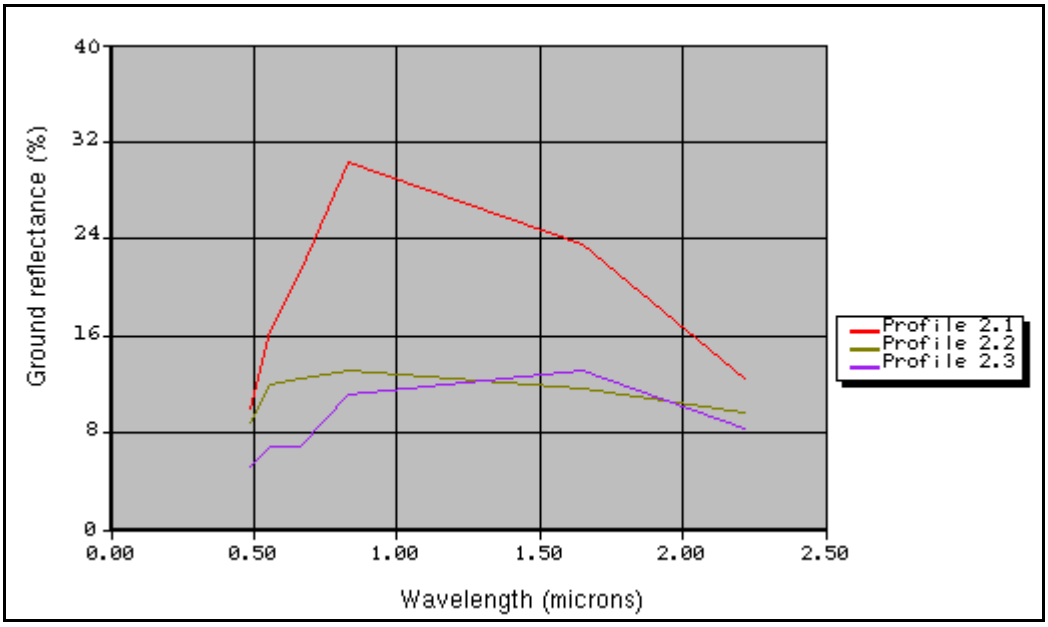


Figure 3.13 Spectral profiles in the slag dumps and affected area nearby Hunedoara steel smelter

The fact that both steel slag and ashes from coal combustion do not highlight as anomalies is related to their mineralogical composition and specific properties. These in fact make them suitable as capping or neutralizing materials for mitigating acid mine drainage due to their high alkalinity. Studies on this topic have been done in the U.S. (Rafalko and Petzrick, 1999; Paul et al., 1996) for assessing the capabilities of these cheap and available materials resulted from processing the mined natural resources in being re-used by the mining activity itself.

3.1.3.2. Tailing ponds for processing the mined material

The tailing ponds represent a mining facility very dangerous for the environment since their dam failures or overflows due to various reasons can spread acid water, cyanide, heavy metals. This was the case of the well known accidents that took place in 1998 at Aznacollar and in 2000 at Baia Mare and Baia Borsa, raising the public awareness on the potential hazard posed by mining wastes. The remote sensing method for regional mapping of mining waste developed within the framework of the PECOMINES project can monitor these sites which usually have intense spectral features characteristic of oxidation and acidification processes. The ponds for flotation and ore processing usually contain water and the method is sensible in pointing out the water that has anomalous spectral features due to the contained suspensions.
A detailed exemplification of the possibility of the remote sensing PCA-based method in mapping the distribution of the materials inside the tailing ponds and monitoring thus if cases of leakage in the environment occur is presented for two representative cases: metallic minerals (Baia Mare) and industrial minerals (Aghires) using multi-temporal Landsat – Thematic Mapper images.

<u>Baia Mare tailing ponds for metallic minerals</u>

The locations and names of the dumps for ore processing at Baia Mare are indicated for referencing in figure 3.14, the satellite images from 1998, respectively 1989 being shown in figures 3.15a and 3.15c. On these subset images the old Bozanta tailing ponds (marked 5 and 6 on figure 3.14) are clearly visible, both being enclosed in a unique CORINE Land Cover polygon. It can be seen that the smaller Bozanta pond had still water on the tailings in 1989, but after ten years, in 1998 it began to be covered by vegetation.

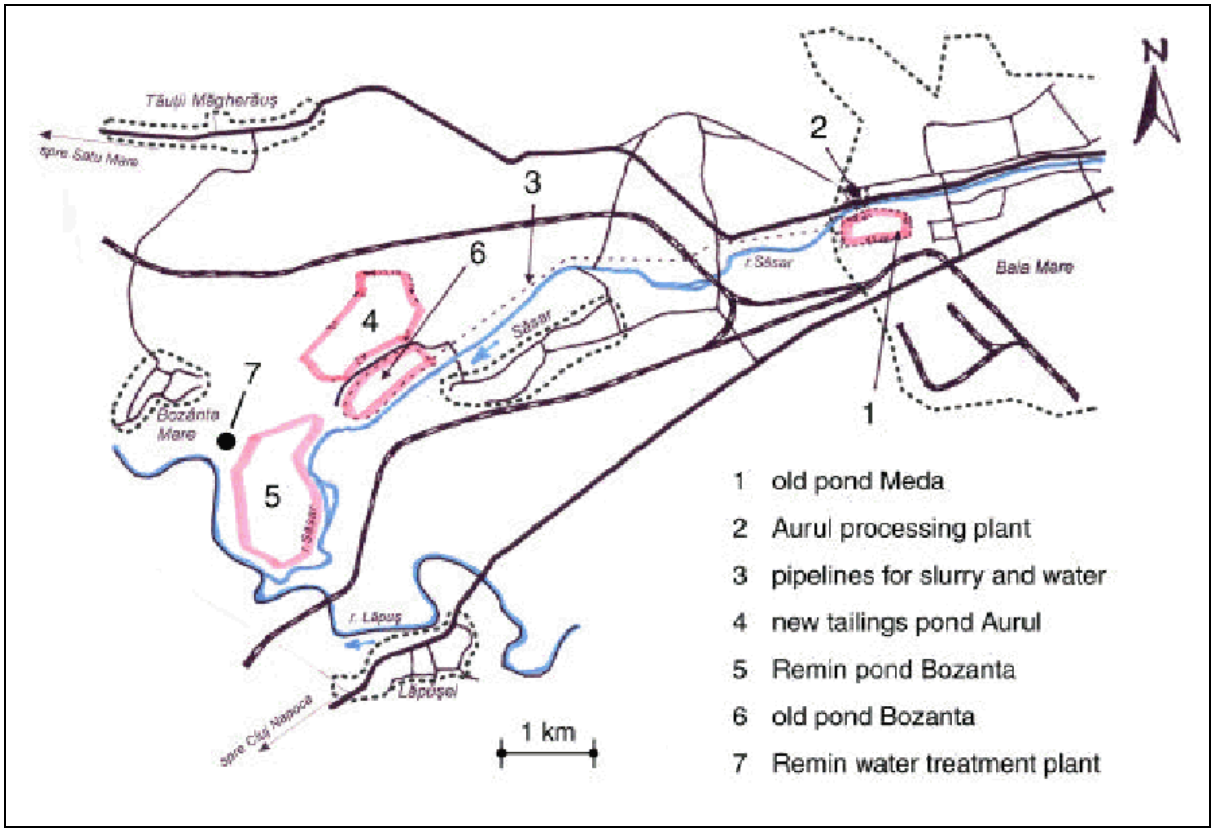
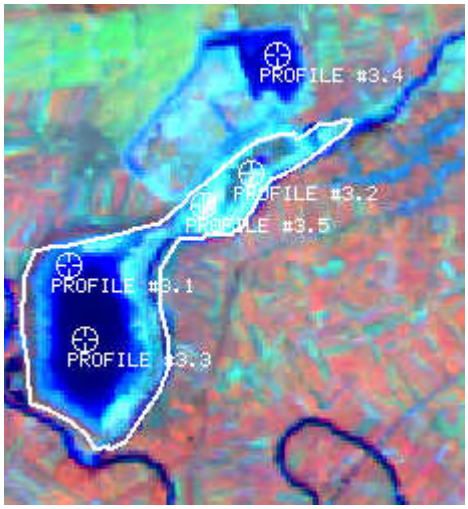
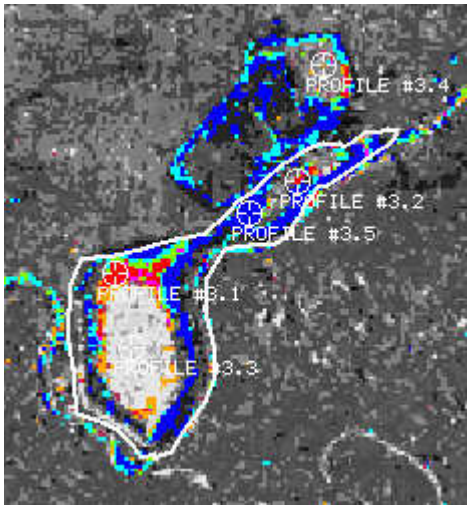


Figure 3.14 – Map of the tailing ponds at Baia Mare (UNEP/OCHA Mission Report, 2000)

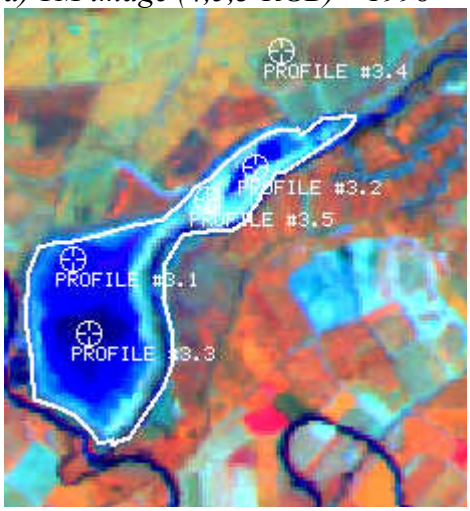
The bigger pond (Remin Bozanta) also presents differentiation between these two dates. In 1989 the area of mixture made up by the finer portion of the grinded gangue was more extended than in 1998, when this is visible as a ring surrounding the dam walls and the outer ring of coarser grinded gangue. It is evident that the different size particle fractions have been deposited in time making up the slopes of the pond and contributing to the thickening and raise in height of the damming walls. The water in the pond appears deeper in 1998, when it can be also noticed the beginning of construction of the Aurul pond for reprocessing the tailings from the old Meda pond in order to extract gold, silver and other metals (Report of the International Task Force for Assessing the Baia Mare Accident, 2000). All these can be observed also on the OH-FeOx processed images (figure 3.15b and 3.15d) corresponding to the two dates, the above-mentioned modifications that occurred in time in the Bozanta ponds being more obvious than on the colour-composite images.



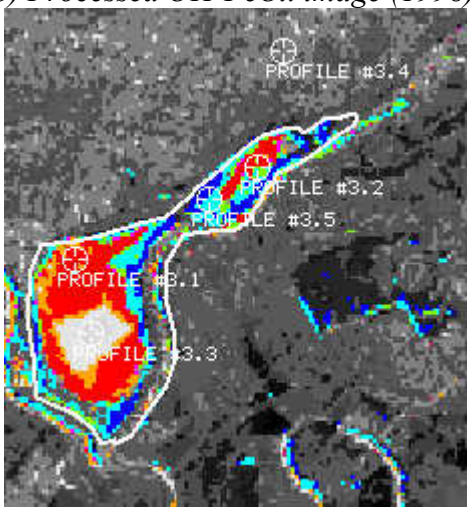
a) TM image (4,5,3-RGB) – 1998



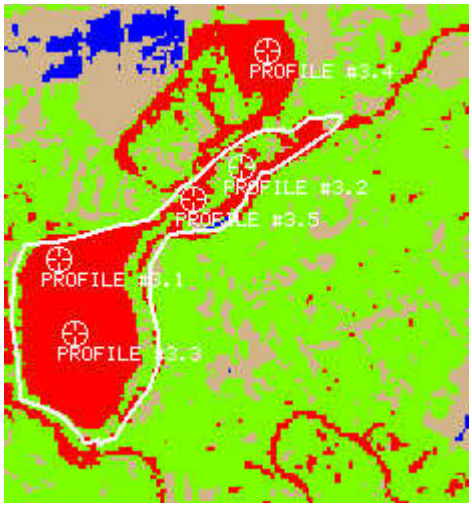
b) Processed OH-FeOx image (1998)



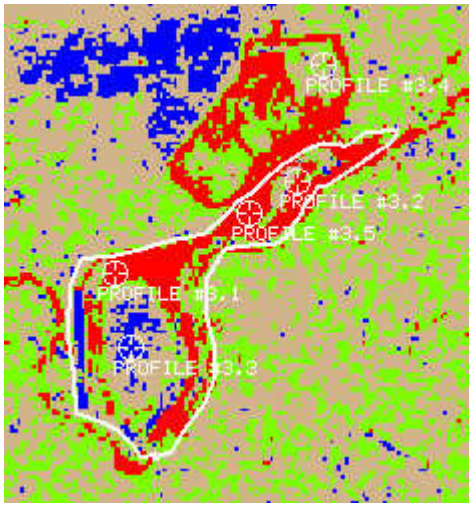
c) TM image (4,5,3-RGB) - 1989



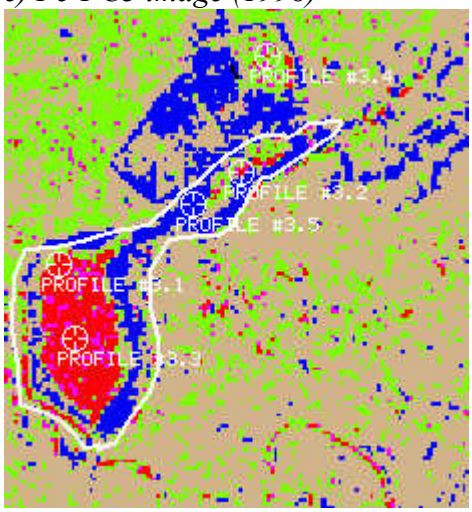
c) Processed OH-FeOx image (1989)



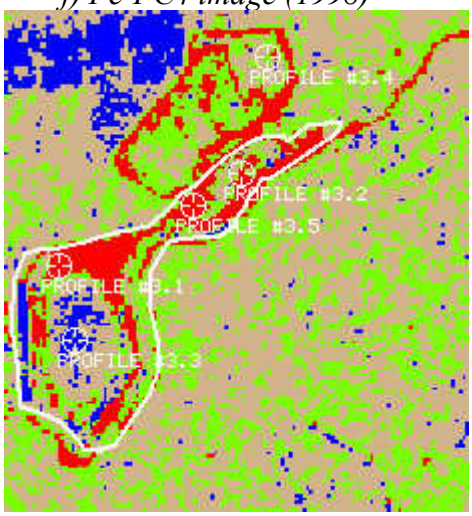
e) Fe-PC3 image (1998)



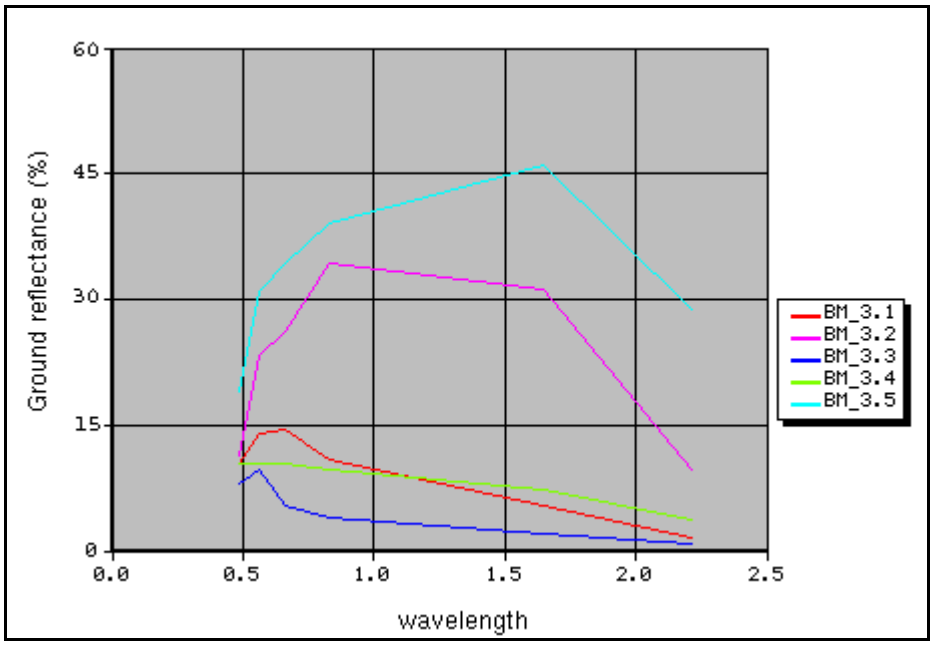
f) Fe-PC4 image (1998)



g) OH-image (1998)



h) Final Fe- image (1998)



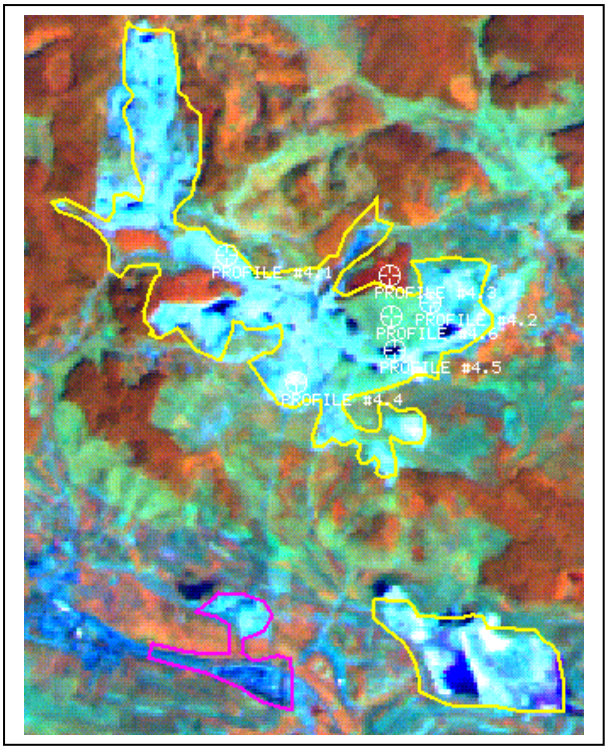
i) Spectral profiles inside the old dumps Bozanta and the new dump Aurul in 1998

Figure 3.15 Landsat-TM colour-composites and processed images for the tailing ponds at Baia Mare

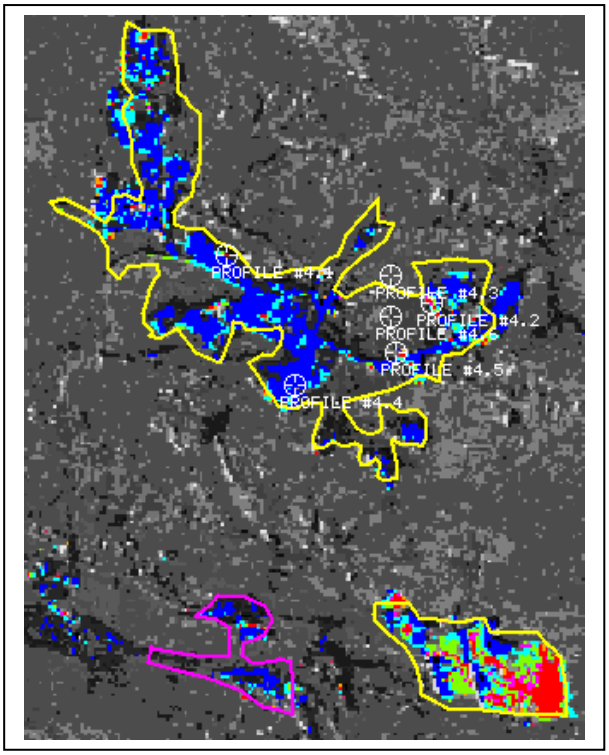
The intermediate processed images for OH-bearing minerals and iron-staining (figures 3.15e – 3.15h) together with the spectral curves at various locations for the image dated 1998 bring a more detailed explanation. Thus locations 3.1 and 3.4 correspond to a mixture of water - fine grinded tailings (gangue) showing high values of OH and being high in both Fe-PC3 and Fe-PC4 for Remin Bozanta pond, high (in Fe-PC3) and moderate-high (in Fe-PC4) for the new Aurul pond. Deeper water is present at location 3.3 and although the values of the reflectance are still high and there is an anomaly of maximum in OH, a minimum is obtained for Fe-PC4, since there is no raise in reflectance in TM3 compared to TM1. A maximum is obtained for Fe-PC3 caused, as it was demonstrated in chapter 2 (table 2.1a) by the sign and magnitude of TM1 loading into this component. Locations 3.2 and 3.5 correspond to dry tailings in the old small Bozanta pond and their spectral curves indicate the fact that both have high reflectance, showing the iron-staining in both PC3 and PC4 components (figures 3.15e, 3.15f, 3.15h). However, even though by visual interpretation they appear in the same shade of bright cyan (4,5,3 - RGB), their difference in OH-bearing minerals is evident (figure 3.15g and the corresponding spectra on figure 3.15i), emphasizing again the possibility of the method in highlighting subtle alteration features.

Aghires tailing pond for industrial minerals

This site selected for presentation is located at the bottom of Gilau Mountain, in the Western Carpathians, North-West of Cluj-Napoca and near to the industrial site "Aghiresu-Fabrici" marked on the figures 3.16 and 3.17. It is a pond for washing the kaolin sands extracted from the big quarry situated approximately 2 km to the North, both features being also present in the CORINE Land Cover database, as it is shown on the above-mentioned figures. These sands were deposited in Oligocen as a result of a strong erosion of the Western Carpathians (Gilau, Vladeasa, Mezes, Preluca Mts.) which caused the disintegration and alteration of the crystalline schists and especially of some igneous rocks rich in quartz and feldspar. The feldspars suffered later more intense alteration during the diagenesis processes, by which sericite and kaolin were formed (Brana et al., 1986).
The deposits in Aghires quarry consist in quartz limonitic sands, kaolin sands, quartz sandstones, sandy marls and sandy clays. The main mineral is quartz, kaolin being found only as microscopic particles surrounding the quartz grains. Examining the processed OH-FeOx images (for 1998, respectively 1989) it can be seen that the quarry was very well delimited on the remote sensing images by the FPCS method, being highlighted by raised levels in ferric/ferrous minerals (present as usual in the oxidized layer of the top rocks) and generally low levels in OH-bearing minerals. Only some isolated pixels present maxima in OH and this low occurrence is explained by the rather low proportion of kaolin in the respective sands (maximum 12 %), combined with the fact that the Thematic Mapper sensor receives the electromagnetic radiation coming from mixed pixels with various amounts of rocks where quartz (featureless in visible, near and short-wave mid infrared ranges when pure) is dominant.

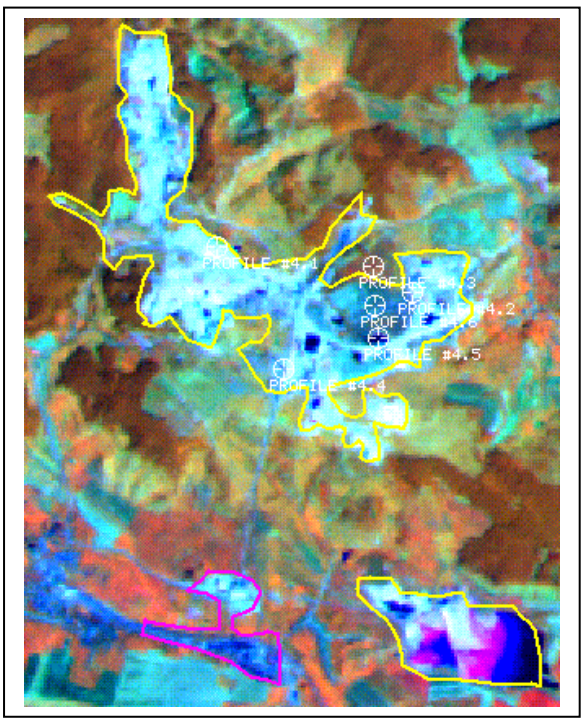


a) TM image (4,5,3 – RGB) – 1998

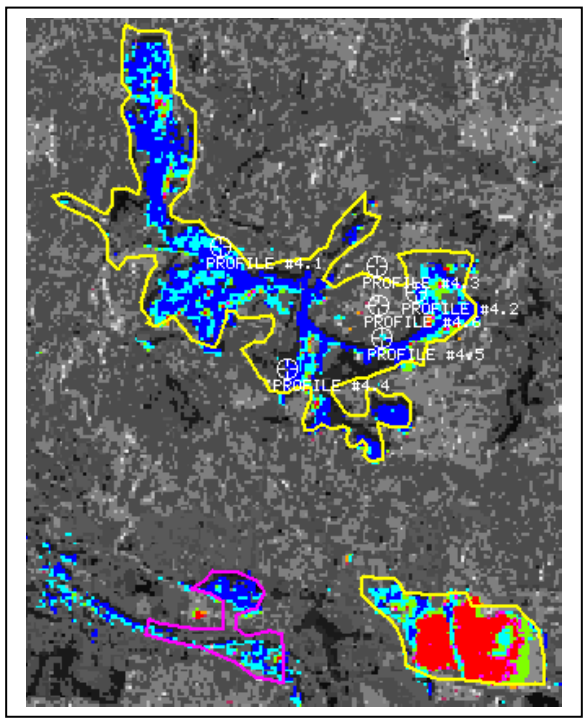


b) Processed OH-FeOx image (1998)

Figure 3.16 Landsat – Thematic Mapper and OH-FeOx processed image (1998) in the area of the quarry and tailing pond for kaolin sands at Aghires, Western Carpathians



a) TM image (4,5,3 – RGB) - 1989



b) Processed OH-FeOx image (1989)

Figure 3.17 Landsat – Thematic Mapper and OH-FeOx processed image (1989) in the area of the quarry and tailing pond for kaolin sands at Aghires, Western Carpathians

Figure 3.18 presents some spectra from the quarry (locations 4.1, 4.2 and 4.4) all these showing maximum in iron-staining, but only 4.1 and 4.2 having also a maximum in OH-bearing minerals. Spectrum 4.4 has the highest reflectance, a raise in TM3 compared to TM1 (therefore it appears as a maximum in FeOx), but values too high in TM7 to cause an OH anomaly. Spectrum 4.3 represents deciduous forest, while 4.6 although located within the mapped boundaries of the quarry, corresponds in fact to pasture and 4.5 is water, having higher values than usual but no anomalies. These last three spectra were presented for comparison and also for demonstrating that the PCA-based method identified correctly the boundaries of the quarry in 1998 (figure 3.16) and 1989 (figure 3.17). The CORINE boundaries for this quarry have as reference the 1989 image and it can be seen the overall general correct delineation (especially when the adjoining class was forest). However, in the left part of the quarry the processed OH-FeOx image for 1989 shows gray values and looking at the satellite image dated 1998 (figure 3.16a) it can be noted that these areas are covered by grown up forest (manifested also in the lack of anomalies on figure 3.16b). Another areas included within the quarry but lacking OH-FeOx anomalies are in its central part and a further examination of satellite colour-composite as well as the spectrum 4.6 in figure 3.18 demonstrate that this area (most probable bare soil in 1989) has become a little more covered by vegetation in 1998, when it corresponds to pasture.

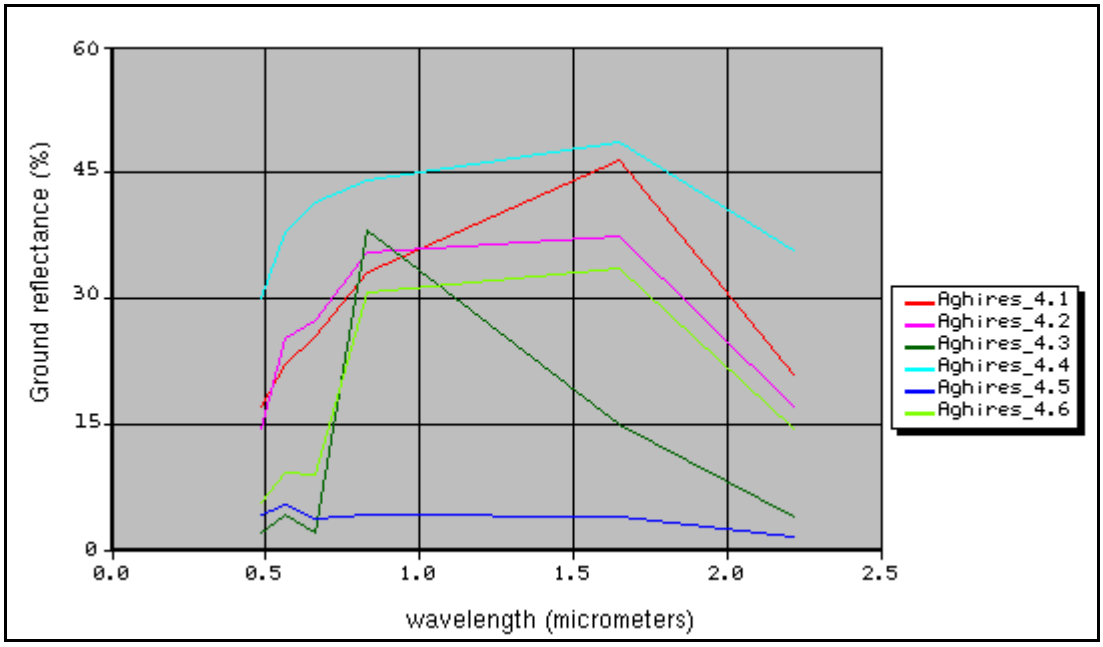
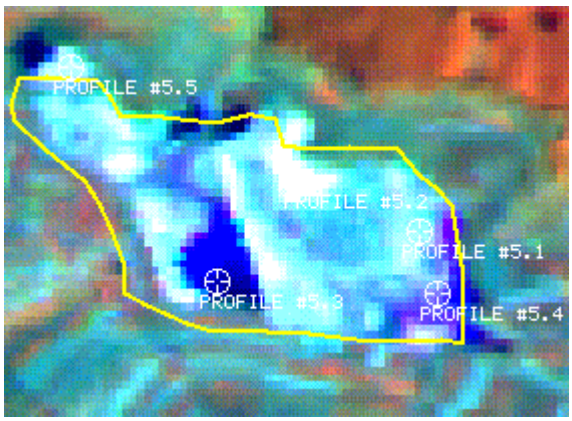
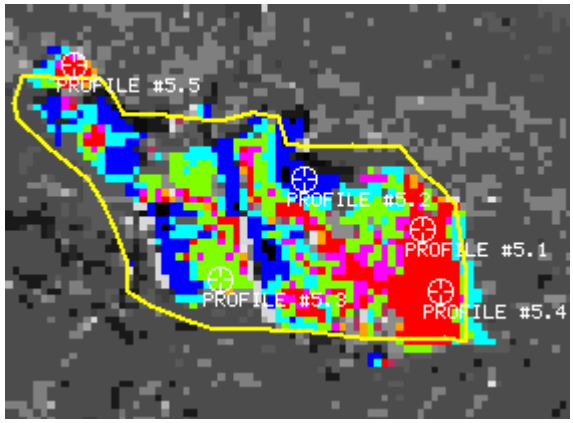


Figure 3.18 Spectral profiles for the satellite image dated 1998 in the zone of Aghires quarry for kaolin sands (Western Carpathians)

It is obvious from this example of the Aghires quarry for kaolin sands that the method proposed by the PECOMINES project can delimitate correctly the spatial extent of the mineral extraction sites and other artifacts related to the mining industry, being furthermore able to locate and assess the extent of the modifications that occurred in time in these areas. As it was previously shown, at Aghires some parts of the mapped quarry became vegetated (pasture, forest) and the processed OH-FeOx image (figure 3.16b) pointed out the zones where the extraction front advanced: to the North-West (a portion of the forest in that area being cut), as well as to the East. A slight modification (advance to the North) of the area covered by the tailing pond in the South-Eastern part of the image can be also noticed.

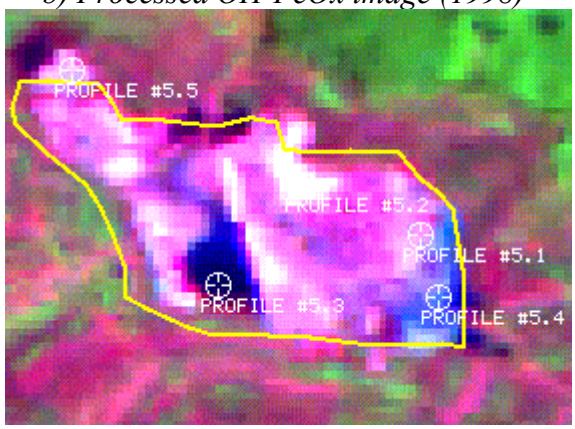


a) *TM image -1998 (4,5,3 – RGB)*

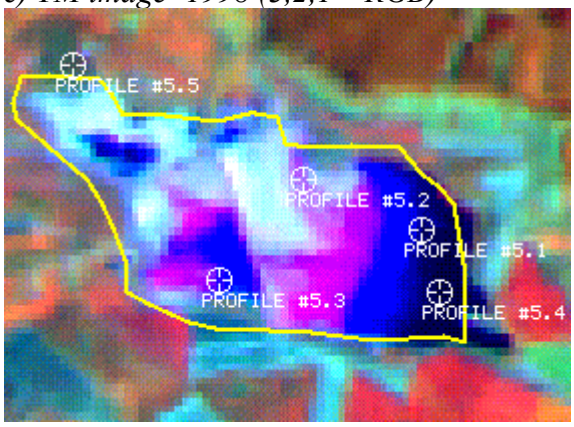


b) *Processed OH-FeOx image (1998)*

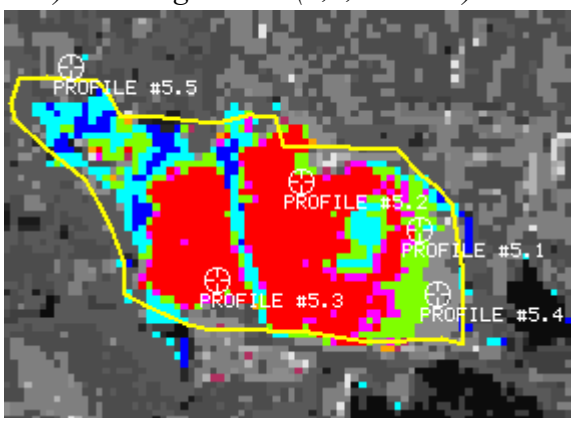
c) *TM image -1998 (3,2,1 – RGB)*



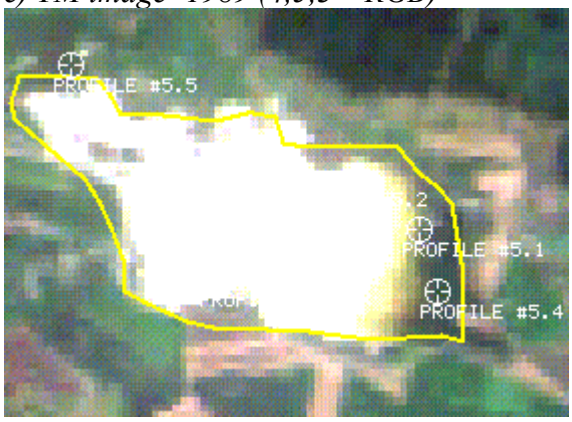
d) *TM image -1998 (7,4,1 – RGB)*



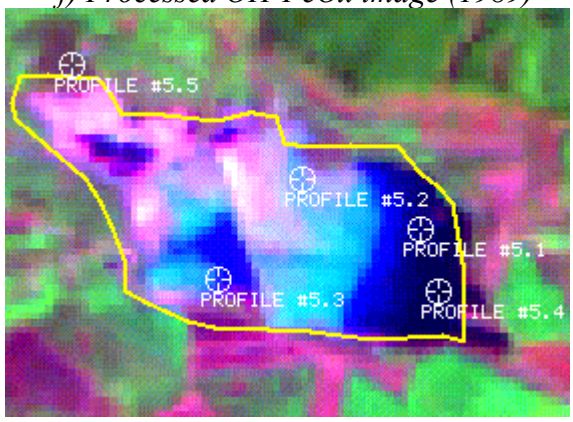
e) *TM image -1989 (4,5,3 – RGB)*



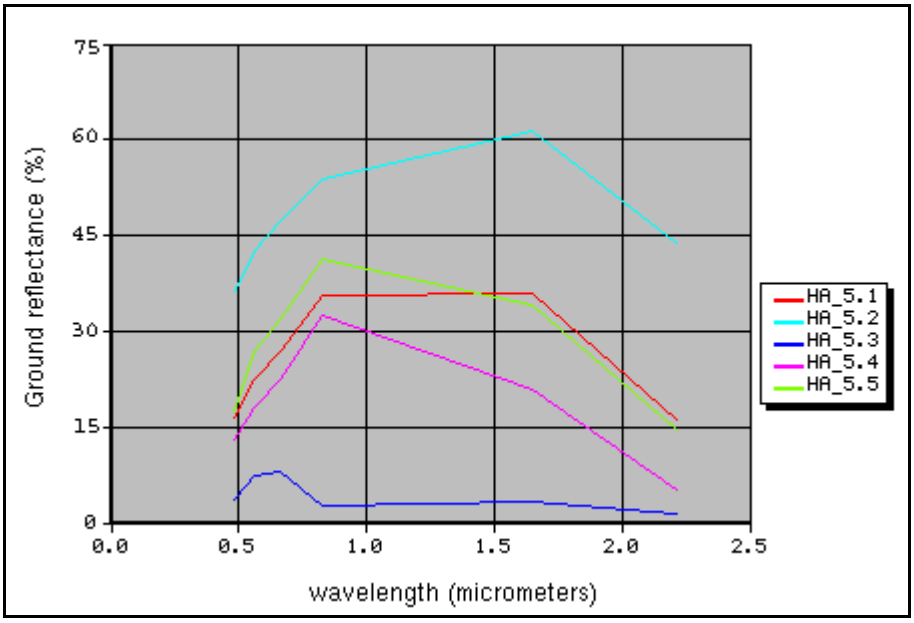
f) *Processed OH-FeOx image (1989)*



g) *TM image -1989 (3,2,1 – RGB)*



h) *TM image -1989 (7,4,1 – RGB)*



i) Spectral profiles inside the pond for kaolin sands for the image dated 1998

Figure 3.19 Landsat-TM colour-composites and processed images for Aghires tailing pond (Western Carpathians)

This tailing pond (mapped in CORINE Land Cover as mineral extraction site) is located on the valley nearby the road, railway and the local industry and it represents the place where the kaolin sands are prepared and washed (the purpose being a sorting of the sand but mainly the kaolin recovery). This way it is obtained a white quartz sand used for the glass industry and smelters and a good quality kaolin used for ceramics industry.

In the figures 3.19a - 3.19d there is shown at a detailed scale the pond in various band combinations, as well as the processed OH-FeOx image (all corresponding to 1998), in the next four figures (3.19e - 3.19h) being presented this site in 1989. The band combinations 7,4,1 and 4,5,3 (RGB) can point out better than the display in "real colours - 3,2,1" the distribution of different materials within the dump site (quartz sand, respectively kaolin) but the best separation (inclusively a net differentiation against the surrounding background) was achieved by applying the FPCS method. The spectral profiles computed for some locations within the 1998 image (figure 3.19i) prove that 5.1, 5.4 and 5.5 present not only strong iron-staining, but also deep absorptions in TM7 (characteristic for kaolin), that cause a maximum OH anomaly. That is demonstrated also by the colour-composite 7,4,1 (RGB), these areas being shown as bluish-cyan (more obvious in the larger zone at the right side). Location 5.2 corresponds to very bright pixels that have overall high reflectance, most probably white quartz sand. Spectrum 5.3 represents the deepest water on the tailings, with high values in both Fe-PC3 and Fe-PC4 and with moderate-high values in OH.

The images presented in figures 3.19a-3.19h show a different distribution of the materials inside the tailing pond in the specified time period, proving the potential of the method in differentiating between simple oxidized material, other mined material with OH-bearing secondary minerals indicators of possible hazard and water with suspensions. The FPCS method can serve for monitoring the materials contained in the ponds for mineral processing, identifying eventual undesired leakage events in the environment.

3.2. Slovakia

The methodology for rapid screening of mining wastes at regional level was validated also on Slovakia, another country with a long history in mining. Although nowadays the necessities in metallic minerals are covered mainly from export and few metallic mines are still operating (Country Report of the Steering Committee), there are numerous active mines producing brown coal and lignite, industrial minerals (magnesite, barite, talc, gypsum, limestone, dolomite, kaolin, ceramic clays, bentonite, zeolites, salt etc.), as well as quarries for construction materials (crushed stones, gravel sands, brick clays).

3.2.1. Description of the area

The area selected in Slovakia for applying the remote sensing methodology is covered by two Landsat – Thematic scenes (187/26 and 188/26) timely spaced between 1985 and 2000, presented in figure 3.20 having as background the CORINE Land Cover map.

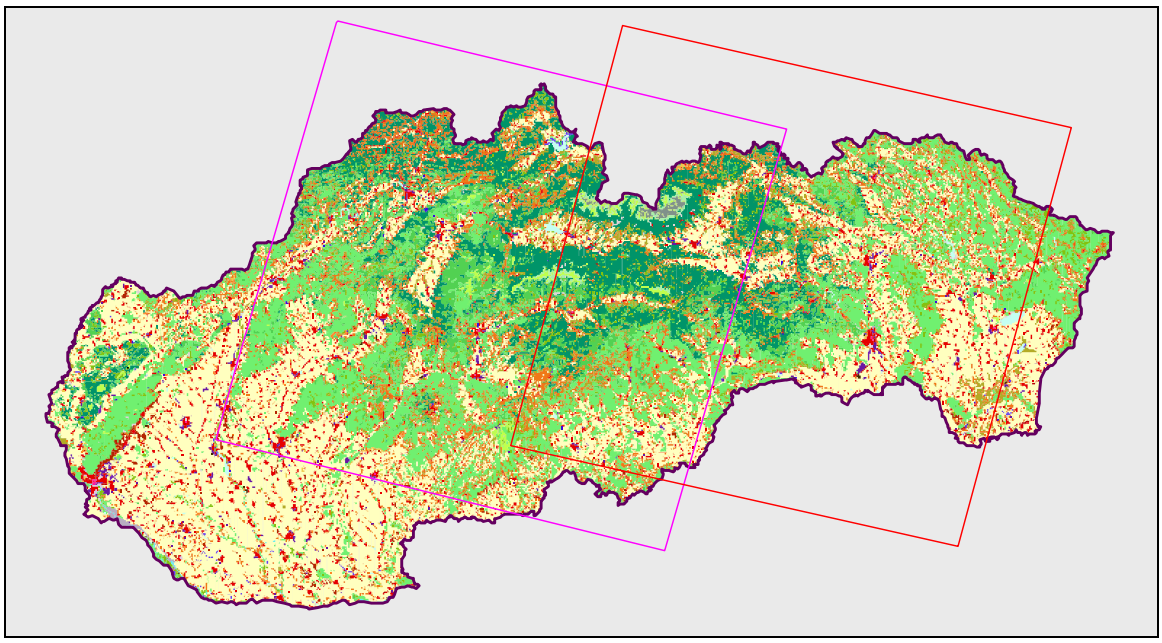


Figure 3.20 Coverage of Landsat – Thematic Mapper satellite scenes used for the validation of the methodology in Slovakia. The background is represented by the CORINE Land Cover map.

Taking into account:

- the smaller surface of the country (approximately 1/5 compared to Romania), being thus covered almost entirely by the above mentioned satellite scenes;
- the fact that this zone corresponds to the distribution of significant historic ore deposits of Slovakia and of most mines and quarries presently in operation;
- almost all top-ranked environmental "hot spots" in the classification system of the Ministry of the Environment fall inside it (SC Country Report);

it can be assumed that the Slovakian territory studied herein is a representative exemplification of applying the remote sensing method at national level.

This area is dominated by the mountain range of the Western Carpathians, belonging to the Alpine-Himalayan system. They are characterized by zoning, making up a

structure of arched nappes composed of flysch, crystalline and carbonate formations separated by basins and grabens where coal or evaporate deposits might be present. In the central, southern and eastern areas there are Neogene volcanic rocks, part of an extensive volcanic region of the Carpathian arc and Pannonian Basin (Geological Map of Slovakia 1:500.000, 1996).
The zone covered by the satellite scenes corresponds to twenty priority "hot spots" identified by the studies carried out in Slovakia by the Ministry of Environment:

- for ore deposits (mainly Pb, Zn, Cu, Hg, Sb, Fe, Au, Ag): Banská Štiavnica, Rudňany – Poráč, Hodruša – Hámre, Slovinky, Kremnica, Smolník, Nižná Slaná, Rožňava, Novoveská Huta, Gelnica, Špania Dolina, Dúbrava – Magurka;
- for brown coal and lignite: Handlová, Cígeľ, Nováky, Baňa Dolina;
- for industrial minerals (mainly magnesite, talc, asbestos, barite): Jelšava, Lubeník, Zlatník, Hnúšťa – Mútnik, Košice – Bankov, Podrečany.

In validating the methodology for regional mapping of mining wastes for the Slovakian territory information regarding these "hot spots" was taken into consideration, together with all other available data from multiple sources.

3.2.2. Available data sets

The data sets available to be used for verifying the output remote sensing anomalies consisted in:

- CORINE Land Cover data base in digital format;
- CORINE Land Cover Tourist Map of Slovakia, 1:500.000 scale (Feranec et al., 1996 - Institute of Geodesy and Cartography, Bratislava);
- Geological Map of Slovakia, 1:500.000 scale (Biely et al., 1996 - Geological Survey of Slovak Republic, Bratislava);
- Map of Mineral Fuels and Metals, scale 1:1.000.000 (Tréger and Baláž, 2000 - Geological Survey of Slovak Republic);
- Map of Industrial Minerals, scale 1:500.000 (Tréger and Baláž, 2000 - Geological Survey of Slovak Republic);
- Map of Construction Materials, scale 1:500.000 (Tréger and Baláž, 2000 - Geological Survey of Slovak Republic);
- Topographical maps;
- Country Report prepared by the national partners from the Steering Committee of the PECOMINES project (Jánová and Vrana, 2004 in *Jordan and D'Alessandro*, eds.);
- Report on the "Methodologies for comparison and prioritization of mining sites in Slovakia" prepared by the national partners from the SC;
- Mining related data (in digital format) provided by the Ministry of Environment of Slovakia from the national database, representing:
    - the location (in geographic co-ordinates) and the commodity extracted of mining sites for metals, solid fossil fuels and industrial minerals mines, as well as their name and code in the database (70 records);
    - the location (in geographic co-ordinates) and code of the sites for construction materials (359 records);
    - the location (in geographic co-ordinates) and codes of old historical dumps. Other parameters, as: mineral commodity, extraction type, status of the mine, name of the dump and of the afferent locality and

the category of the hot spot were also included. All these 5898 dumps originated from underground closed mines.

Like in the case of Romania, when it was requested by verification purposes, some of the thematic maps were scanned and geo-referenced. The mining related digital data were projected from geographic co-ordinates into the specific map projection system of the Landsat – Thematic Mapper images and the above mentioned items were transformed into attributes in order to enable a spatial analysis with the remote sensing anomalies within a GIS.

3.2.3. Validation

The validation of the anomalous pixels (ferro oxy-hydroxides and secondary OH-bearing minerals) obtained by applying the PECOMINES method for regional mapping of mining wastes followed the same steps as for the case of Romania. The OH-FeOx map was checked against the available data sets mentioned above. A supplementary step was done by integrating all data in a GIS and performing the calculation of anomalous pixels falling inside first order catchments of Slovakia (CCM – Catchments Characterization and Modelling Database of the European Commission[1]).

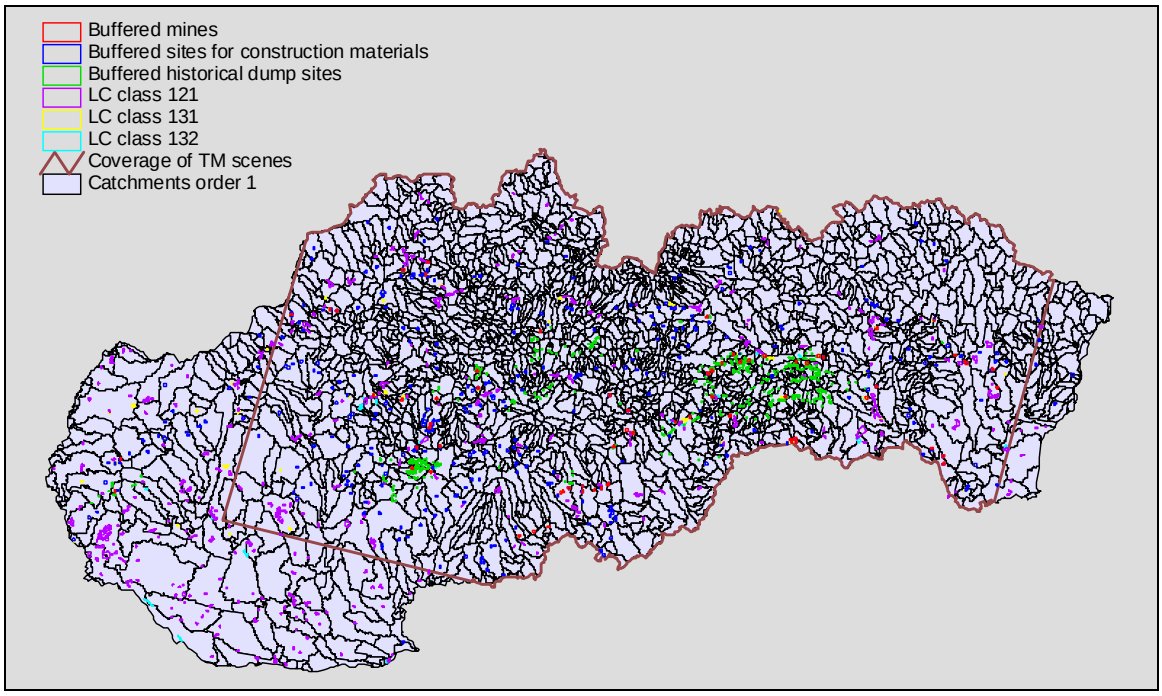


Figure 3.21 First order catchments map of Slovakia. The remote sensing OH-FeOx anomalies are validated in a GIS against mining related data from pan-European and national databases.

For every first order catchment (figure 3.21) it was computed the co-occurrence of anomalous pixels detected by remote sensing with the areas covered by the classes from available databases representing features related to the extractive industry. The scope was obtaining a quantitative estimation of validation and furthermore, a differentiation of the mining sites from the point of view of the hazard they might

[1] CCM River and Catchement Database JRC/LMU © European Commission - JRC

cause, based on the observed anomalies within the natural barriers represented by the catchments borders.
From the analysis it resulted that for the study area in Slovakia, 76% of the first-order catchments contained anomalous pixels and the global co-occurrence with features related to the extractive industry raised to 23%. The ratio "co-occurrence pixels/total anomalous pixels" varies from 0.2 up to 100 % (the latter for a number of 14 catchments), the mean being 27%. The scatterplot of co-occurrence pixels versus total anomalous pixels is shown in figure 3.22 and the results are in good agreement with the mining "hot spots" in the Country Report elaborated by the Ministry of Environment in Slovakia (Steering Committee).

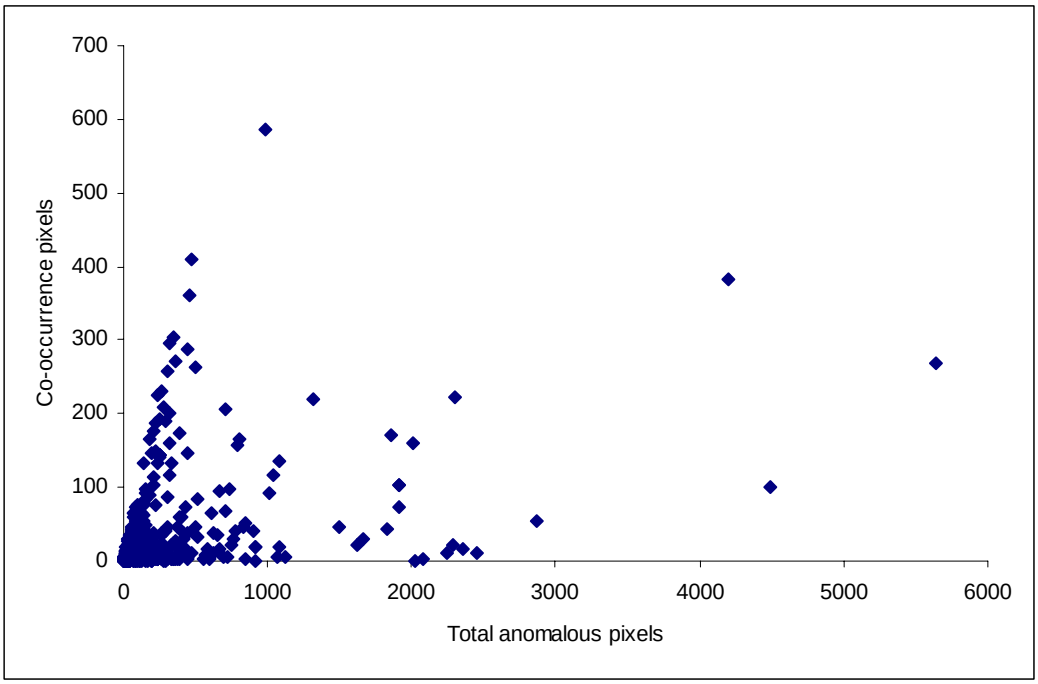


Figure 3.22 Scatterplot of co-occurrence pixels versus total anomalous pixels for first order catchments in Slovakia

In presenting the results of validating the remote sensing methodology for the case of the Slovak territory reference will be made to this scatterplot of co-occurrence pixels, either in absolute figures, or computed as a percentage ratio. The examples selected represent catchments having a particular and meaningful position in the scatterplot and with a known activity in the extractive sector.

The first example refers to the catchment with the highest number of co-occurrence pixels (587 co-occurrences on the scatterplot in figure 3.22). It corresponds to the zone of Jelšava with mines for magnesite, confirmed as the top ranked "hot spot" in the Country Report of Slovakia. Another neighbouring catchment with Lubeník "hot spot" (magnesite) shows also high values and the entire region is known for the problems of soil alkalization due to magnesite mining and treatment. The map of co-occurrence pixels for the catchments in this area is presented in figure 3.23, the satellite image and processed anomaly image (OH-FeOx) being shown in figures 3.24a, respectively 3.24b. It can be noted that the main part of the remote sensing anomalous pixels falls inside the mining related classes from the CORINE Land

Cover database or/and buffered (for precision reasons) locations of mines, sites for construction materials and old dumps from closed mines.

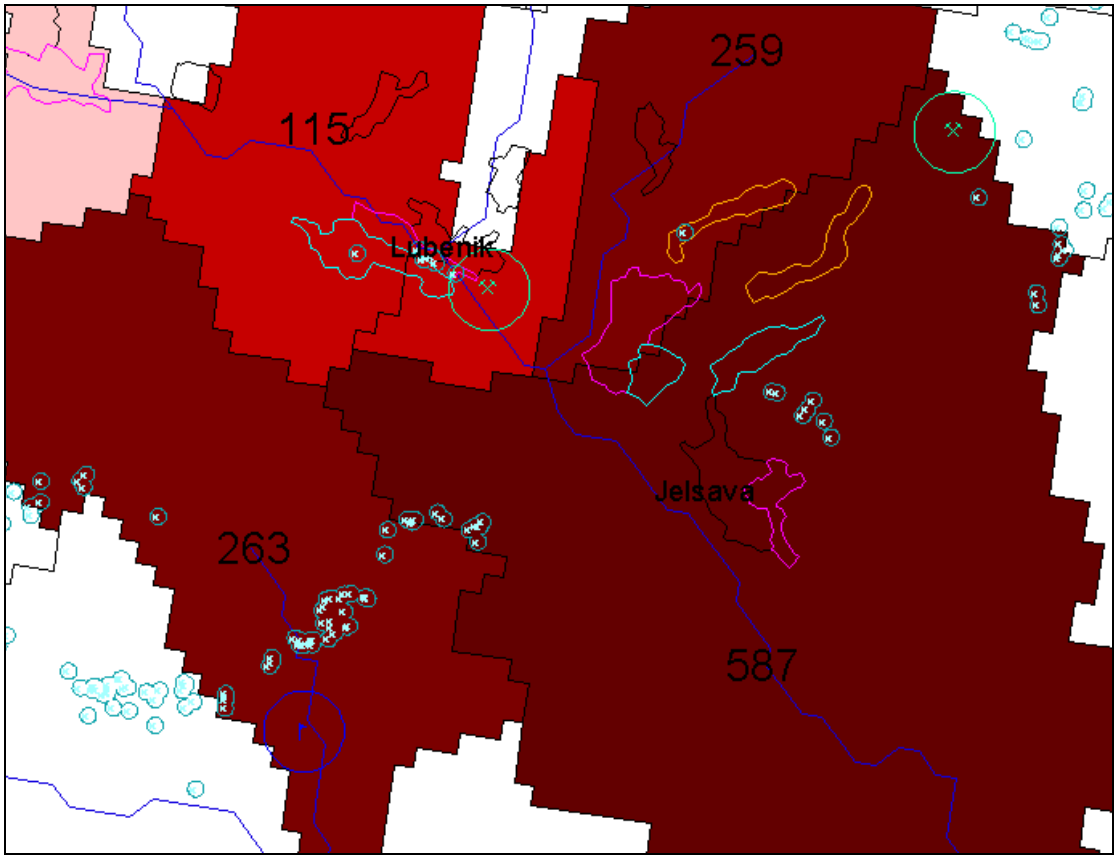
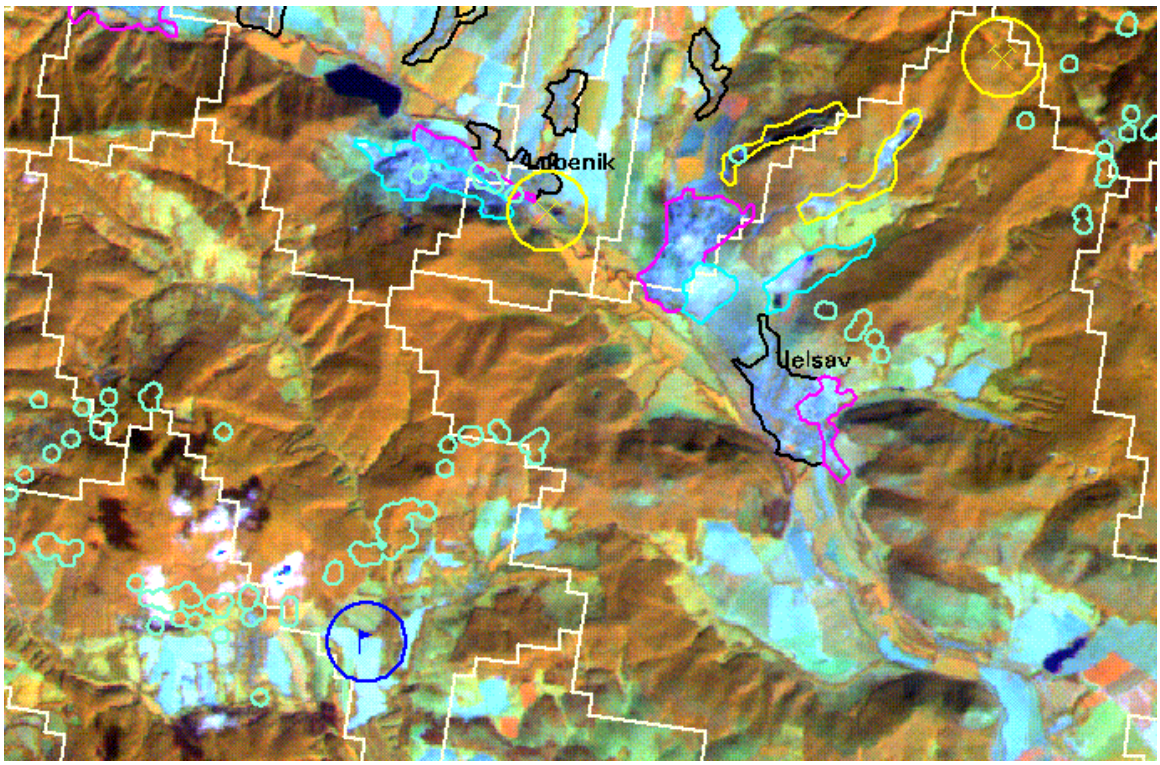


Figure 3.23 Map of co-occurrence pixels in Jelšava and Lubeník magnesite mining region, showing the CORINE Land Cover classes (131 – mineral extraction sites, 132 – dumps sites, 121 – industrial units), as well as the locations of mines, sites for construction materials and old dumps. Jelšava catchment exhibits the highest number of co-occurrence anomalous pixels, being ranked in SC Country Report in the top of the "hot spots" list.

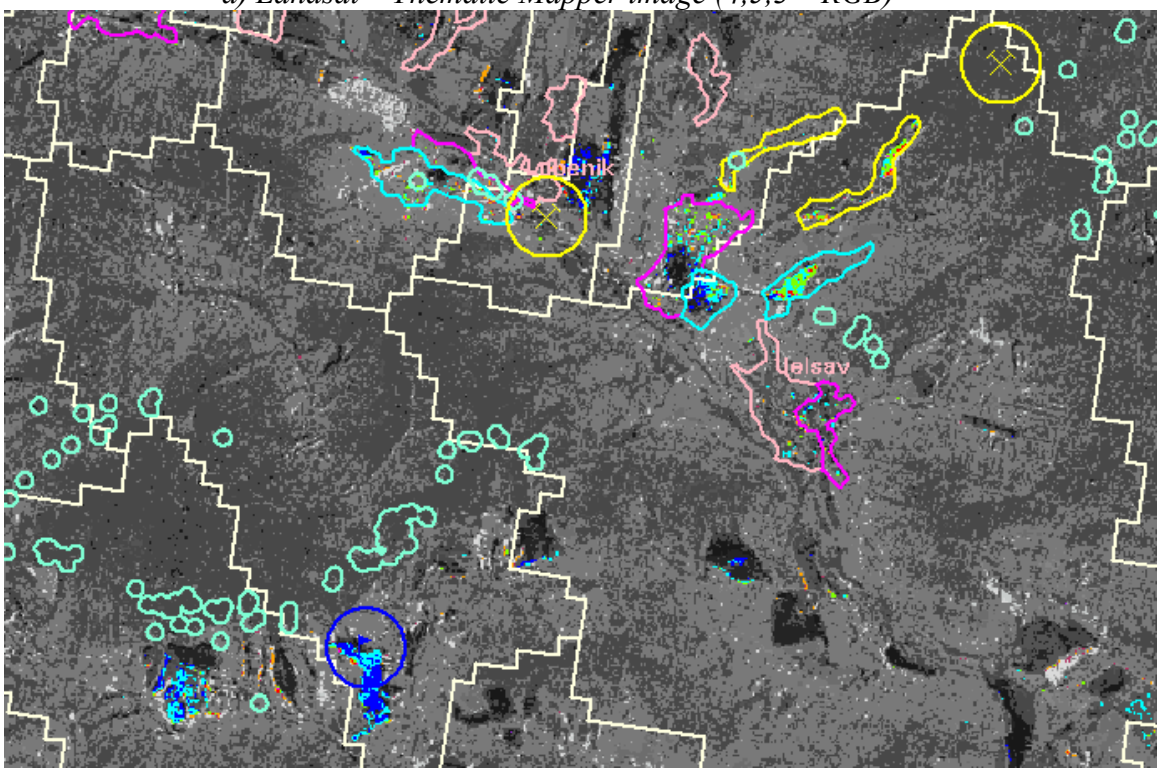
Some other anomalous pixels can be seen outside the above mentioned classes, but in the vicinity of Lubeník mine, or in the bottom-left part of the image (figure 3.24b), nearby a site for construction materials and the old historical dumps. The comparison with the Landsat-TM image (figure 3.24a) suggests the idea that the latter cluster of pixels most probably corresponds to another site where mining activity is present, leading to exposed oxidized material. These pixels are represented by blue and cyan colours indicative of heavy iron-staining and low levels in minerals with absorptions in TM7 (OH-bearing secondary minerals or carbonates). Such absorptions are represented on the image by green, orange, red pixels (medium-high and high levels in these minerals), which in our case correspond to magnesite, occurring mostly inside the mining related classes at Jelšava and Lubeník localities.

The example presented for this mining region of Slovakia proves the applicability of the remote sensing method not only for acidification issues, but also in the case of contamination with carbonates causing alkalization. The separation between these processes can be done by combining the remote sensing derived information with

auxiliary data regarding the nature of the mined commodity, the geological background of the area and the types of soils.



a) Landsat – Thematic Mapper image (4,5,3 – RGB)



b) Anomaly (OH-FeOx) image

Figure 3.24 – Distribution of anomalous pixels in Jelšava and Lubeník magnesite mining region. A great number of the anomalous pixels showing absorptions in the short wave infrared (TM7) falls inside the mining related features from the CORINE Land Cover or national database.

For every first order catchment it was also computed the ratio "co-occurrence pixels/total anomalous pixels". High values of this ratio were found for catchments with mining related features, demonstrating once more the potentiality of the remote sensing method in regionally mapping deposited materials from the extractive industry. As an exemplification in figure 3.25 it is presented the area situated south of Spišská Nová Ves, a well known mining region of Slovakia. The mining sites of Novoveská Huta (Cu, U, talc), Rudňany – Poráč (Fe, barite), Slovenky (Cu) in the South of Krompachy and Smolník (Fe, Cu, Sb) are specified as "hot spots" in the SC Country Report and the respective catchments show a high percentage of co-occurrence with CORINE Land Cover and/or national data.

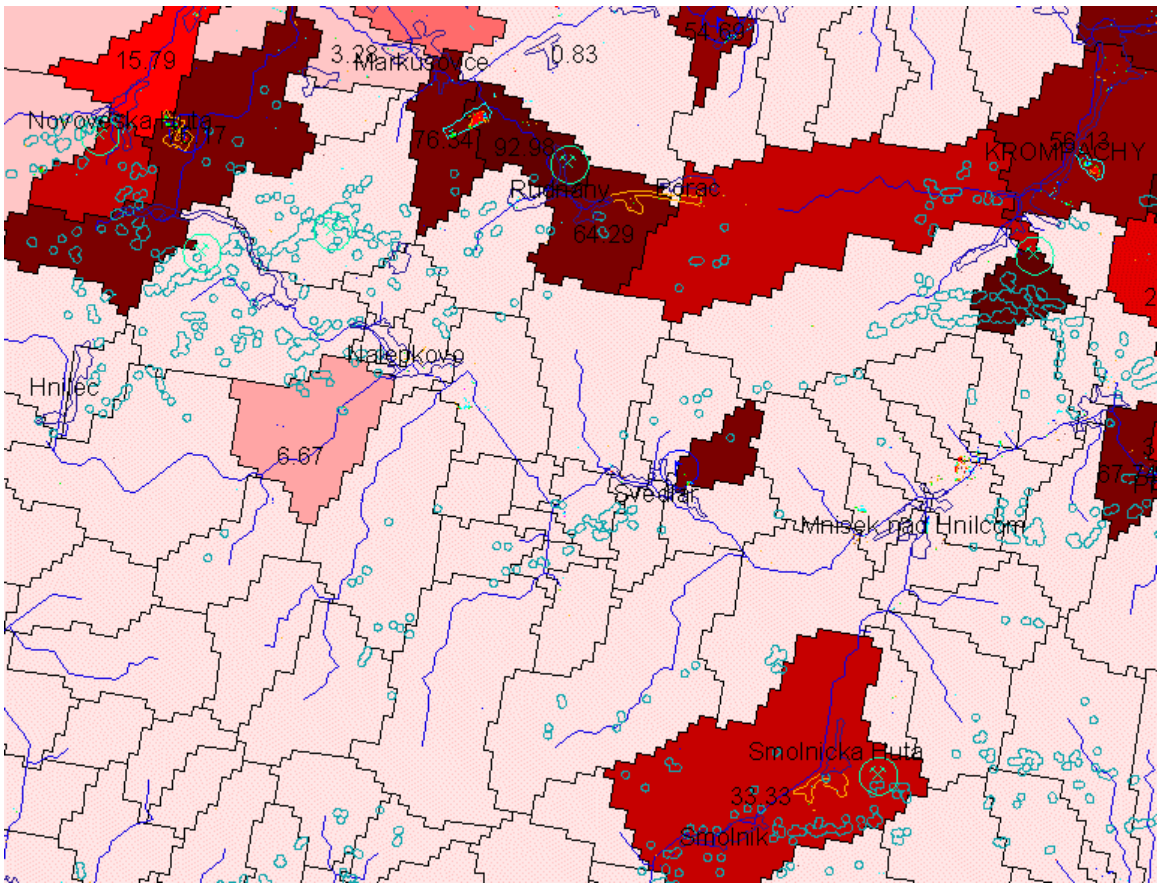
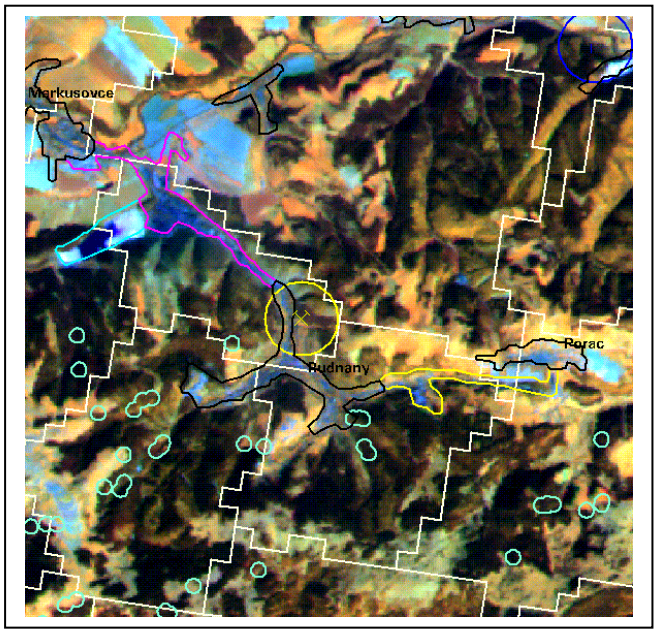


Figure 3.25 Map of ratio "co-occurrence pixels/total anomalous pixels" showing high values for the catchments of mining "hot spots" Novoveská Huta (Cu, U, talc), Rudňany – Poráč (Fe, barite), Slovinky (Cu), Smolník (Fe, Cu, Sb), as well as for the smelters at Rudňany and Krompachy

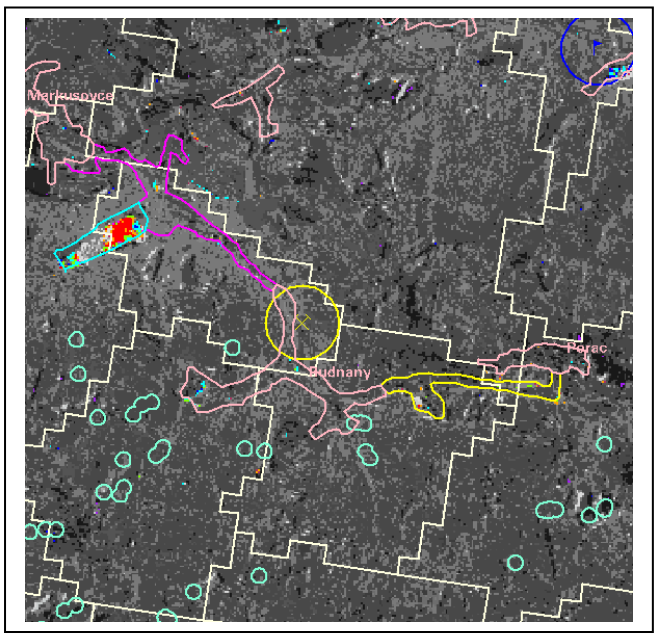
Figure 3.25 shows also the anomalous pixels of the remote sensing processed image, the biggest and most intense anomalies (ferro oxy-hydroxides plus OH-bearing secondary minerals due to the transformation reactions of the complex barite-siderite-sulphide ores) occurring in the dumps of the smelters from Rudňany (South of Markusovce) and Krompachy.

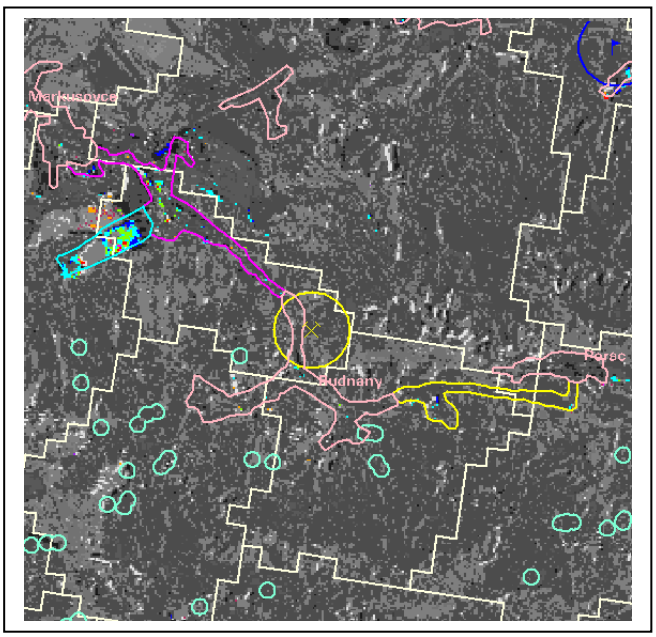
In figure 3.26a it is presented at a more detailed scale the satellite image in the area Markusovce - Rudňany – Poráč, the processed remote sensing image (OH-FeOx) being shown in figure 3.26b. There can be easily observed the anomalous pixels in the dump of the smelter, as well as some other isolated pixels inside the CORINE Land

Cover polygon representing the mineral extraction site of Rudňany – Poráč. The site for construction materials in the upper right corner of the image is highlighted also by a discrete anomaly.



a) Landsat – TM image (4,5,3 – RGB) dated 1985



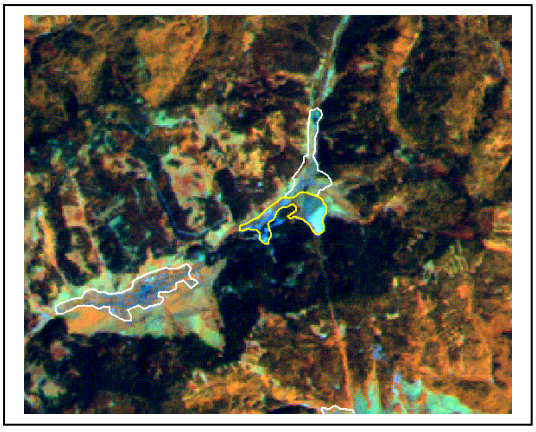


b) Anomaly (OH-FeOx) image - 1985 *c) Anomaly (OH-FeOx) image - 1992*
Figure 3.26 Modifications of surface properties of the materials in the dump of the smelter at Rudňany between 1985 and 1992, materialized by a decrease in the intensity of the hydroxyl anomaly

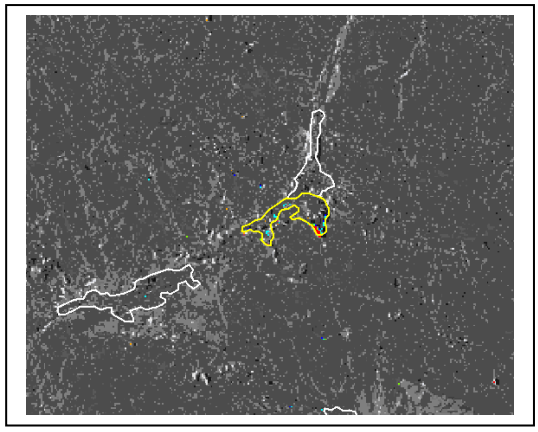
Comparing this anomaly image (dated 1985) with another one from 1992 (figure 3.26c), a difference can be noted in the dump of the smelter in this time period, indicating a modification of the surface properties of the materials in the dump. On both processed images no anomalies are observed inside the old historical dumps from closed mines and this is explicable by the fact that generally these dumps are

located in forested areas. Here the signal reaching the Landsat – Thematic Mapper sensor represents the incoming electromagnetic radiation reflected by the vegetation canopy. This observation applies to all mining features located in dense forests, where no clear-cuts are present.

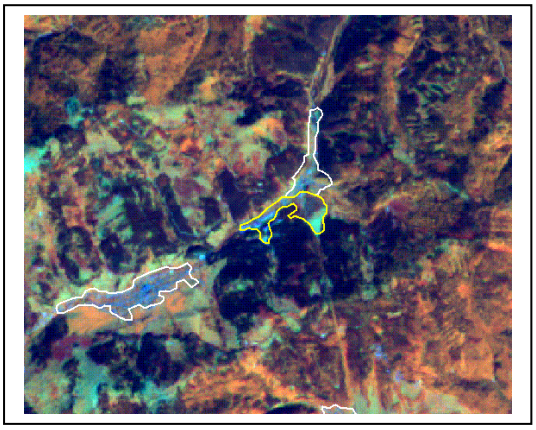
The conditions of remedied tailing ponds belonging to closed mines can be monitored by use of multi-temporal satellite images processed with the FPCS method for mapping mining wastes. Such an example is given for the Smolník area where the mine for Fe, Cu, Sb (the last mined commodity being sulphidic Cu ore), located 4 km ENE of Smolník, near Smolnícka-Huta, was closed in 1990 and then flooded, causing acidic waters from the mine to enter Smolník stream that further away flew into Hnilec river. The tailing pond was remedied by coverage with a 0.5 m layer of saw-mill chips. In the satellite images dated 1992 and 2000 (figures 3.27a and 3.27c) the tailing pond and the adjoining mining facilities are mapped together in a unique CORINE LC polygon as a mineral extraction site (class 131). The OH-FeOx anomaly images (figures 3.27b and 3.27d) show that in 1992 there were still high concentrations in both iron oxides and OH-bearing secondary minerals on some small zones of the dump, but in 2000 no anomalies could be seen there, except one-two pixels representing only iron-staining, related to the demolished mining facilities. A view of the remedied tailings pond (as of 2001) is presented in figure 3.27e and the growing vegetation that began to cover it can be easily noted. During the field trip made at this site by representative of the JRC and Comenius University of Brastislava the indicators of acidification were observable only at a limited number of places lacking vegetation, located on the slopes of the tailings.
This acidification caused by leakage from the tailing pond makes up an insignificant contribution compared to the acidification of the ground waters and soil by mine waters. In 1994 the acidification of Smolník and Hnilec rivers was so intense that it caused the death of a great number of fish, therefore a complex project for remediation was prepared in 1996 (SC Country Report).
Presently the mine waters are collected by means of an in-situ leaching facility with anoxic limestone in order to neutralize their acidity prior of flowing into Smolník stream. Since the pH of waters is still high in the immediate zone of discharge into the stream this leaching facility represents a point source of acidification, but, similar to the remedied tailing pond, its hazard is minor comparatively to the acidification of ground waters. This acidification problem, accompanied by the impact of de-watering of the aquifer horizons, changes in hydrological regime of surface and ground water, as well as geo-mechanical phenomena, determined the site to be considered an environmental "hot spot" (SC Country Report).
In this zone where the greatest hazard was caused by underground phenomena, the acidification manifestations at the surface being of reduced areal extent and importance due to the remediation measures taken, the respective remote sensing anomalies were located only on small areas (1992) or missing (2000), being in accordance with the field observations. This way it is illustrated the potentiality of the PCA-based method in monitoring the surface conditions of a mining site over time. For a complete assessment of the status of the closed mines, as required by the proposed Mining Waste Directive, the information derived from the remote sensing method regarding the deposition of potentially hazardous mining waste material should be combined with other information referring to the underground conditions and the geo-mechanical stability.



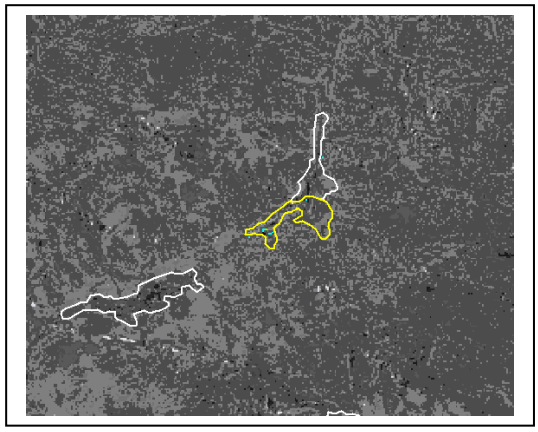
a) Landsat – TM image (1992)



b) Anomaly (OH-FeOx) image – 1992



c) Landsat – TM image (2000)



d*) Anomaly (OH-FeOx) image – 2000*

e) The remedied tailing pond (covered by a layer of saw-mill chips) in 2001

Figure 3.27 Reduced areal extent of the remote sensing anomalies in 1992 and their lack in 2000 for the Smolník remedied tailing pond, in agreement with the field observations and the SC Country Report. In this case the hazard consists in acidification of the ground waters and soil by the mine waters, hydro-geological and geo-mechanical phenomena.

Another area for exemplifying the validation of the remote sensing methodology in Slovakia refers to the catchments with mining sites and smelters located in Southern Slovakia, in the region Stara Kremnicka, Ziar nad Hronom, Banská Štiavnica. The respective catchments show also high values of the ratio "co-occurrence pixels/total anomalous pixels". In figure 3.28 the anomalous pixels corresponding to the mines for quartzite, limno-quartzite, as well as some sites for construction materials are easily noticed, together with other anomalies inside the CORINE Land Cover polygons for the industrial unit and the dump representing the smelter at Ziar nad Hronom. The dump site at Banská Štiavnica, nearby Banská Bela exibits also an anomaly and high values of co-occurrence (84.62%, respectively 83.56%) are met for the catchments in the right side of figure 3.28, where the anomalies correspond to sites for construction materials and the industrial unit at Zvolen.

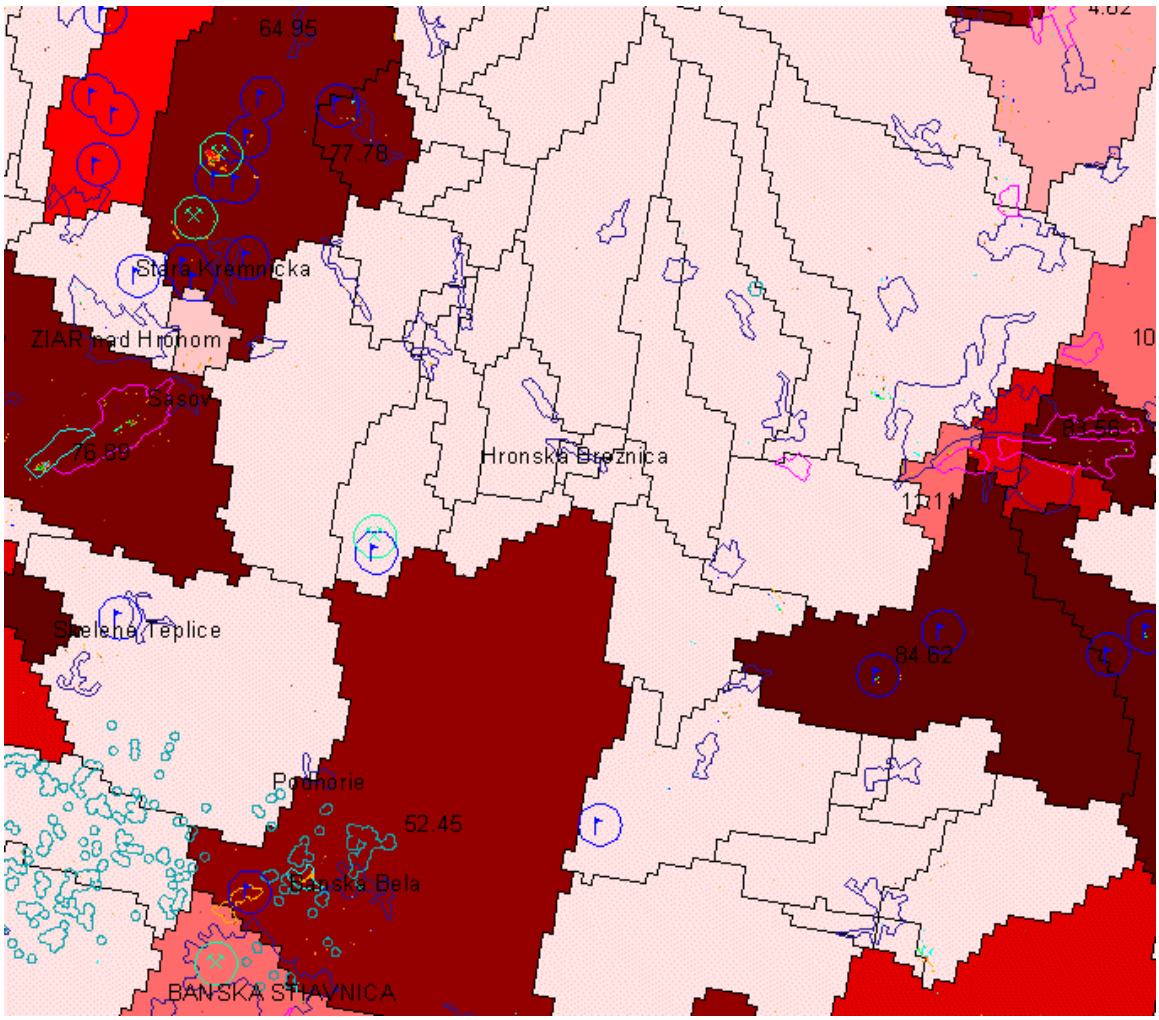
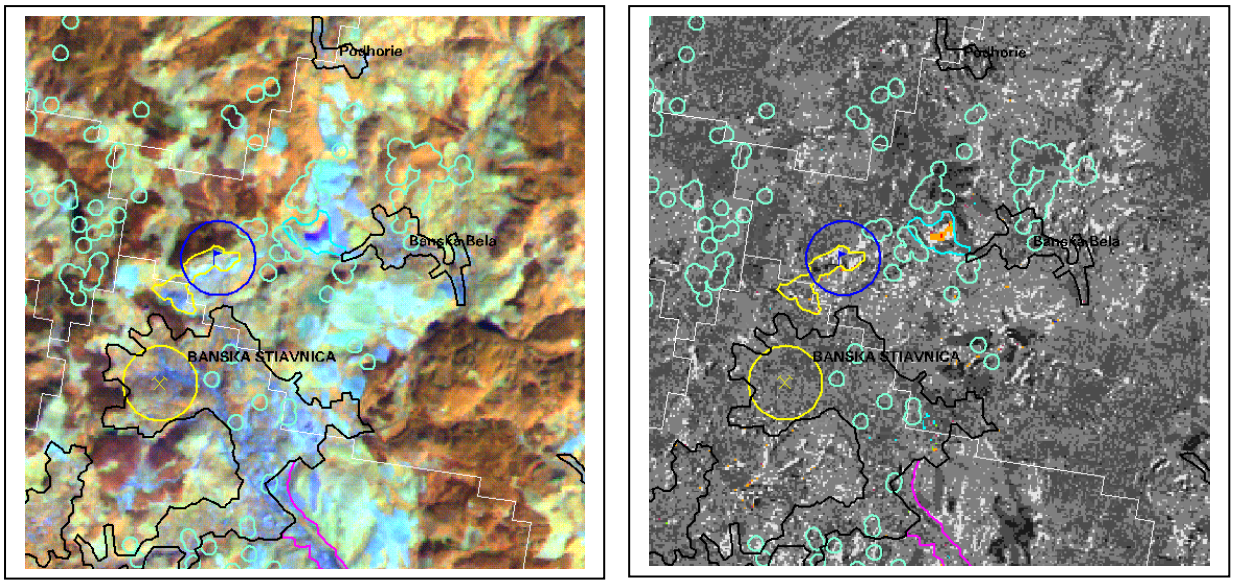


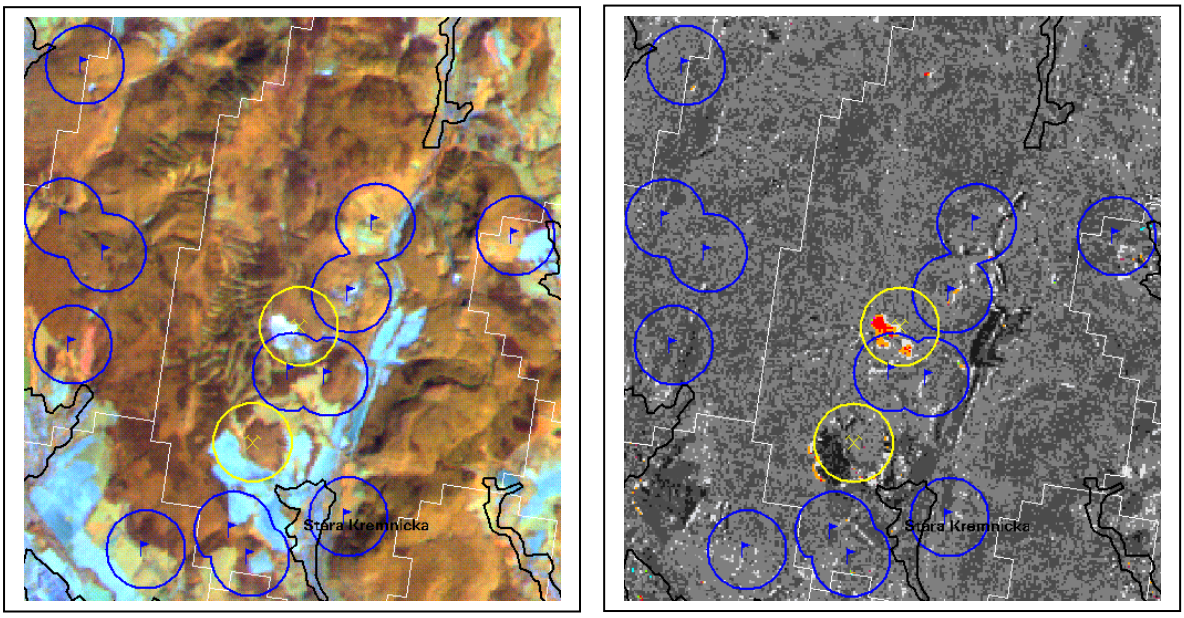
Figure 3.28 Map of the ratio "co-occurrence pixels/total anomalous pixels" in the region of Stara Kremnicka (mines for quartzite, limno-quartzite), Ziar nad Hronom (smelter), Banská Štiavnica (old mine for Au, Ag).

Details of the region are shown in figure 3.29 (for Banská Štiavnica dump site, included on the list of first category "hot spots" in the SC Country Report) and figure 3.30 (for the mines and sites for construction materials North of Stara Kremnicka). On the latter, besides the anomalies that fall inside the buffered locations it can be noted a small size anomaly (one-two red pixels) in the upper part of the image in figure 3.30b, which corresponds on the satellite image to non-vegetated pixels. This anomaly

indicates both iron-staining and high amounts in OH-bearing secondary minerals, most probably corresponding to another mineral extraction site not included in the database but potentially hazardous.



a)Landsat – TM image (4,5,3 – RGB) *b)Anomaly image (OH-FeOx)*
Figure 3.29 The old mining area of Banská Štiavnica, pointing out the anomalous zone of the dump site near Banská Bela. This zone is considered (SC Country Report) an environmental "hot spot".



a) Landsat – TM image (4,5,3 –RGB) *b) Anomaly (OH-FeOx) image*
Figure 3.30 Distribution of anomalous pixels inside the buffered mining locations (quartzite, limno-quartzite) and sites for constructions materials in the area North of Stara Kremnicka. Another small FeOx-OH anomaly could represent a new mining site, potentially hazardous.

The last example presented for Slovakia refers to the category of catchments with a big number of anomalous pixels and also co-occurrence with the features related to

the extractive industry, but having the ratio "co-occurrence pixels/total anomalous pixels" much lower (between 2 and 9%). They correspond to points at the extreme right side of the *x* axis on the scatterplot in figure 3.22 (more than 2000 total anomalous pixels) and their geographical distribution in the Central-South of the country, between Divín, Poltár, Lučenec localities is shown in figure 3.31.
Analyzing the processed remote sensing image (figure 3.32b) it can be noted that these catchments where several pits of ceramic clay and kaolin are located, as well as quarries for construction materials show indeed anomalous co-occurrence pixels. However a large number of anomalous pixels (mostly belonging to the classes rich only in FeOx) can be observed in the surrounding area, related to correspondence between soil mineralogy and the extracted material. This region where the satellite image (figure 3.32a) indicates a predominantly agricultural land use is considered of interest for prospecting new deposits of raw materials to be used in the ceramic and china industries of Slovakia.

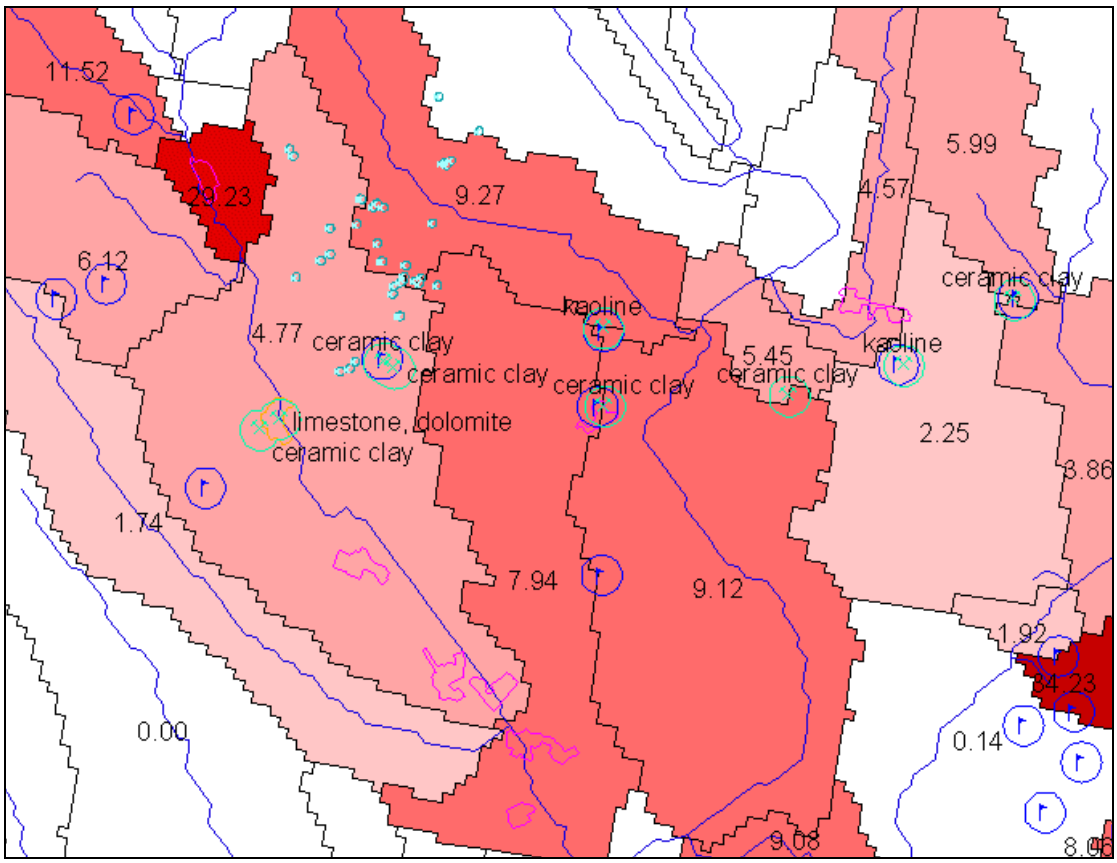
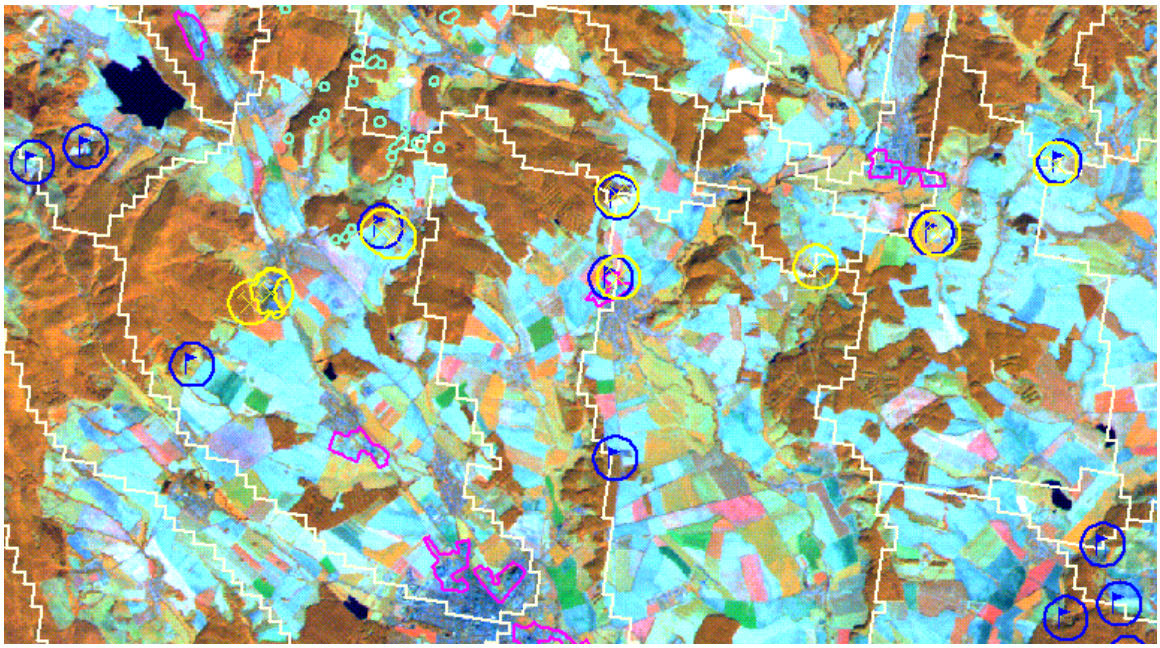


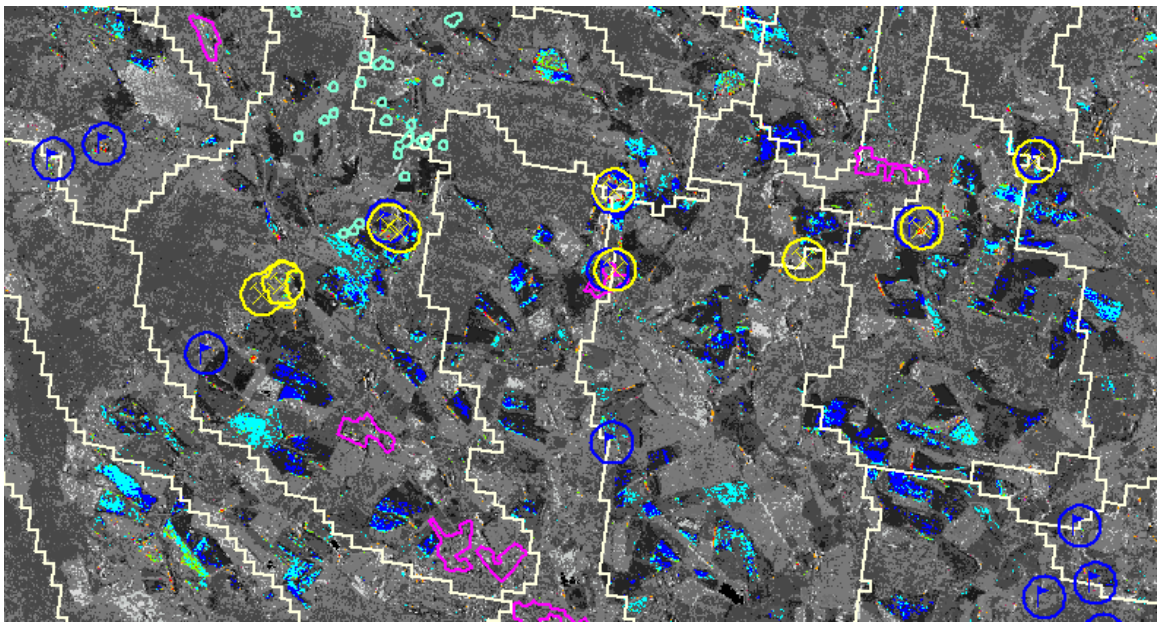
Figure 3.31 Map of the ratio "co-occurrence pixels/total anomalous pixels" for the region of mines for ceramic clay and kaolin in the southern part of Slovakia, between Divín, Poltár, Lučenec localities. Opposite to the above examples, the catchments in this area exhibit a high number of anomalous pixels, co-occurrences with locations of pits and quarries from the national database, but the ratio has much lower values.

This example, like all the rest, highlights the general potential of the FPCS-based method in mapping the distribution of materials resulted from the extractive industry even when the exposed surface is very small (but at least one pixel). The separation between different types of mining materials can be done based on the types of anomalies produced (only iron-staining or co-existence of OH-bearing secondary minerals/carbonates) combined with additional information regarding the geology,

soil types, but also land cover and land use. By computing within the catchments boundaries the co-occurrences between the output anomalies and the mining related features from CORINE Land Cover or/and national database, the validation of the remote sensing methodology in Slovakia gained a quantitative dimension. This served for performing a statistical analysis of the relationship between the remote sensing anomaly classes and the features they characterize on Earth surface.



a) Landsat – TM image (4,5,3 – RGB)



b) Anomaly (OH-FeOx) image

Figure 3.32 A great number of anomalous pixels in the catchments located in the South of Slovakia, between Divín, Poltár, Lučenec localities. Co-occurrences with pits for ceramic clays and kaolin exist, as well as with quarries for construction materials. Some other anomalies represent correspondence with the same soil mineralogical components as in the extracted materials.

4. STATISTICAL ANALYSIS OF REMOTE SENSING ANOMALIES AT CATCHMENT LEVEL

The validation of the remote sensing anomalies for Slovakia was done by computing the co-occurrences of anomalous pixels with the mining related features from pan-European or national databases. As it was shown in chapter 3.2, the global number of co-occurrence anomalies or the respective percentage to all anomalous pixels found within a catchment proved a good agreement with the available data. The examples presented correspond to mining sites which are indeed considered as environmental "hot spots" by the national authorities (SC Country Report).
However, it is desired to differentiate in a quantitative way between catchments with a high number of anomalous pixels representing mainly iron-stained minerals and catchments where there are secondarily formed minerals indicating a potential hazard, such as acidification (or soil contamination by carbonates). The way to achieve this implies that the relationships between the types of anomalies produced within various land biophysical occupation categories are statistically analyzed. Based on this analysis an anomaly index is developed, capable of pointing out the catchments which are most prone to become "critical".

4.1. Distribution of remote sensing anomalies within various land cover classes and mining related features

In order to assess the patterns of most hazardous mining sites having the catchments borders as natural barriers, the GIS analysis performed for globally validation of the remote sensing anomalies in Slovakia (chapter 3.2) was completed with a more detailed statistical analysis. The pursued objective consisted in statistically determining the distribution of different anomaly categories within the land cover classes and mining related features.
The CORINE Land Cover (CLC) classes used in the analysis consisted in the biophysical land occupation categories which are related to the features of the extractive industry, i.e. mineral extraction sites (class 131) and dump sites (class 132). Another CLC class that presented anomalous pixels corresponded to smelters or other plants for mineral ore processing, sometimes having adjacent dump sites and representing industrial units (class 121). However, the definition of this CLC class included also commercial units and some other categories (sanatoriums, hospitals, military bases, major livestock rearing facilities, cement fish farming ponds etc. - CORINE Land Cover Technical Guide, 1993) and this should be taken into consideration when interpreting the statistics. These areas do not show anomalies, except maybe one-two isolated pixels and this is in accordance with the FPCS-based method.
The visual inspection of the anomaly (OH-FeOx) images pointed out anomalous pixels spread out in other land cover classes, some of them occurring in the buffered areas constructed around the locations of mining sites, open-pits for construction materials and historical dumps (data provided by the Slovak Ministry of Environment from national database). In order to assess the possibilities and the limitations of the method for identifying accumulations of materials with high concentration in iron oxy-hydroxides and OH-bearing secondary minerals located in various land cover categories, the latter were recoded and introduced in the statistical analysis performed. The following categories were analyzed:

- class 111 – continuous urban fabric

- class 112 – discontinuous urban fabric
- class 121 – industrial or commercial units
- class 131 – mineral extraction sites
- class 132 – dump sites
- class 133 – construction sites
- class 2 - all agricultural areas
- class 3.1 – forest
- class 3.2 – shrub and/or herbaceous vegetation associations.

A GIS analysis for first order catchments (CCM – Catchments Characterization and Modelling Database of the European Commission) performed for the whole area of Slovakia covered by available scenes (approximately 65000 sq km) implied computing for every catchment:

– the number of pixels belonging to every land cover class mentioned above;
– the number of pixels belonging to the 500 meters buffered mining sites, 500 meters buffered open-pits for construction materials and 100 meters buffered historical dumps;
– the number of anomalous pixels co-occurring in the land cover classes and buffered mining features (separately for every combination FeOx-OH of interest from the anomaly image, per total 7 categories).

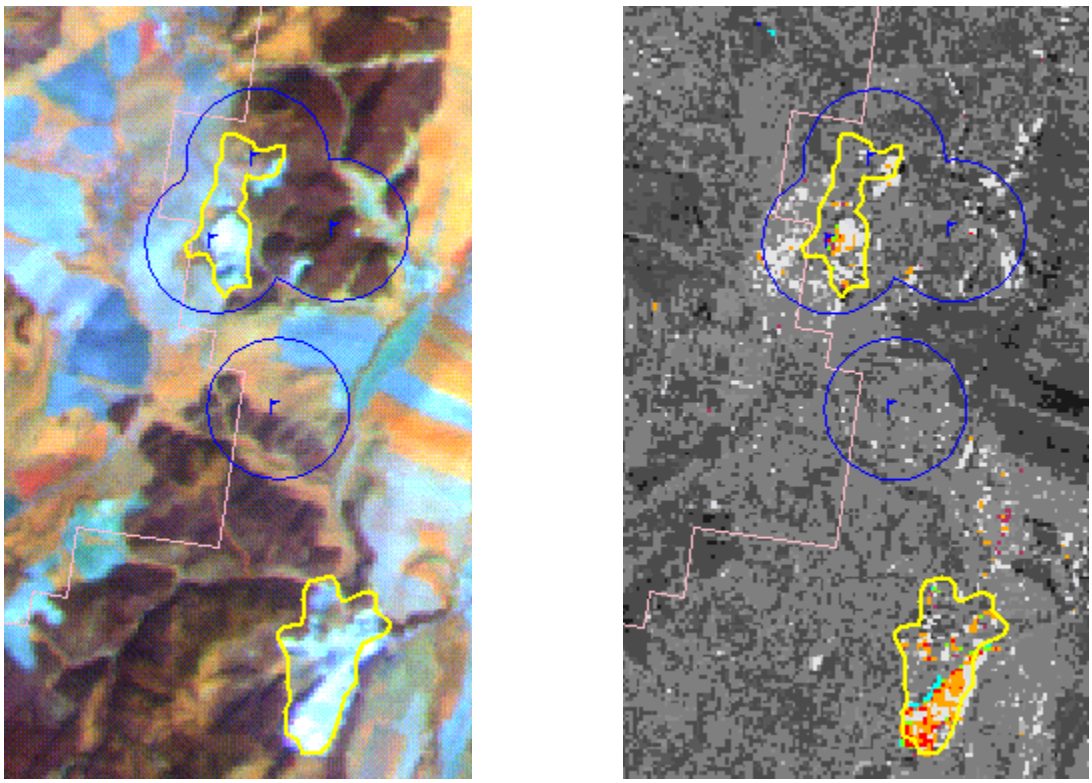
The results of the preliminary statistical analysis, presented in table 4.1, took into consideration, from a number of 2960 total catchments of first order existent for Slovakia only those where there was a complete data coverage (areas with no clouds within the satellite image), i.e. a number of 2237 catchments.

Table 4.1 Global statistics of anomalous pixels within different land cover classes for first order catchments of Slovakia

Class (from CORINE or national database)	No. of catchments where the class is present (Nc)	No. of catchments with anomalies within the class (Nac)	Global Ratio Rn=Nac/Nc (%)	Total no. of pixels belonging to the class (Tc)	Total anomalous pixels inside the class (Tac)	Global Ratio Rtp=Tac/Tc (%)	Mean Rtp
CLC 131	86	74	86.05	42953	3809	8.87	9.87
CLC 132	21	15	71.43	15976	1718	10.75	15.88
CLC 121	259	198	76.45	274215	4949	1.80	2.7
CLC 111	21	14	66.67	7196	93	1.29	2.26
CLC 112	1314	938	71.39	2030610	15019	0.74	0.89
CLC 133	10	6	60.00	6100	86	1.41	1.86
CLC 2	1975	1405	71.14	22505096	201473	0.90	0.95
CLC 31	2179	226	10.37	23488394	14092	0.06	0.95
CLC 32	1287	226	17.56	1832135	1024	0.06	0.25
Bufferred mines	93	51	54.84	81661	2620	3.21	5.1
Bufferred constr.mat.	313	183	58.47	348975	5590	1.60	2.92
Bufferred historical dumps	273	52	19.05	141984	206	0.15	1.17

From this table it can be seen that the mineral extraction sites and the dump sites of CORINE are pointed out as anomalies in a big percentage of the catchments where these classes occur. Checking individually the cases of mismatch (where the class exists in the catchment but it does not show anomalies) it was found that this was due mostly to the division of the class between catchment boundaries. Figure 4.1

illustrates this, showing how a couple of pixels of class 131 that fall into the neighbouring catchment do not exhibit anomalies, while these do exist for the part of class 131 that is not covered by vegetation (forest, as it can be checked with the satellite image). The example explains also why not all the pixels mapped as class 131 produce anomalies, since, due to the level of generalization of CORINE Land Cover, sometimes, in order not to loose a land cover unit which had an area less than 25 ha, some adjoining pixels are also included.

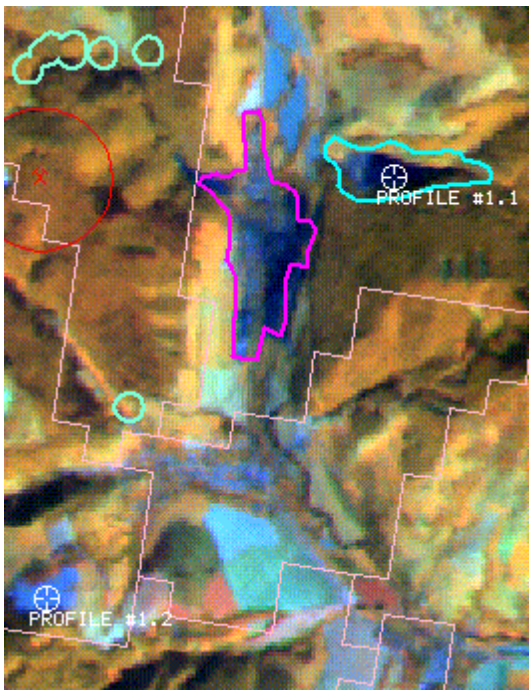


a) Landsat-TM image (4, 5, 3 – RGB) *b) Anomaly (OH-FeOx) image*

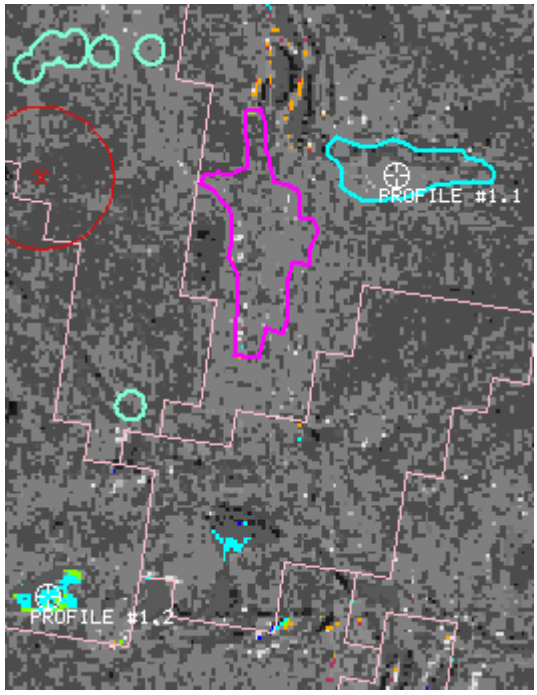
Figure 4.1 The majority of cases where no anomalous pixels were found within the catchments for mineral extraction sites or dumps are due to generalization in mapping and/or scale of catchment delineation.

It can happen that the feature of interest (class 131 or 132) is located entirely inside a catchment, but it does not cause anomalies, due to its specific spectral characteristics. An example of this type is illustrated in figure 4.2, where the spectrum inside the dump site shows that the surface is covered by turbid water. A group of anomalous pixels, corresponding to bare soil seems (by means of its spectrum, which presents an increase in reflectance in TM3 compared with TM1), enriched in FeOx. The same figure shows also that mining sites and old historical dumps do not produce anomalies when located in dense forest.

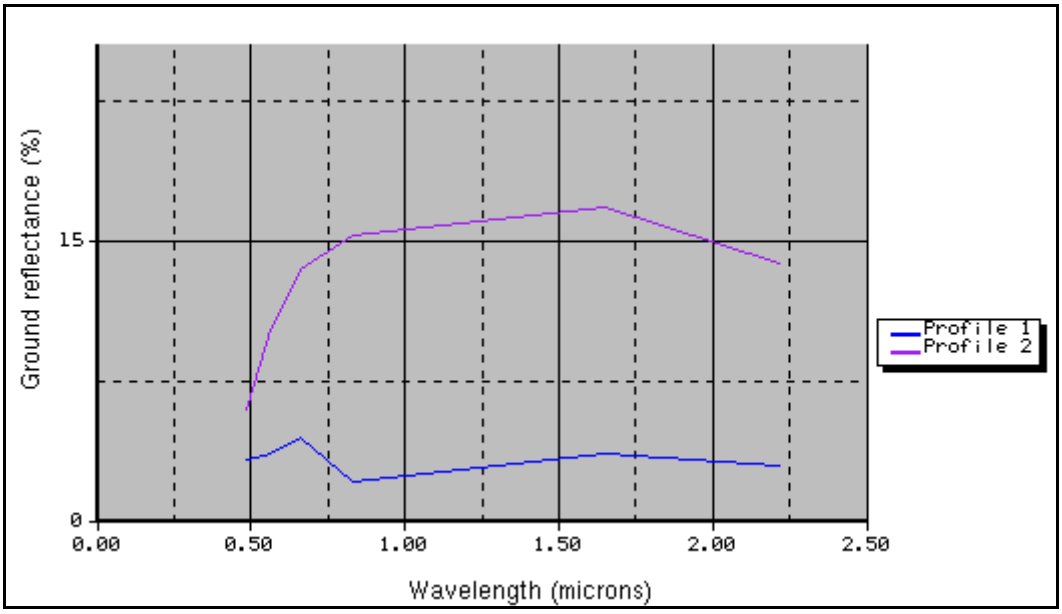
Examining in table 4.1 the percentage of "Co-occurred anomalous pixels/Total number of pixels" (Rtp) of the respective class computed globally for all 2237 catchments in the study area, it can be seen that the highest values are given by the dumps and mineral extraction sites of the CORINE database (classes 132 and 131), followed by buffered mines and sites for construction materials of the Slovakian database. Figure 4.3 emphasizes more clearly this observation. Other classes that have the above mentioned ratio higher than 1% are: industrial units (121), construction sites (133) and continuous urban fabric (111).



a) Landsat – TM image (4, 5, 3 – RGB)



b) Anomaly (OH-FeOx) image



c) Spectra in a dump site covered by water (1) and on a field enriched in iron oxy-hydroxides (2)

Figure 4.2 The rare cases when no anomalies were found for dumps or mineral extraction sites located entirely within the catchments are due to their spectral response determined by local conditions.

The dumps and mineral extraction classes of CORINE LC (132, 131) and the buffered mines and quarries for construction materials of the Slovakian database also possess the highest *mean* of the ratio "Co-occurred anomalous pixels/Total number of pixels" (Rtp). There is a net difference between these on one hand and on the other hand class 2 (agriculture) and 112 (discontinuous urban fabric). These two classes usually produce anomalous pixels in almost every catchments where they are present, which leads to a high global ratio Rn (71.14%, respectively 71.39%), but their anomalous

pixels represent a very small amount of the total area of the class. Therefore both the *global ratio Rtp* "Co-occurred anomalous pixels/Total number of pixels" and the *mean Rtp* have low values, below 1%.

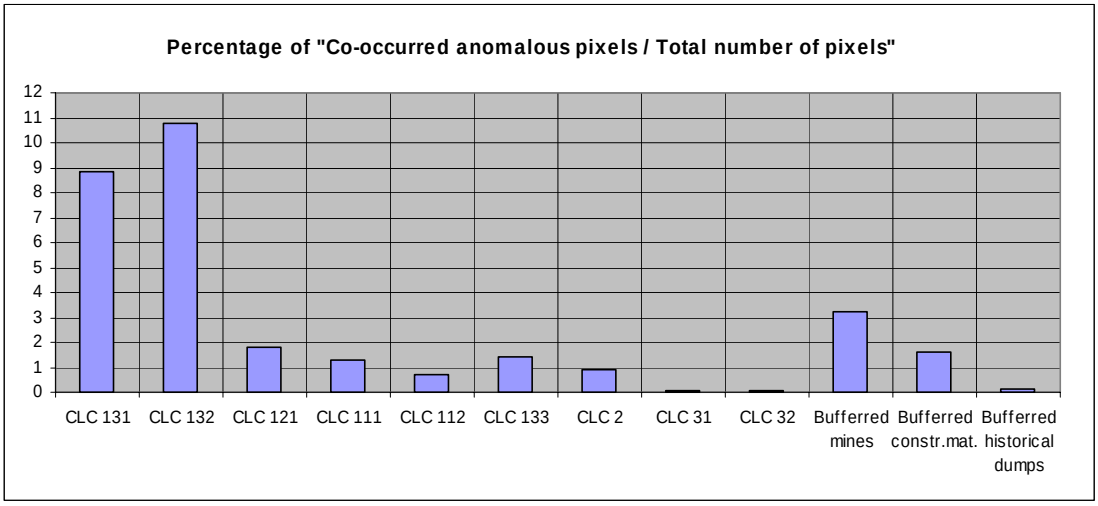
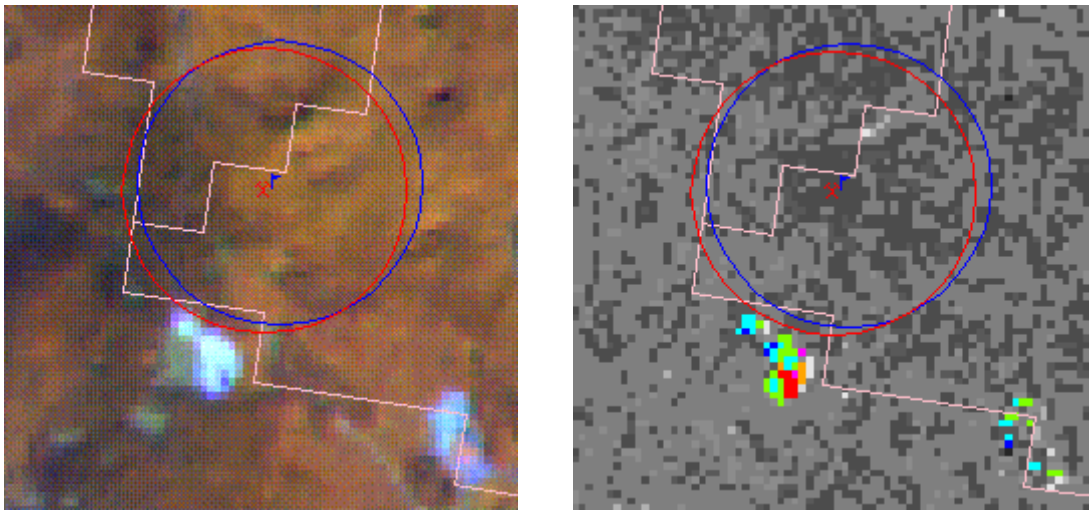


Figure 4.3 Distribution of the global ratio "Co-occurred anomalous pixels/Total number of pixels" (Rtp) for various classes

By checking the original satellite image and the processed OH-FeOx anomaly image against all above mentioned available data it could be noted that clusters of anomalous pixels in the forest most probably are due to the presence of accumulated material from a mine, even if sometimes they do not fall inside the 500 m buffer built around the provided point coordinate. Such an example is illustrated in figure 4.4 for the mine of ceramic clay at Teplicany, North-East of Košice, proving once more the importance of including in the database, if possible, mining perimeters instead of point coordinates. The other group of pixels, with less content in OH, seems related to the site of construction materials, indicated in the provided data as almost co-incident with the mine for ceramic clay.



a) Landsat – TM image (4, 5, 3 – RGB) *b) Anomaly (OH-FeOx) image*

Figure 4.4 No anomalies can be detected in forested areas. However, clusters of anomalous pixels have a high probability to be related to mining features, even if they do not fall always inside buffered mines or sites for construction materials.

Table 4.2 Co-occurrence pixels of different anomaly categories within various land cover classes and mining related features

Number and percentage of co-occurrence pixels across anomaly categories							
Class (from CORINE or national database)	Category 4	Category 8	Category 12	Category 15	Category 19	Category 16	Category 20
CLC 131 Mineral extraction sites	399 10%	932 24%	821 22%	247 6%	934 25%	75 2%	401 11%
CLC 132 Dump sites	118 7%	360 21%	443 25%	119 7%	328 19%	49 3%	301 18%
CLC 121 Industrial or commercial units	554 11%	1666 33%	840 17%	575 12%	1070 22%	49 1%	195 4%
CLC 111 Continuous urban fabric	16 17%	33 36%	15 16%	10 11%	17 18%	1 1%	1 1%
CLC 112 Discontinuous urban fabric	2147 14%	5039 34%	1930 13%	1942 13%	3517 23%	97 1%	347 2%
CLC 133 Construction sites	5 6%	39 46%	6 7%	14 16%	19 22%	3 3%	0 0%
CLC 2 Agricultural areas	56558 28%	82261 41%	13751 7%	16505 8%	29391 15%	632 0%	2375 1%
CLC 31 Forests	2476 18%	4190 29%	1854 13%	2074 15%	3173 22%	77 1%	248 2%
CLC 32 Shrub and/or herbaceous vegetation associations	113 11%	270 26%	148 14%	168 16%	272 28%	14 1%	39 4%
Bufferred mines	462 18%	824 30%	410 16%	124 5%	486 19%	33 1%	281 11%
Bufferred construction materials sites	1012 18%	1723 32%	835 15%	410 7%	1124 20%	82 1%	404 7%
Bufferred historical dumps	24 12%	35 17%	43 21%	37 18%	57 27%	2 1%	8 4%

From the total of 20 possible combinations of anomalies used in the processing chain representing Fe oxy-hydroxides and OH-bearing secondary minerals, seven anomaly categories were considered as the most interesting for the topic of mining waste. These were separately analyzed within each class of the CORINE LC and Slovak database for the study area of 2237 catchments. The global results are presented in table 4.2, where the colours assigned to the columns correspond to those used in the legend of the anomaly OH-FeOx images. By examining this table it was pointed out clearly that the anomaly categories 4 and 8 that represent enrichment in FeOx but low content in OH-bearing minerals are found in the highest proportion in agricultural areas (class 2) and construction sites (class 133). The cause is the presence of some fields with exposed soil having certain characteristics, e.g. a high content of iron oxides or, in the case of the construction sites, artificial surfaces made up of building materials where these minerals are also present. These two LC classes exhibit also low proportion of anomalies in the categories 16 and 20 (rich both in FeOx and in OH-bearing minerals), which are found in the greatest proportion in the mining related classes. This observation is highlighted by the pie-charts in figure 4.5 built for the CORINE mineral extraction sites, dumps, agricultural areas and buffered mining locations of the Slovakian database.

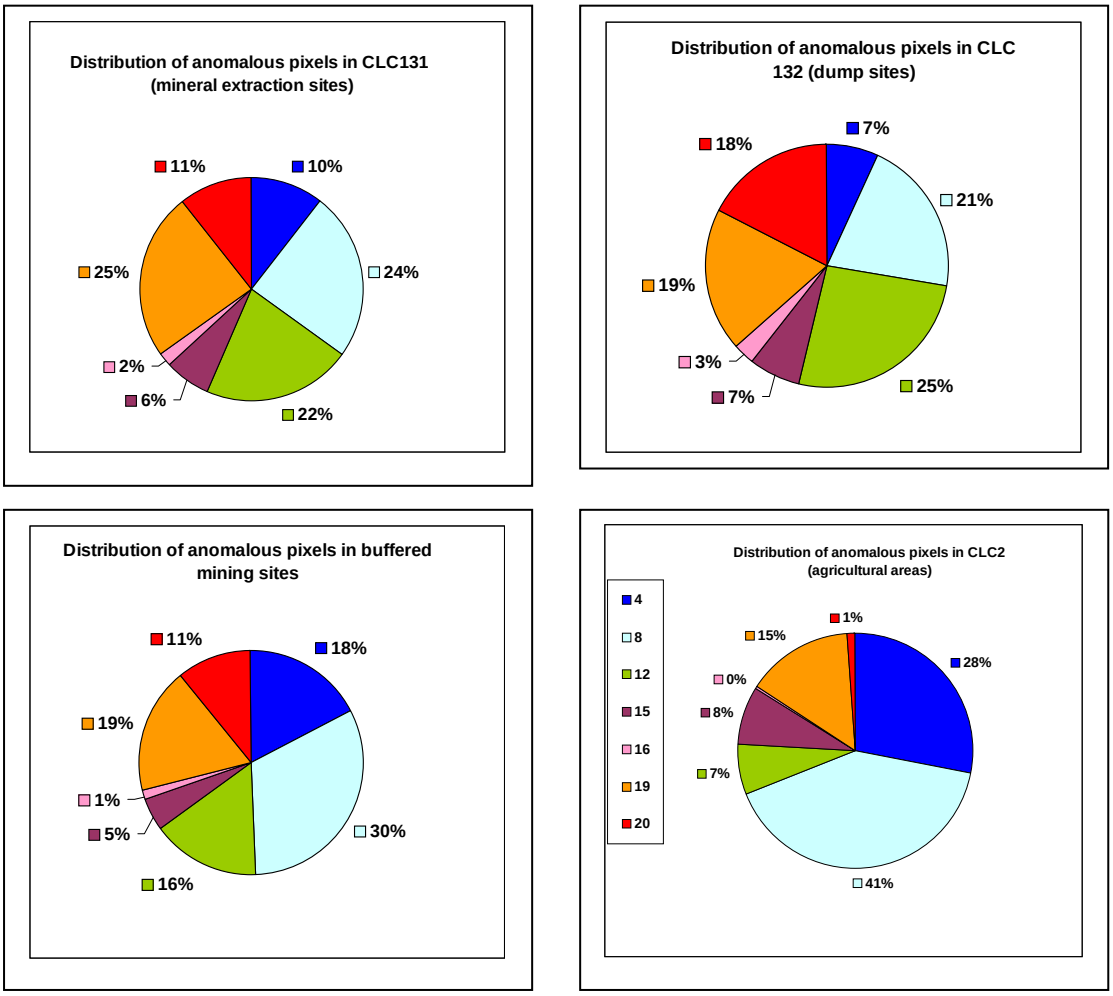


Figure 4.5 Pie charts pointing out a higher percentage distribution of the anomaly classes rich in both FeOx and OH (16 + 20) for the mining related features compared to agricultural areas, where the proportion of simple oxidized minerals (classes 4 + 8) is by far dominant

The distribution of the summed percentage of these two anomaly categories (16 + 20) for all analyzed classes is presented in figure 4.6. It can be seen that the highest percentage is shown by the CORINE dumps, then the mineral extraction sites of the CORINE nomenclature and the buffered mines from the Slovakian database, followed by buffered sites for construction materials, buffered old dumps and industrial units.

It is worthy noting the general resemblance to the histograms of "Co-occurred anomalous pixels/Total number of pixels" in figure 4.3. The highest occurrences of anomalous pixels obtained using the FPCS method are met for the mining related features and for these classes the anomaly categories 16+20 have the highest percentage. It is therefore reasonable to assume that these two classes summed together are most specific for the mining industry and based on them, in combination with other criteria indicators could be developed to point out accumulations of hazardous materials.

The anomalous pixels used for computing both tables (4.1, 4.2) and all resulting histograms presented in figures 4.3, 4.5 and 4.6 took into consideration the occurrence of anomalous pixels inside buffered point locations of mines, sites of construction materials and historical dumps that were located in the CORINE classes 2, 31 and 32

(agricultural areas, forests and semi-natural vegetation associations). These classes occupy a big surface of the Slovakian territory. From the total anomalous pixels of these land cover classes there were extracted those existent also in the buffers of mining related features, therefore the values used for the histograms represented "pure" anomalous pixels for the respective classes.

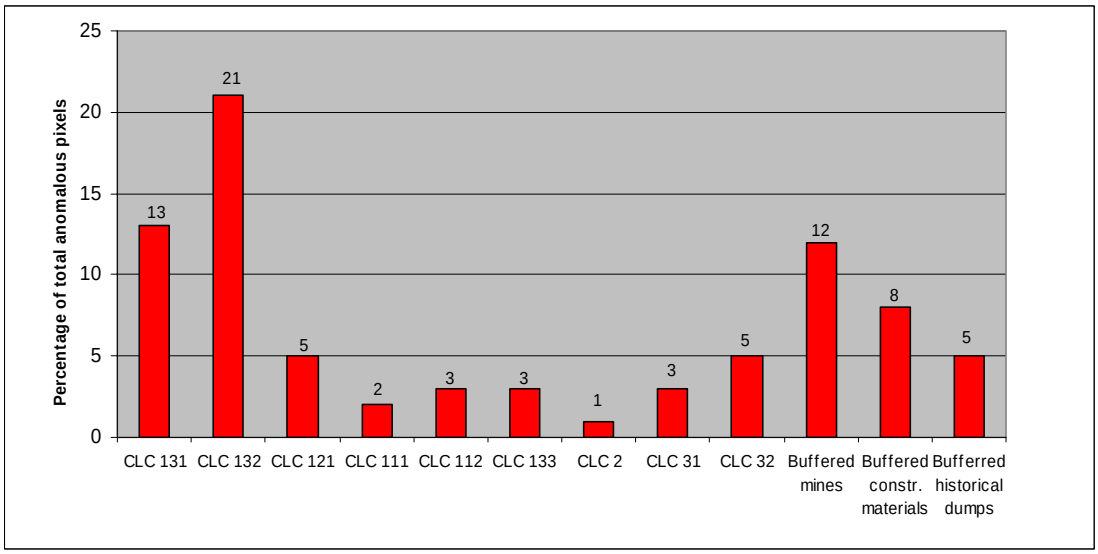


Figure 4.6 Distribution of anomalous pixels (16 + 20) in various classes

The distribution of the pixels inside the buffers located in these classes is shown in figure 4.7 as percentage of the total anomalous pixels present there. Examining these histograms it can be noted that for forests (class 31) and semi-natural vegetation associations (mainly grasslands and transitional woodland/shrub) the anomalous pixels of category 16 and 20 (rich both in FeOx and OH) have a higher proportion, meaning that a great part of the anomalous pixels found are caused by mining related features. These anomaly categories (16+20) raise to a percentage of 40.15 % of the total anomalous pixels of this type for forest and 22.06% for semi-natural vegetation associations, as shown in figure 4.8.

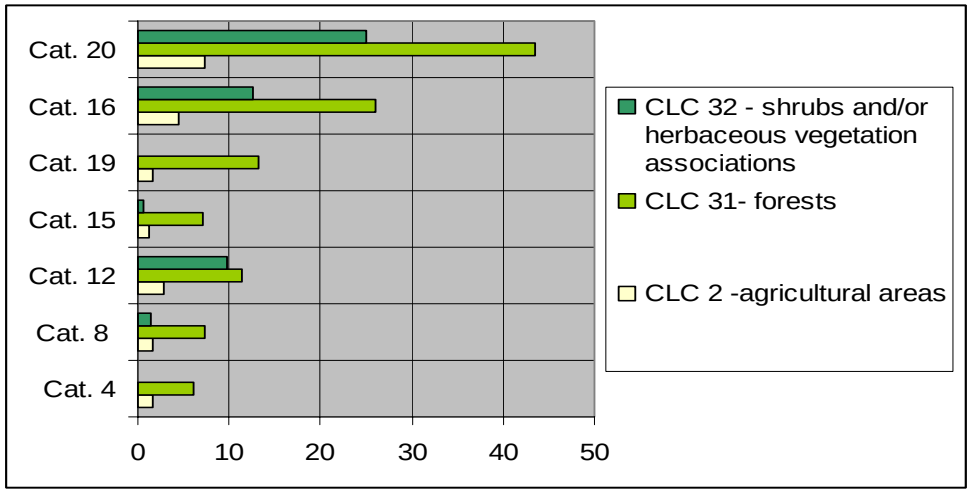


Figure 4.7 Co-occurrence of anomaly categories inside buffered mines, sites for construction materials and historical dumps located in agricultural areas, forests and areas with semi-natural vegetation (expressed as percentage of total anomalous pixels of these LC classes)

Remembering the case shown in figure 4.4, where the anomalies in the forest were outside the buffer, it can be presumed that these figures would be even higher. This observation could be applied also for figure 4.6, where class 32 had a percentage of 5% for the anomalous pixels belonging to categories 16+20. From these so-called (in absence of other supporting data) "pure" anomalous pixels, it is not unreasonable to believe that some could be caused by accumulated hazardous material.

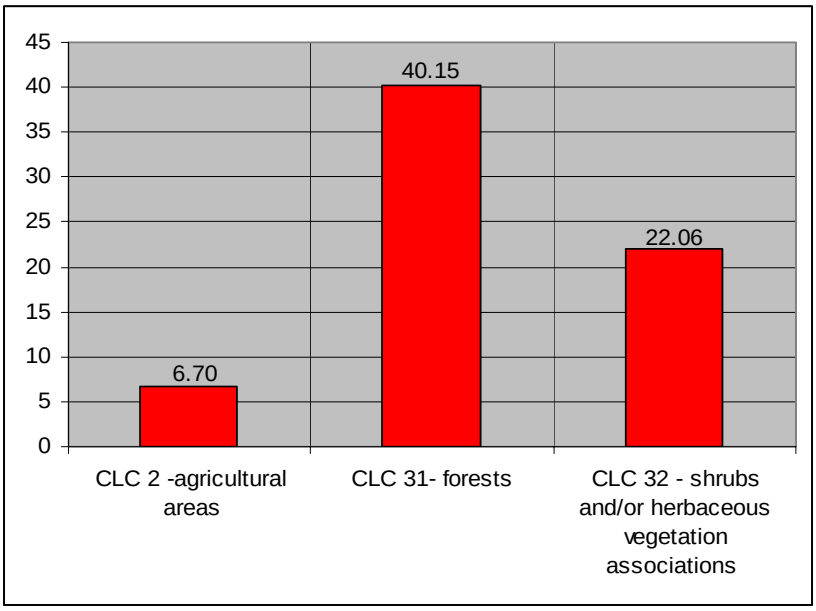


Figure 4.8 Summed anomaly classes (16 + 20) inside buffered mines, sites for construction materials and historical dumps located in agricultural areas, forests and areas with semi-natural vegetation (expressed as percentage of total anomalous pixels of categories 16+20 for these LC classes)

4.2. Comparison of available databases for mining related features

In analyzing the remote sensing anomalies by comparisons against mining related features from CORINE Land Cover and the national database of Slovakia it was important to see also how much correspondence exists between these two independent sources of information. In order to achieve it, a GIS analysis was performed for computing:

- the number of point coordinates of the Slovak database falling into all analyzed land cover class (the most rigorous overlapping);
- the area co-occurrence between the buffered mining features and the mineral extraction sites (class 131) and dumps (class 132) from the CORINE LC database (less rigorous) ;
- the number of hits between the buffered mining features and the CLC classes of interest (for finding out if, despite location precision, the same mine was present in both databases – the least rigorous).

The results of the point-in-polygon overlay are presented as histograms in figure 4.9, where it can be seen that the CORINE mineral extraction sites are represented by open-cast mines for industrial minerals and coal. Metallic mines are located in forests (class 31) or in different types of agricultural land (class 2), the open-pits for construction materials and the historical dumps having the same distribution. The greatest part of the CORINE mineral extraction sites are represented in Slovakia by open-pits and quarries for construction materials.

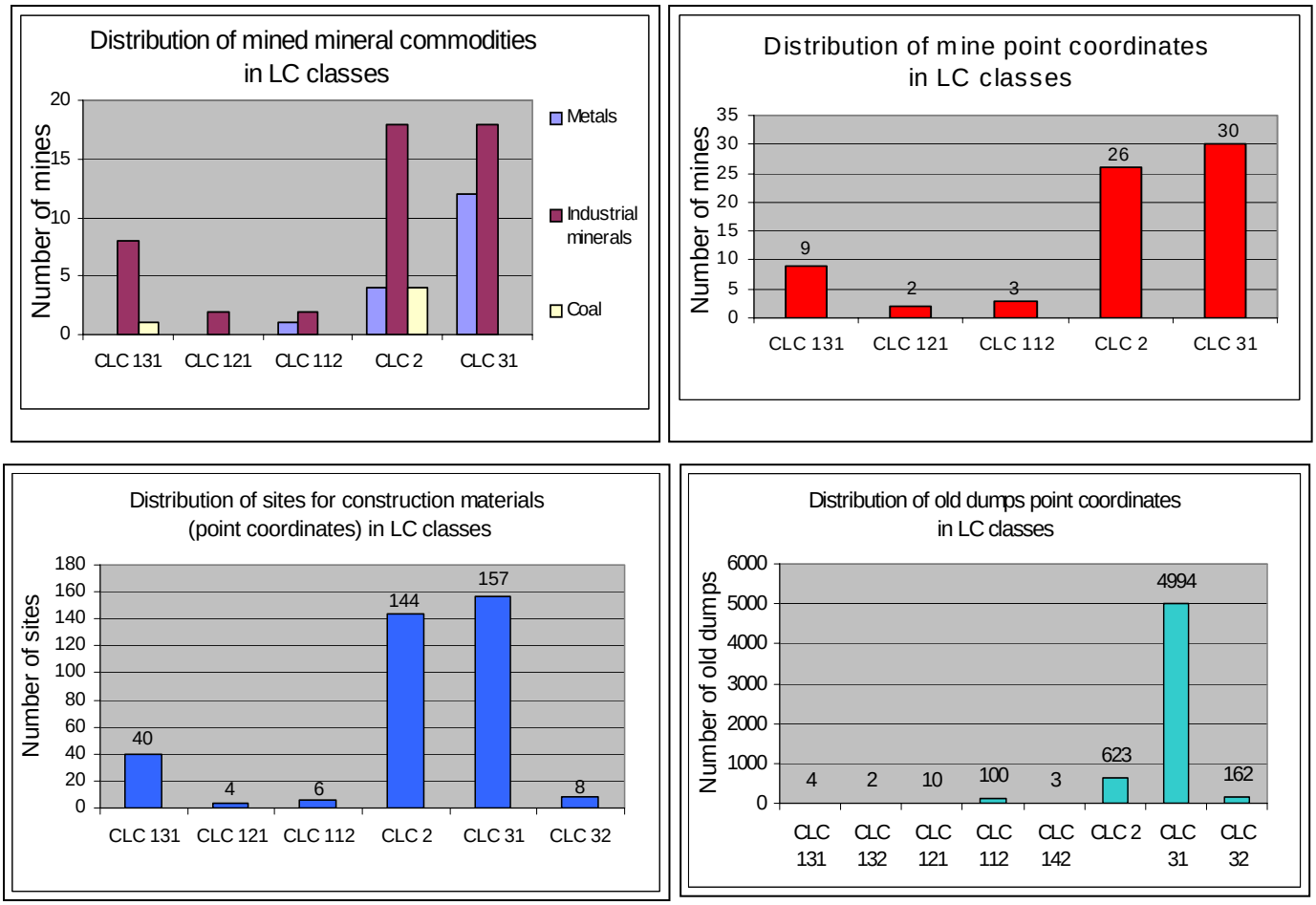
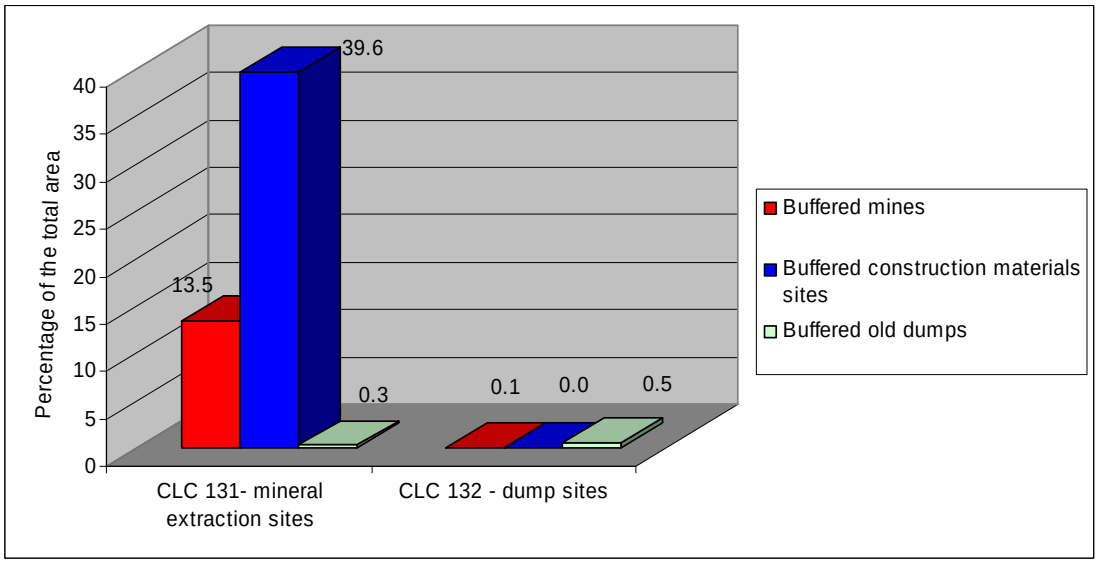
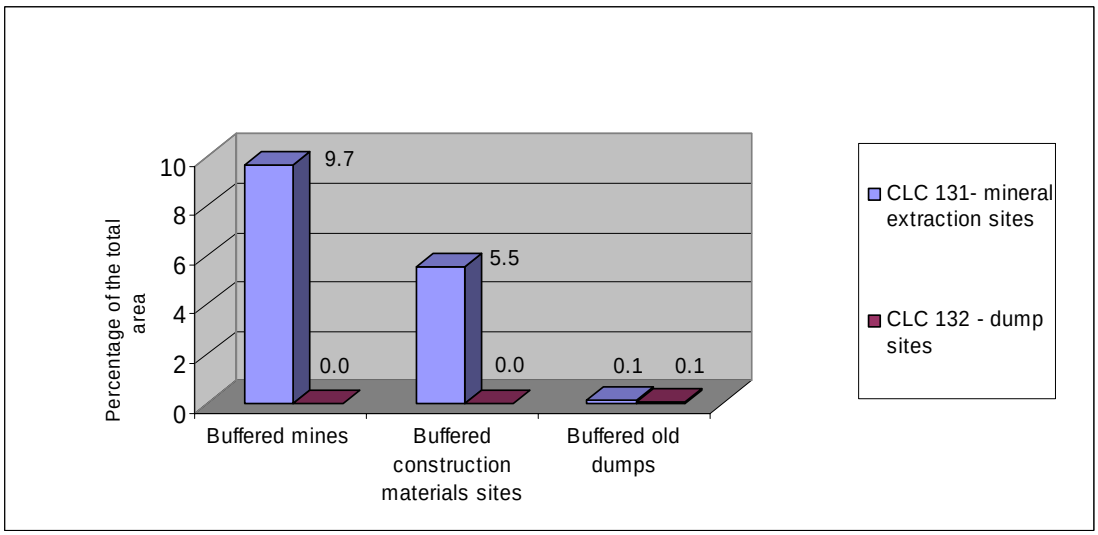


Figure 4.9 Distribution of point coordinates for mines (inclusively per type of commodity), sites for construction materials and old historical dumps of the Slovak database in CORINE Land Cover classes

The computation of the area co-occurrence emphasizes once more the above observation, 39.6 % of the total surface of CORINE polygons that belong to class 131 being overlapped by the 500 m buffers of the sites for construction materials (figure 4.10a). On the whole more than 53 % of this class area is common to the buffered mining features of the Slovak database. From the number of 70 mines in the Slovakian database, the area of 9 buffered mines (representing 12.8% of the total area) that corresponds to CLC 131 rise up to 9.7 % (figure 4.10b).
This remark, together with the number of hits between the buffered mines and sites for construction materials and the CORINE mineral extraction sites boundaries (73 hits for 82 polygons of class 131, representing 89 % of those) confirms the good selection of the buffer radius (20 pixels, making up 500 m that produces a 78.5 ha buffer area). This is only 3 times bigger than the minimum mapping unit for CORINE (which has an accuracy of 100 m) and the visual examination of the satellite images (for example, figure 4.1) confirmed a rather good correspondence between buffers and the mineral extraction sites. For the old historical dumps a buffer radius of 100 m was considered acceptable, as these dumps were generally not visible on the satellite images and often the distance between adjoining point coordinates was less than 25 m.



a) Percentage of the total area of the CORINE LC class covered by the area of the buffered mining features



b) Percentage of the total area of the buffered mining features covered by the area of the CORINE LC class

Figure 4.10 Co-occurrence pixels in buffered mining features and CLC classes

In conclusion it can be said that the informational content in the two databases is not redundant, since the more detailed description of the point sites in the Slovak database is completed with the spatial dimension of the CORINE polygons. In the same time, neither of the two is sufficient (at least in the form that was available) to give a full image of the distribution of the deposited mined materials and to differentiate among them the simple oxidation from the more hazardous types. Taking into account the localization of many metallic mines in forests or lands of agricultural use, the anomalies obtained by applying the FPCS method represent the third source of information, which, combined with the first two, is able to offer a more complete view about the distribution of the mining wastes.

4.3. Computation of the mining anomaly index

Based on the conclusions resulted from the statistical analysis of anomalous pixel classes (chapter 4.1) it seems appropriate to compute an anomaly index that takes advantage of the highest occurrence of FeOx-OH anomalies (classes 16 + 20) within the biophysical land occupation categories representing mining related features. These two anomaly classes representing co-occurrences of high levels in both Fe oxy-hydroxides and OH-bearing secondary minerals are furthermore indicative of potential risk of acidification (or soil alkalization – in the case when the short wave infrared absorptions are caused by the CO_3^{2-} anion).
Considering the fact that common iron-staining (anomaly classes 4 and 8 summed) is present in almost equal proportions in all studied land cover classes (excepting class 133 – construction sites and class 2 – agriculture, where it is by far dominant), as well as in buffered mines, open-pits for construction materials and historical dumps, a combination of these anomaly classes with those belonging to classes 16 and 20 could differentiate the catchments as regards the deposition of potentially hazardous mining waste material.
The proposed anomaly index is therefore defined as:

$$Mining\ Anomaly\ Index = \left(0.001 + \frac{SUM16 + SUM20}{1 + (SUM4 + SUM8)}\right)\left(\frac{Total\ Anomalous\ Pixels}{Catchment\ area}100\right)$$

This index emphasizes the catchments with anomalous pixels of classes 16+20, representative for mining sites and dump sites and is related also to the catchment area, being meanwhile normalized to the "common iron oxidation". In the cases where there are numerous pixels of classes 4 and 8, the index becomes smaller due to the division to a greater number. It takes into consideration the fact that there are many anomalous pixels in the catchment but the value assigned to it is lower due to the smaller proportion in minerals with SWIR absorptions. When no anomaly of classes 16 or 20 occurs the index is defined only by the percentage of total anomalous pixels, but the value is ten times reduced, thus indicating the presence of less hazardous material.
Examining the map of total anomalous pixels (figure 4.11) and the map of the "mining anomaly index" (figure 4.12) computed for first order catchments of Slovakia (CCM – Catchments Characterization and Modeling Database of the European Commission) using the above defined formula, the differences are easily noted. Thus, the areas with a high number of anomalous pixels located in the Central-South of the country and in the zone of Košice are represented as belonging to classes A, B or C of the mining anomaly index, corresponding to low - medium hazard. Some other catchments are pointed out instead as potential hazards for acidification due to the properties of the deposited mining waste.
The values of the mining anomaly index were normalized such that they lie within the range 0 – 1 and the division into classes was made taken into consideration the statistics of the normalized values. Thus:

- class A represents the interval up to the median (0 – 0.003]
- class B is the interval between the median and the mean (0.003 – 0.01]
- class C is the next interval, mean plus one standard deviation (0.01 – 0.07]
- class D is the successive interval, between the mean plus one standard deviation and the mean plus two standard deviations (0.07 – 0.13]

- class E is the interval with values greater than the mean plus two standard deviations (0.13 – 1]

Class A represents practically no hazard from the point of view of the deposited mining material and in figure 4.12 it can be seen that generally corresponds to catchments lacking mining related features or with sites for construction materials, where the exposed material is usually characterized only by iron-staining.

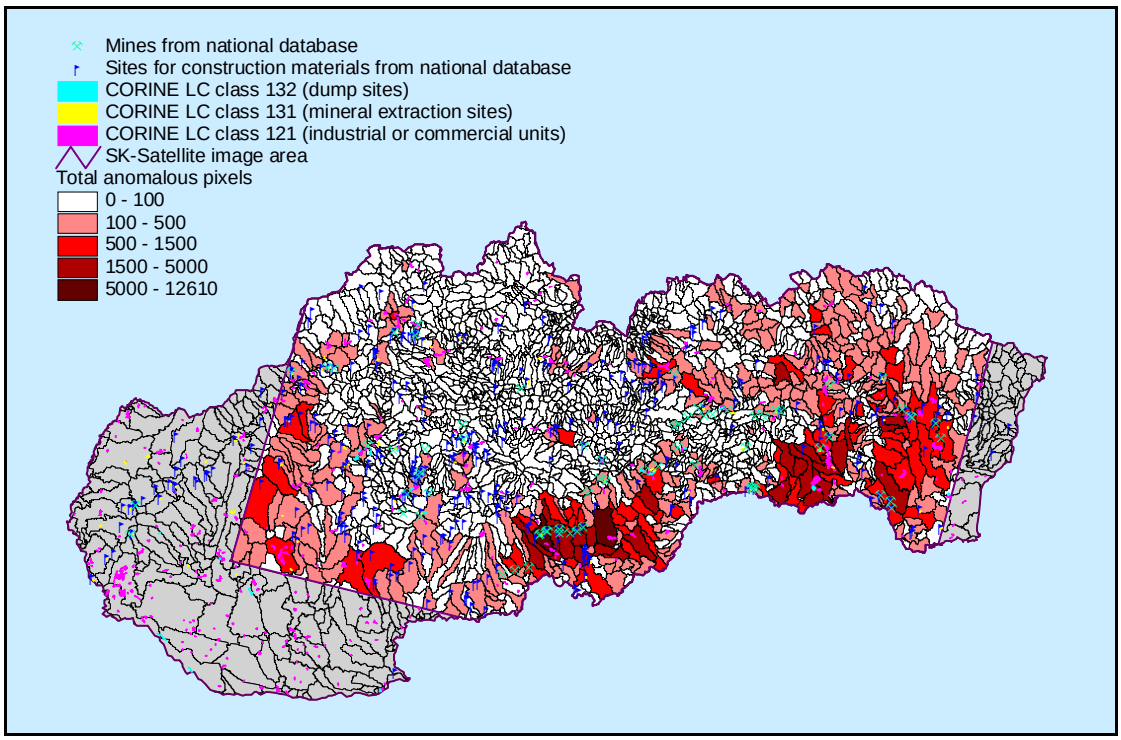


Figure 4.11 Total anomalous pixels for first order catchments of Slovakia

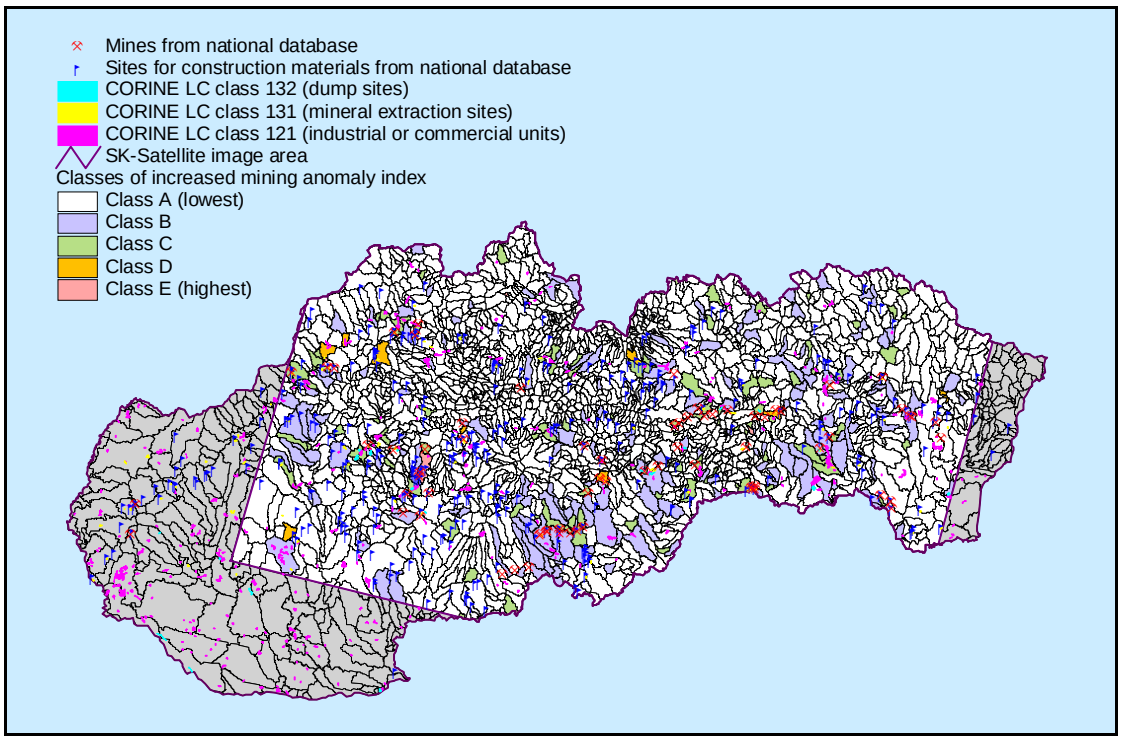


Figure 4.12 Map of mining anomaly index for first order catchments of Slovakia

Class E has the highest values of the index and the catchments classified into this category contain deposited mining material that indicates a possible hazard for the environment, such as acidification. The respective catchments are exemplified at a more detailed scale herein.

The first example refers to the smelter at Rudňany, already presented in chapter 3.2.3 as a case with a high ratio "co-occurrence pixels/total anomalous pixels". The anomaly image (OH-FeOx) overlaid on the map of the mining anomaly index (figure 4.13) shows indeed a big number of pixels in class 20, leading to the highest index value for all the Slovakian territory.

The second highest value of the index is found also for a catchment where a dump site is situated, nearby the industrial site representing the power plant at Nováky (figure 4.14). This locality is indicated in the SC Country Report as a "hot spot" for the coal industry and in the centre and right side of the image there can be seen two mines for brown coal from the "Hornonitrianska Coal Basin", present also in the CORINE database. For the above mentioned dump the OH-FeOx anomaly image highlights a great number of anomalous pixels with medium to high (green colour – anomaly class 12) and high (red colour – class 20) content in OH-bearing secondary minerals. The fact that both the highest values of the index correspond to the dump sites at Rudňany and Nováky, where the accumulated material has certain properties is a proof of the suitability of the index for identifying the sites with potentially hazardous materials.

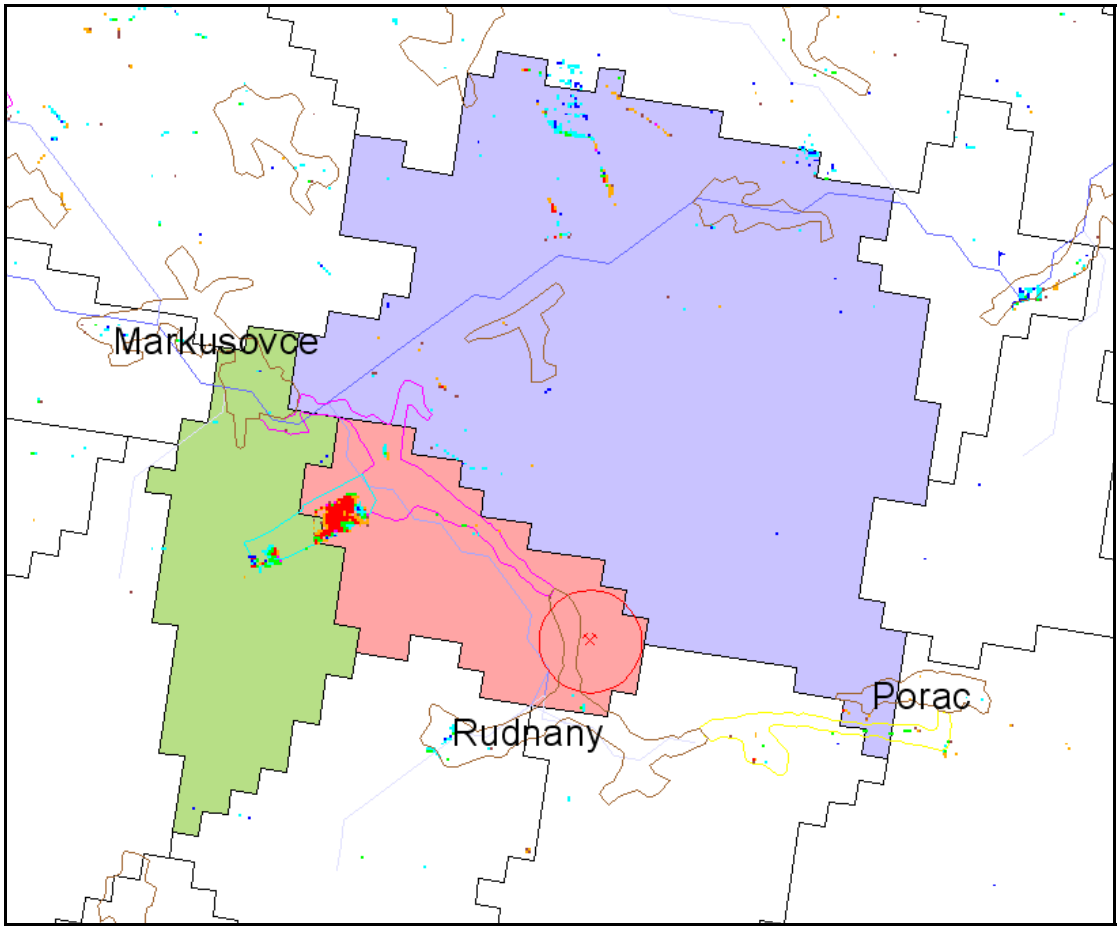


Figure 4.13 Map of mining anomaly index pointing out the highest value in the area of the smelter at Rudňany

The other catchments in figure 4.14, corresponding to other two dumps and the Nováky power plant, show anomalies too, but with a lesser extent and intensity, belonging to class C. With the same class or with class B are represented also the catchments which make part of the zones of Cígeľ and Handlová hot spots, located East of Nováky (Steering Committee Country Report - Jánová and Vrana, 2004 in *Jordan and D'Alessandro*, eds.). In all these cases the surface manifestation of the respective dumps is rather weak, being in agreement with the Country Report which mentions that the environmental hazard is caused mostly by "activation of geodynamic processes on slopes and undermining of area", followed by "de-watering of mining fields and changes related to hydrological and hydro-geological conditions of the region". Like in the case of Rovinari opencast mine for lignite in Romania (described in chapter 3.1), acidification does not constitute an environmental problem and the types of the anomalies produced confirm it once more.
In the left side of figure 4.14 there can be seen also other anomalous pixels corresponding to CORINE polygons for mineral extraction sites and confirmed in the Slovak database as sites for construction materials, belonging to the same category of index classes (B and C).

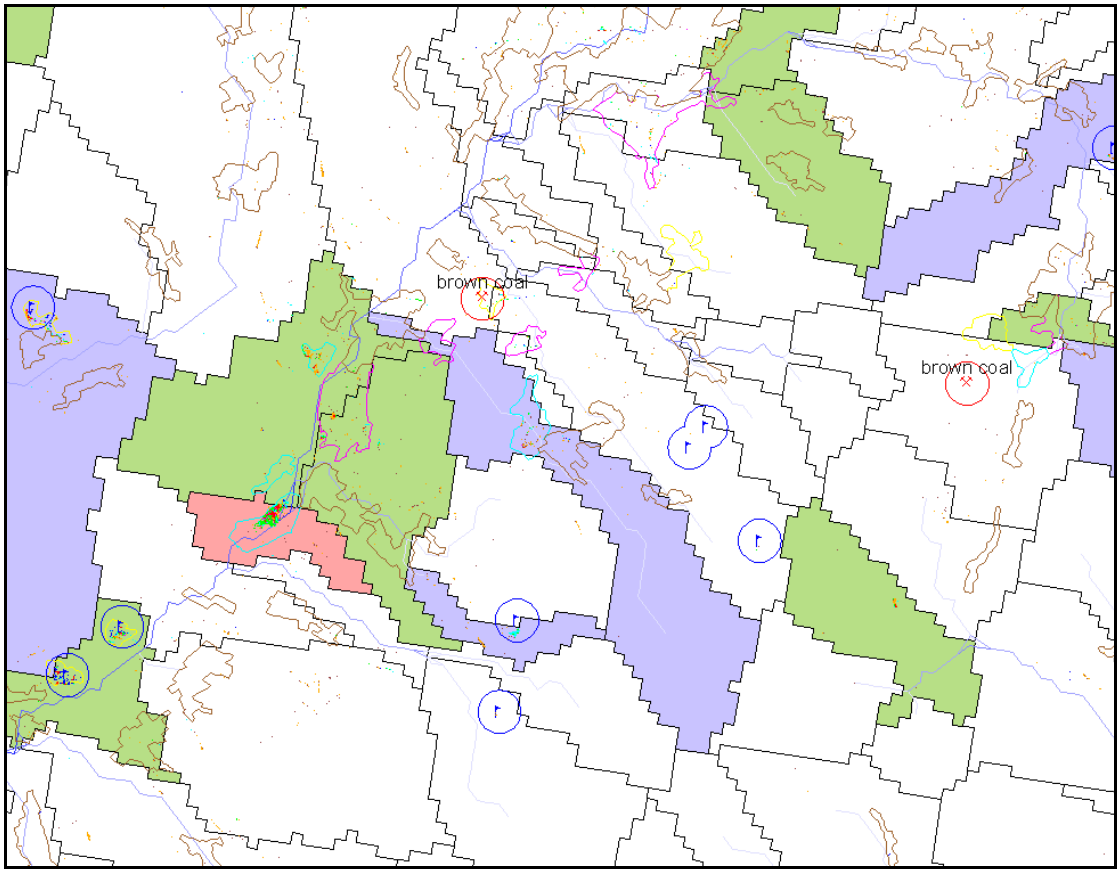


Figure 4.14 Map of mining anomaly index in the area Nováky - Cígeľ - Handlová (hot spots for the coal industry)

Another region with high values of the mining anomaly index is located in the Volovsk Mts., East of Spišská Nová Ves. The smelter at Krompachy and the catchment of Gelnica with an industrial unit (listed as a "hot spot" in the SC Country Report) are highlighted on the map in figure 4.15 as belonging to class C (intermediate levels), while higher levels (class D and E) are found in the neighbouring catchments with open-pits for limestones and dolomites in the vicinity

of Jaklovce and Margecany. These two mining sites exhibit absorption features in TM7 causing anomalies of the highest class (20). In this case consultation of auxiliary data (geologic, pedologic) together with more detailed information about site specific conditions could help in assessing if the site should be maintained on the list of areas with accumulated hazardous material.

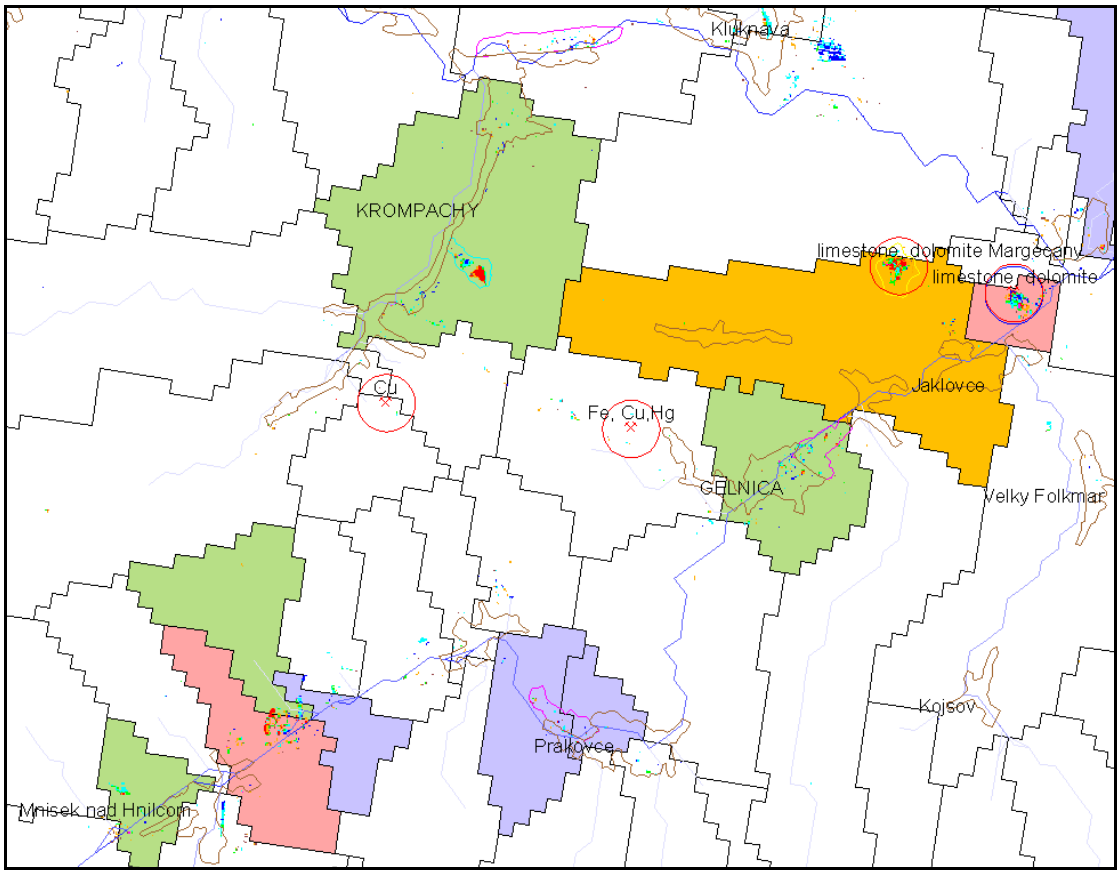


Figure 4.15 Map of mining anomaly index in the region of Krompachy (smelter), Jaklovce (open-pits for limestones, dolomites), Gelnica (Fe, Cu, Hg - hot spot) and Minisek nad Hnilcom

It should be noted, however, that in case of very small catchments or inter-basins with occurrences of anomalous pixels belonging mainly to class 16 or 20, the index value remains rather high when dividing to a small number (the catchment area). This parameter that contributes to the computation of the index has an influence upon the output values especially in the case of a very big difference between catchments areas, as it happens for the above mentioned limestone and dolomite mining sites. The observation will be furthermore exemplified with other cases.

Regarding figure 4.15, it can be noted that a high index value is found also for the catchment nearby Minisek nad Hnilcom and the anomalous pixels can be easily observed. Comparing the anomaly (OH-FeOx) map with the satellite image dated 1985 it was found that on that date exposed material was present on the valley of Hnitec river, having iron-staining and absorptions in SWIR (TM7). Checking with other available Landsat – TM scenes from 1992 and 2000 it was seen that the anomalies did not exist anymore and the site began to be covered by vegetation. This is in agreement with a reduction in the mining activity in that area North of Smolník, many mines being closed after 1990 and their dumps remedied.

Another zone selected for exemplification contains the catchment with a high index value (class E) corresponding to the mines for quartzite, limno-quartzite North of Stara Kremnicka and situated downstream of Kremnica mine (Au, Ag), listed as a "hot spot" in the SC Country Report (figure 4.16). The other catchments with intermediate index values (class C) represent the areas of the smelter at Ziar nad Hronom, the industrial unit nearby the brown coal mine at Handlová, other industrial unit in the South-East of the image, at Zvolen. The region includes also the zone of Špania Dolina (class D), with its mine for Cu considered a "hot spot" in the SC Country Report. On the image in figure 4.16 it can be seen that several other mines for limestone, dolomite, pearlite, diatomite, as well as numerous open-pits for construction materials are present in the region, but they do not produce anomalies.

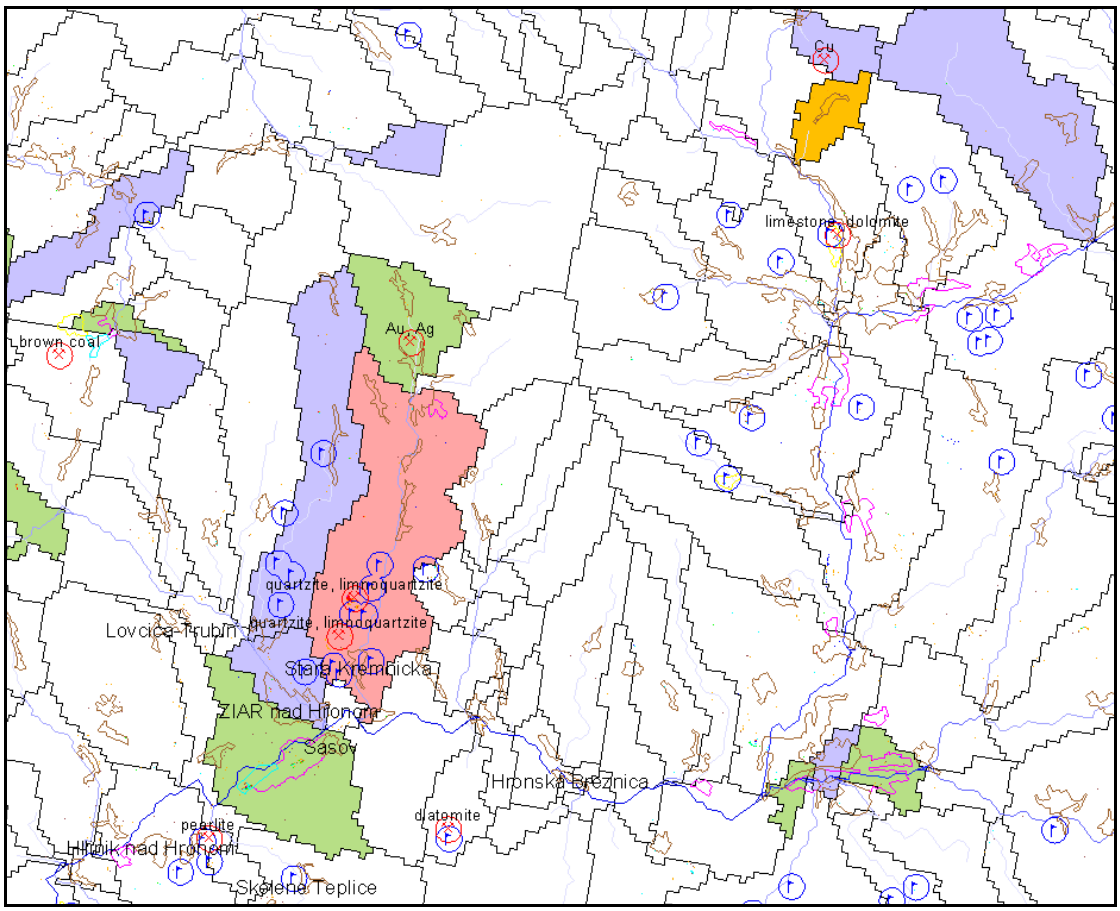


Figure 4.16 Map of mining anomaly index in the area of Stara Kremnicka mines (quartzite, limno-quartzite), Kremnica (Au, Ag – hot spot), Špania Dolina (Cu – hot spot)

The next zone presents some catchments with mines for industrial minerals, included on the "hot spots" list in the SC Country Report (category I and II). These show high values of the mining anomaly index, as it can be seen in figure 4.17. The highest value in this zone (class E) represents the open-pit for limestones, dolomites at Tisovec - Čremošné, mapped in the CORINE Land Cover as an industrial site. The anomalous pixels are easily visible and this leads to the idea of reconsidering the catchments with mineral extraction sites for the same type of minerals in the Margecany – Jaklovce zone, which produced also strong anomalies. In any case more information should be gathered for the latter in order to decide if they should be considered or not hazardous material. According to the newly issued report of the

Institute for Prospective Technological Studies (EIPPCB, 2004), in case of processed limestones and dolomites, their tailings management facilities are included in the category that could have an environmental impact if not handled properly.
On the image in figure 4.17 the other catchments with higher values (class D), correspond to the "hot spots" of talc mines located at Hnúšťa - Mútnik and Hačava. The talc mine at Kokava can be also distinguished from its surroundings, as well as the industrial unit at Revuca, both belonging to class C. One of the first order catchments (in fact an inter-basin) located between Jelšava and Lubeník, also "hot spots" for magnesite mining, has values of the mining anomaly index in the range of class C. However, the catchment of Jelšava which presented (chapter 3.2.3) the highest number of occurrences, exhibits now a low value of the index (class B). This is due to its area (114510 pixels), almost 16 times greater than that corresponding to the above mentioned inter-basin (7203 pixels). This case together with other available examples emphasizes the idea that it might be advisable to use bigger order catchments as a reference (order 2 or 3). The advantage would consist primarily in computation of the mining anomaly index taking in consideration a dump, mining or industrial site as a whole entity, without artificial separation caused by the original scale of catchments delineation.

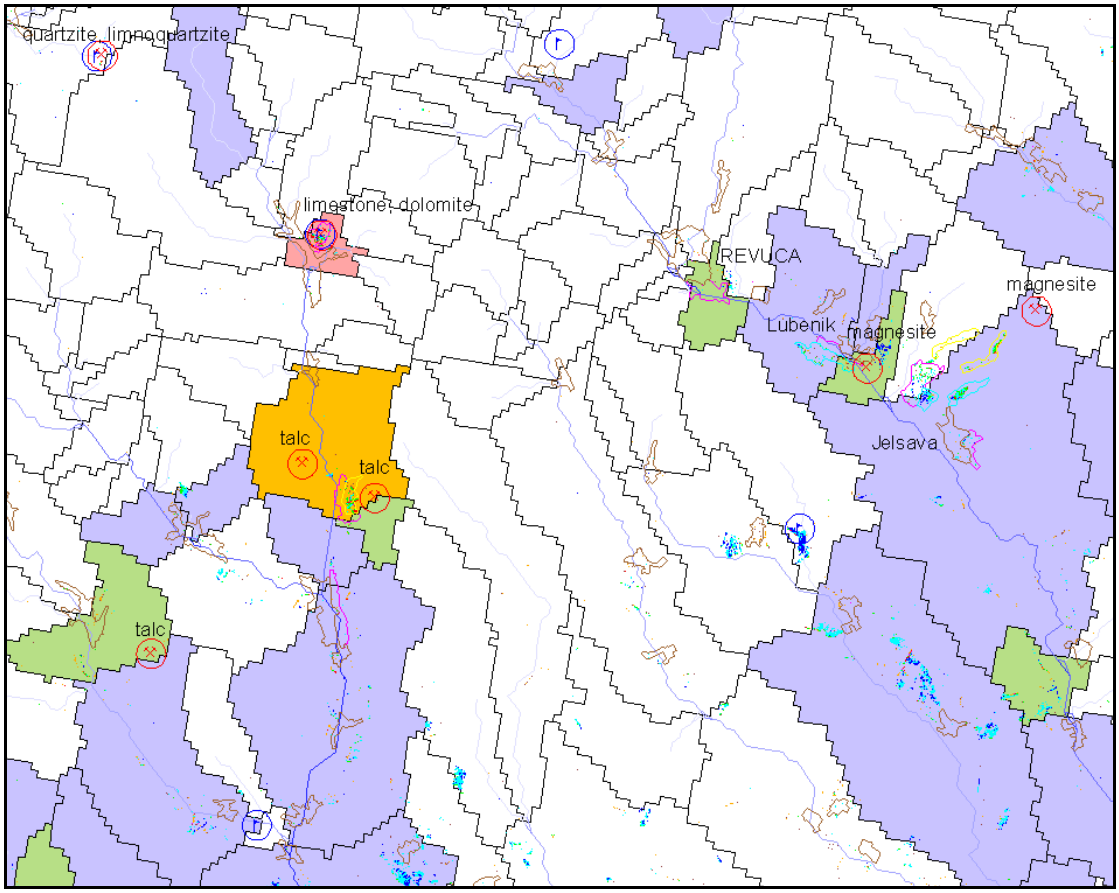


Figure 4.17 Map of mining anomaly index in the area of hot spots for industrial minerals: talc (Hnúšťa - Mútnik, Hačava), limestones, dolomites (Tisovec-Čremošné), magnesite (Jelšava, Lubeník)

An area in the West part of Slovakia corresponding to a catchment having a high index value (class E) is presented in figure 4.18. The region includes also the mine for limestone, dolomite at Ladce - Budkov, considered in the SC Country Report a "hot

spot of II category". There can be seen the anomalous pixels co-occurred in the respective CORINE polygon and the buffered mining site, the index value produced being moderate (class B).

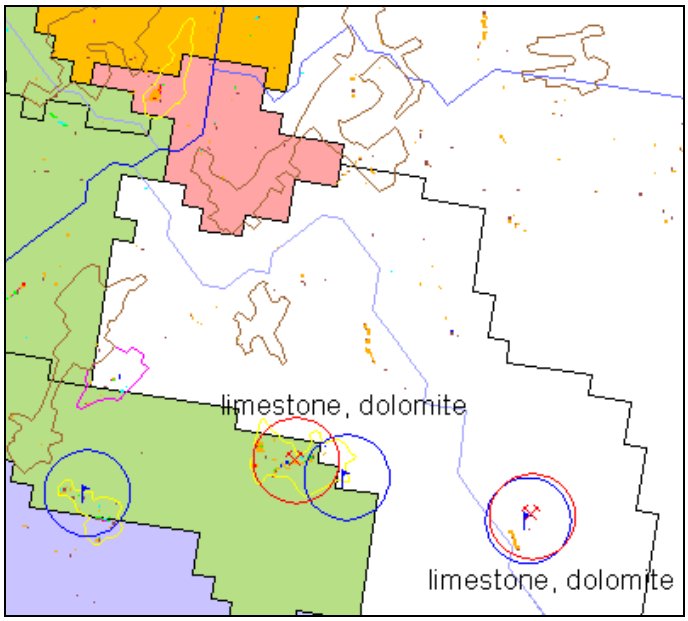
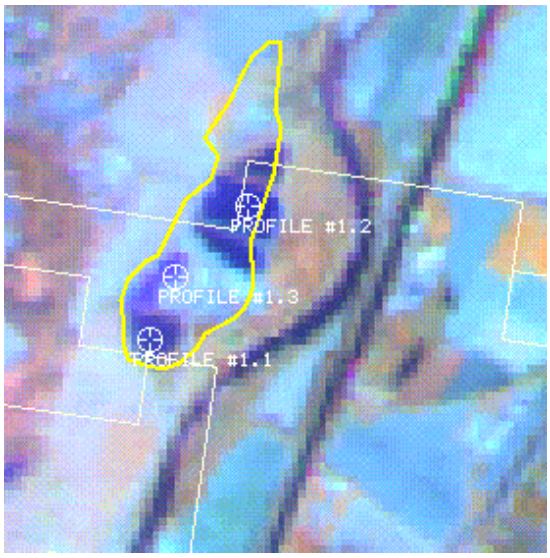
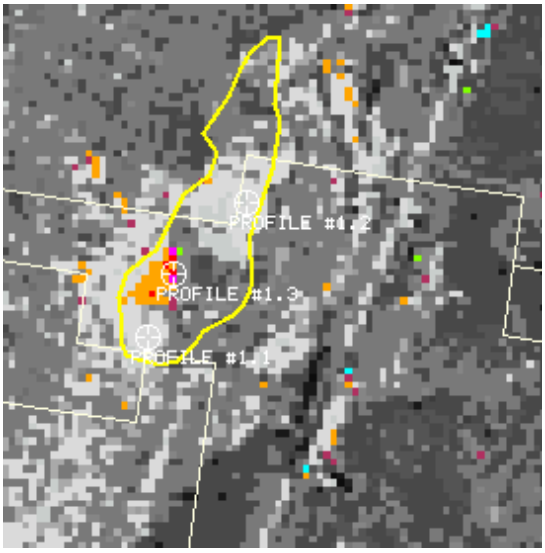


Figure 4.18 Map of mining anomaly index for the area of dump site North of Ladce-Budhov "hot spot" (category II) with open-pit for limestone, dolomite

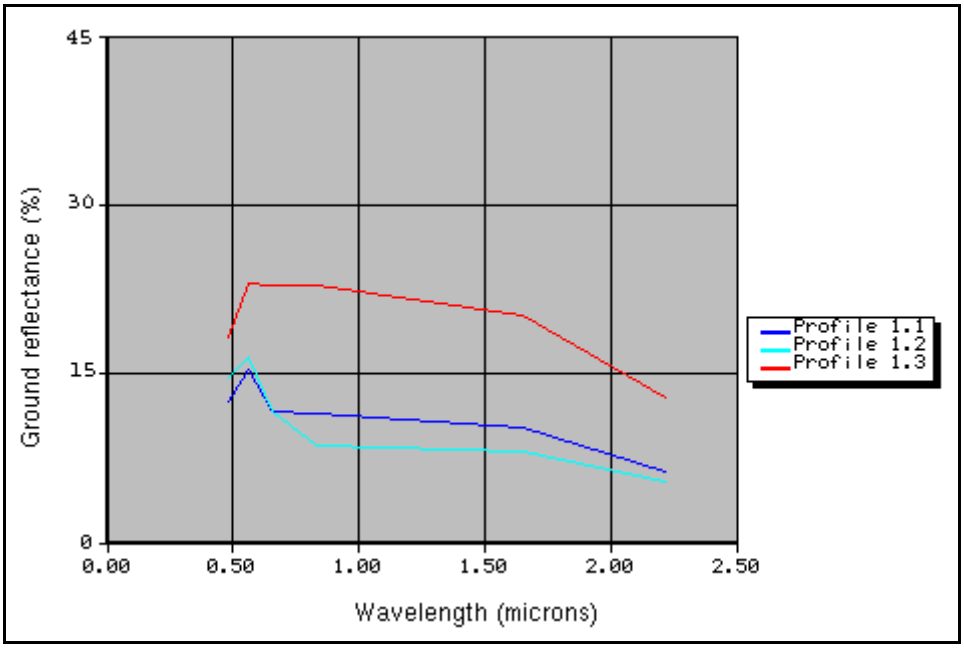
The high value of class E mentioned above was checked against the Landsat – Thematic Mapper image (figure 4.19a) and it was seen that in fact the polygon mapped as mineral extraction site (class 131) in the CORINE database corresponds more probably to a dump site. The spectra computed for three locations inside the polygon (figure 4.19c) represent water (very turbid – profiles 1.1 and 1.2) and mixed pixels (profile 1.3) generators of FeOx – OH anomalies, as it results by examination of the anomaly image in figure 4.19b.



a) Landsat – TM image (4,5,3 – RGB)



b) Anomaly (OH-FeOx) image

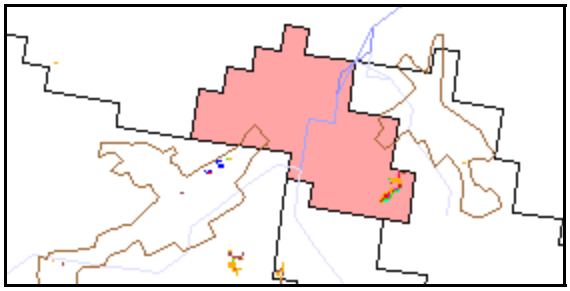


c) Spectra of water (1.1, 1.2) and mixed pixels (1.3) rich in FeOx and OH-bearing secondary minerals

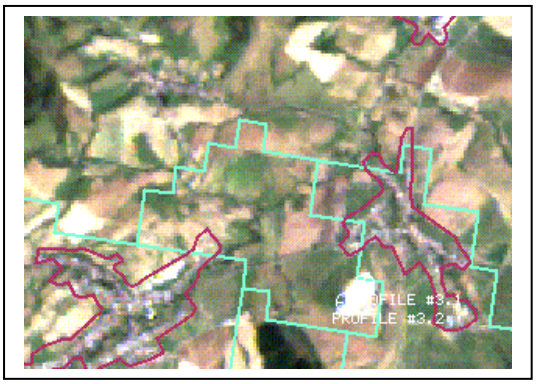
Figure 4.19 Verifications with Landsat - Thematic Mapper image confirm the high index value assigned to the respective catchment due to the properties of the materials in the dump site

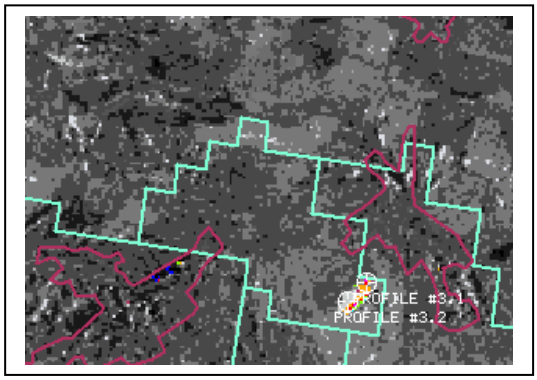
The last zone from the list of the eight highest index values catchments (class E) corresponds also to a small inter-basin (figure 4.20a) with an area of only 219.03 ha (equivalent to 3509 pixels) where a small group of pixels rich in both FeOx and OH-bearing minerals produces a high index value. This is caused partially by the fact that there are only 2 pixels in the summed (4+8) anomaly classes and few anomalous pixels of other classes. The most hazardous anomalies (10 pixels of the summed classes 16+20) keep their weight in the computed index, and the checking against the satellite image (displayed as natural colors in figure 4.20b) confirms the existence of a bare field. At location 3.1 the exposed material exhibits intense FeOx-OH anomalies (figure 4.20c), while immediately nearby (location 3.2) there are no iron oxidation features since the mixed pixels do not have an increase of the reflectance in TM3 compared with TM1 (figure 4.20d). The verification with other available satellite data (for example with one dated 1995) showed that the site with potentially hazardous material in a period of ten years became covered by vegetation.

This situation is similar with that presented for the other small inter-basin near Mnisek nad Hnilcom (figure 4.15), demonstrating the possibility of solving this type of cases (caused by a small but intense anomaly within a tiny catchment) by use of multi-temporal Landsat – Thematic Maper images.

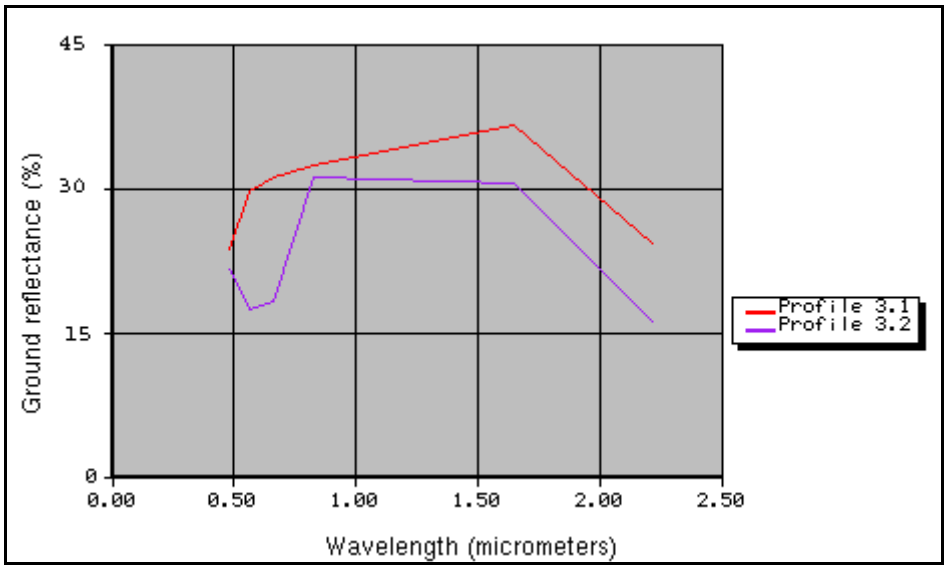


a) Map of the mining anomaly index for a small inter-basin where some anomalous material was temporarily exposed





b) Landsat – TM image (3,2,1 – RGB) *c) Anomaly image (OH-FeOx) image*



d) Spectral profiles for two locations within the small dimensions inter-basin (3.1-FeOx-OH anomaly, 3.2 – no anomaly)

Figure 4.20 A small anomaly located inside an inter-basin of reduced dimensions can cause a high value index. These types of problems caused by accidentally deposited material can be solved by verifications with multi-temporal Landsat-Thematic Mapper images in order to determine if the material was left at the site for a short time period or has remained in place for several years.

5. CONCLUSIONS AND RECOMMENDATIONS

Within the framework of the PECOMINES project it was developed a methodology for mapping mining wastes at regional to national and even multi-country scale by use of time-series satellite images. By processing the Landsat - Thematic Mapper images with a PCA-based method (Feature-Oriented Principal Components Selection - FPCS) originally designed for exploration geology, it is possible to map the distribution of deposited mined material if the respective surface is exposed and has an area of at least one pixel (30 m).

The method is semi-automated and straightforward, requiring as preliminaries only atmospheric and geometrical corrections (sometimes also cloud masking) and it can be applied on whole satellite scenes. The output, which consists in an anomaly image (OH-FeOx) is already in digital format, ready to be integrated into a GIS together with other thematic layers from available databases. The temporal dimension (time-series) allows the detection of changes and observation of the evolution trend of a mining site in time, inclusively its monitoring after the closure and remediation. This issue is especially important in the view of articles no. 16 and 19 of the proposed Mining Waste Directive, referring to the requirement of performing an inventory of closed mines and quarries and declaring their global environmental conditions.

The remote sensing based method was tested on large areas (four satellite scenes in Romania and two in Slovakia, summing up approximately 195000 sq km) and the validation of the results was done against mining related features from available databases. These consisted in the classes of interest from the CORINE Land Cover or/and national databases and registries provided by the members of the Steering Committee of the PECOMINES project through means of a filled-in questionnaire.

Based on the output anomaly image an index named “mining anomaly index” was computed for the zones of interest (catchments as natural barriers, but it can also be applied to administrative boundaries, etc.), differentiating them regarding the deposited mining material. By computing this index for the first order catchments of Slovakia (CCM – Catchments Characterization and Modeling Database of the European Commission), it was possible to distinguish between catchments with no surface traces of the mining activity or where only open-pits and quarries for construction materials are present (characterized usually solely by iron-staining of the waste rock pile) and others where the oxidations are accompanied by the formation of OH-bearing secondary minerals, indicative of hazard processes, such as acidification.

The results were in good agreement with the “hot spots” indicated by the Country Report of the Ministry of Environment in Slovakia, the zones belonging to the index class most prone to hazard corresponding to the areas with big accumulation of wastes, such as the dumps of the smelter at Rudňany or nearby the power plant at Nováky. Other catchments in the same index class or in the next two classes with high and intermediate values correspond to some mining “hot spots” (Špania Dolina, Kremnica, Gelnica, Hačava, Hnúšťa – Mútnik, Rožňava, Košice, Lubeník, Tisovec-Čremošné), smelters (Ziar nad Hronom, Krompachy), other industrial units (Zvolen, Revuca, Handlová). A high value is obtained for the catchment where the mines of quartzite, limno-quartzite between Kremnica and Stara Kremnička are situated. Of particular interest are the catchments located in the Volovsk Mts. where open-cast

mines for limestone, dolomite in the vicinity of Jaklovce and Margecany are shown with intense FeOx-OH anomalies and correspond to the highest index classes (D, respectively E). In this case the remote sensing derived information should be combined with other available thematic layers (geology, soil), supplemented by detailed data regarding site specific conditions, in order to assess if the respective deposited mining waste needs to be considered a potential hazard. The tailings management facilities for processing limestones and dolomites are included (EIPPCB, 2004) in the category that could have an environmental impact if not handled properly.

As the remote sensing sensor receives the electromagnetic radiation reflected by the objects on Earth surface, when the underground mines are located in the forest no FeOx-OH anomalies can be obtained. However, small clusters or isolated anomalous pixels within the cover of forest or natural vegetation associations are usually related to rock waste piles from the underground mines in the zone, since they originate from exposed terrain (of at least one pixel size) and the FPCS method was developed such as to avoid vegetation anomalies. The validation example given for the Neogene volcanic area of Ilba – Baiut metallogenetic district in Romania, where the anomalies in the forest were confirmed by checking with the detailed geological maps, comes in support of this observation. Furthermore, a GIS and statistical analysis done for the whole study territory of Slovakia regarding the distribution of anomalous pixels in various CORINE Land Cover classes and buffered mining sites of the Slovak national database, buttresses it up once more. This analysis revealed that in the forests and areas with semi-natural vegetation associations, 40 % and respectively 22 % from the total number of anomalous pixels representing co-occurrences of the highest amounts in both iron oxides and secondarily formed OH-bearing minerals are falling into the buffered mining sites located in these land cover classes. Taking into consideration some proved cases of mismatch, when the anomalies were located outside the buffer but in the immediate vicinity, almost touching it (for example the mine of ceramic clay at Teplicany), it can be considered that the above mentioned percentages could be even higher.

The tailing ponds (e.g. Baia Mare, Aghires – Romania) and dumps associated to the smelters for ore processing (Rudňany, Krompachy – Slovakia) are generally pointed out on the anomaly images as areas with rather large clusters of anomalous pixels. However, if the water on the dump is deep, the respective zone does not show anomalies, as water is highly absorbing the electromagnetic radiation. Shallow water with sediments and mixtures of water - mined material in the dumps exhibit anomalies, enabling that eventual leakage into the surroundings is observed.

Some dumps with slag and ashes resulted from coal combustion, as well as steel slag do not highlight as anomalies due to their mineralogical composition and specific properties. It can be quoted the case of the slag and ashes dumps near Rovinari termo-electric power plant for lignite burning (Romania), where the anomalies are lacking. This site was specified as a “hot spot” due to the geodynamic phenomena, sinks, landslides, qualitative and quantitative modifications of surface and underground water and of air quality. Here acidification is not an issue due to absence of pyritic material and this is reflected by the lack of anomalies. Another example refers to the steel smelter at Hunedoara (Romania), where the intense FeOx-OH anomaly corresponding to the industrial unit is extended in the surrounding area, indicating the

emissions of dust particles rich in iron oxides, but on the dumps the anomalies are missing. The high alkalinity of steel slag and coal ashes makes them in fact suitable as capping or neutralizing materials for mitigating acid mine drainage, as is shown by studies done in the U.S. for assessing the possibility of reusing in the mining activities these cheap and available materials resulted from processing the mined natural resources. The fact that some of the dumps are highlighted by anomalies and others not depends, as it was previously said, on the mineralogical composition of the surface materials in the dumps, which determines or not the steep increase in reflectance between Thematic Mapper bands 1 and 3 that is characteristic for iron oxides.

The FPCS method can map the distribution of deposited mining materials, differentiating based on co-occurrences of high amounts of iron oxy-hydroxides and OH-bearing secondary minerals the most hazardous ones, sources of potential acidification, from some common and more harmless types, characterized only by iron-staining. In the cases when the major contribution to acidification comes from underground mine waters and the surface manifestation of this phenomenon is on a too reduced area extent there are not many pixels belonging to the anomaly class that indicates the highest hazard. This is for example the case of Smolník mine in Slovakia, where the acidification caused by underground mine waters, together with the impact of de-watering of the aquifer horizons, changes in the hydrological regime and geo-mechanical phenomena determined the site to be considered a “hot spot”. In situations like this the remote sensing based method can contribute in monitoring the surface conditions of a site over time and this is reflected in the absence of anomalies on the 2000-image for the remedied tailings pond while on 1992-image, two years after the closing of the mine, this pond still exhibited anomalies. It is however necessary to combine the information derived from the remote sensing method regarding the deposition of potentially hazardous mining waste material with other information about the underground conditions and the geo-mechanical stability. This way a complete assessment of the state of closed mines could be achieved, as required by the proposed Mining Waste Directive.

The multi-temporal satellite scenes serve also for checking the zones characterized by an index class representing deposited material with increased hazard risk located in very small catchments or inter-basins. In these cases there is the suspicion that the anomalous values caused by the quasi exclusive presence of several pixels belonging only to the anomaly class representing co-occurrences of high concentrations in iron oxides and OH-bearing secondary minerals were artificially increased by division to the tiny areas. This can occur in two situations:

- when the anomalous pixels are confirmed by CORINE LC or national databases as being indeed related to the activities of the extractive industry, but due to the scale of DEM used for catchments delineation (1:250,000) sometimes the mining facility is artificially divided into several adjoining catchments, having very small inter-basins intercalated between. In this case the anomalous pixels falling into the small inter-basin give rise to a higher index value than the neighbouring catchments only due to its much smaller area.
- when the available data do not confirm the presence of mines in the tiny inter-basin, but the verifications with time-series satellite images can determine if there was only a temporary deposition of anomalous material, or if it stayed in

place for years. The fact that the inter-basin is located in a region with history in mining is a further help in solving this type of cases.

It is therefore proposed to use as reference for computing the "mining anomaly index" higher order catchments (2 or 3), where the main advantage would consist in having the mining related features in their whole entity without artificial separation caused by the original scale of catchments delineation.

An advancement in source characterization would be the combination of the anomaly images (OH-FeOx) which offers information on the surface properties of deposited mined material with data layers referring to the geological background, soil type and particular conditions of the site (hydro-geological, geo-mechanical phenomena, emissions types, on-site processing, impact caused, proximity to water courses and bodies etc.). It could be thus determined if there is a sufficient buffer capacity in the surroundings of the mine for neutralizing the negative effects of hazardous mining material, generator of acidification. For achieving this objective, a first step would be generating a pan-European digital layer of host-rock geology that could start from the already available European Soil database. This would use the data on the soil parent material types, improved with more detailed information gathered through means of the questionnaire produced within the framework of the PECOMINES project.

On the other hand, the newly obtained ranking of the zones taken as reference for assessing the global state of the mining sites (catchments as natural barriers or administrative boundaries at different levels of detail) would reflect the complexity of situations by combining the at-surface information obtained by the remote sensing based method with data on the underground conditions and emissions in the water and air (when available). A monitoring of these sites could be realized this way, including also the closed mines and quarries, for which a special attention is given in the proposed Mining Waste Directive. The potential environmental risk posed by the mining sites and their facilities could be assessed by combining these ranked zones with data on population density, proximity to natural parks and reservations or to residential areas and a vulnerability map at national to multi-country scale could be obtained, pointing out the zones needing more surveillance.

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