



## EXECUTIVE SUMMARY

This report presents the summary of the results of the work done in the four ImpactMin study areas, Kristineberg (Sweden), Mošć (BosniaHerzegovina), Rosia Montana (Romania) and Chelyabinsk Orenburg (Southern Urals)

The overall aim of the ImpactMin project was to identify and develop effective tools and approaches for monitoring environmental impacts related activities, using a combination of ground-based observations and remotely sensed information.

As the ImpactMin project clearly illustrates, there is a very wide range of situations.

In its strictest sense, mining refers directly to the activity of extraction of metallic or non-metallic resources from the Earth's crust (Merriam Webster).

It also refers to intricately associated processes such as urbanization and development of primary and secondary industries. Besides those physical aspects, the enormous social implications of mining have to be taken into account, and therefore form an integral part of the project.

Mining has taken place since prehistoric times, is taking place today and will continue to take place in the future, and with our living planet increasing environmental pressure because of growing population and higher standards of living it is of great importance that the environmental aspects of mining are responsibly managed. Therefore it is essential that appropriate tools and guidelines are developed to monitor environmental impacts.

Revolutionary technological developments are taking place with respect to measuring devices such as optical and geophysical sensors as well as airborne and spaceborne carriers. The advanced

surface from a distance, providing spatially and temporally continuous information in a highly cost-effective manner.

The study areas that were selected for this project are diverse with respect to the nature and scale of the environmental impact. This diversity allowed us to explore the use of remote sensing technology under a wide variety of conditions, identify appropriate procedures for combining discrete field data and continuous remote sensing data in order to optimize the balance between efficiency of feature detection and cost of data acquisition and processing.

This study clearly demonstrates that current state-of-the-art in remote sensing is sufficient for the monitoring of a variety of complex environmental processes such as surface water, soils and vegetation, related to different aspects and stages of mining.

Mining areas such as Rosia Montana (figure 1), that have been active producers for thousands of years are revisited at intervals throughout their history. As extraction technologies become more efficient, it becomes economic to mine higher grade ores, leading to the displacement of exponentially growing volumes of rock, increasing the areal extent of mining activities and disturbance of the surface associated environmental impact.

Many countries have, as a result of increasing environmental awareness, over the last two decades put strict environmental regulations into place. As a mining sequence, any mine that opens or

re-opening such a country will have to comply with strict environmental regulations and will be obliged to monitor environmental impacts and to predict catastrophic events. Because remote sensing can provide information over large areas at a relatively low cost, it is valuable for monitoring the relatively subtle and slow environmental changes that typically take place over tens of years in the life cycle of most systems. Systematic recording of the situation at regular intervals is important in order to monitor changes during mining and subsequent remediation, and may provide important evidence in environmental disputes.

In the case of abandoned mines such as the *Uhovici Coal mine*, often very little or no remediation has been carried out, and this presents hazardous situations, such as access to dangerous open pits, dumps and tailings with high concentrations of toxic substances. Instability, illegal dumping of domestic and industrial waste in former open-pit areas, a health risk for the public. Urban growth leads to construction of new housing in close proximity to unstable pits, whose collapse could cause many fatalities. Responsible authorities are well aware of the situation and need Earth observation data in order to manage the risks in a responsible manner.



Figure 1. Locations of ImpactMin demo sites.

Mine sites such as those at *Karabash* and *Mednogorsk* have fallen into the trap of becoming a consciousness, poor planning, economic mismanagement, outdated technology, etcetera. The fact that the local population in these mining centers is at great risk seems to be categorically ignored by the responsible authorities. Access to important information is often held by the local management, and remote sensing data can therefore provide us with important environmental information that otherwise would not be accessible for outsiders.

Mining areas like *Kristineberg* are located in an environmentally sensitive part of the world. Ecosystems in boreal regions are extremely vulnerable and even the smallest footprint of human activity can remain visible for many years. It is vital that the environmental impact of mining has on these delicate habitats is investigated in order to understand the extent to which the mining affects wildlife and vegetation. Because of the harsh climatic conditions and generally poor access to these regions, conducting fieldwork to support these investigations is not without risk. These factors, combined with the short time window for such fieldwork in this region, create a need to collect relevant information in a fast and efficient manner and to replace as much as possible the work on the ground by observation from a distance or space.

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## 1. INTRODUCTION

As described in the executive summary, the U.S. Environmental Protection Agency (EPA) has a wide variety of topics. It ranges from the mining itself, to environmental issues directly caused by mining (such as acid drainage, dumps, wind-blown dust, damage to the landscape, change of groundwater regime, etc), to indirect impacts (such as related industries, human settlement, water quality issues, etc), and finally post-mining issues (such as slope stabilization, remediation of open pits and dumps, cleaning up, etc).

Five carefully chosen study areas allowed us to address different aspects of mining-related environmental impacts using a combination of ground-based sensing methods. We were able to push the limits of traditional sensing data (such as Landsat, Spot Vegetation) and to explore and understand new sources of imagery (e.g., SAR imagery, very high resolution hyperspectral imagery). We were able to collect large amounts of field spectra from tailings, dumps, rocks, soils, stream precipitates, leaves, grass, and the most modern portable field spectrometers. This data, in combination with traditional geochemistry, as well as some innovative environmental forensics, can identify diagnostic trends in surface waters, soils, vegetation and air that could be correlated very well with various types of sensing data.

During the ImpactMin project large amounts of very valuable data were collected. Most of these data had a clear spatial component and proper spatial data management using GIS technology was an important aspect of our work. A major investment in data demands standardization and proper data documentation. In order to guarantee appropriate accessibility and integrity of all information, Inspire compliant data documentation was adapted for this project.

## 2. TEST SITE OVERVIEW

The selection of test sites (Figure 1) was done in such a way that we would be able to study different aspects of environmental impact related to mining, using different Earth observation techniques and to investigate different methods of processing data:

- Kristineberg (Sweden) (Husson et al, 2012) is a large district with a long history of mining. It is located in the boreal forest zone and is characterized by a very delicate ecosystem. Our work focused on the assessment of long-lasting environmental impact by continued release of heavy metals into a delicate ecosystem.
- Mostar (Bosnia Herzegovina) (Smailbegovic et al, 2012) lies in an area of abandoned coal mines and partly abandoned heavy industries. There is strong urban development in close proximity to the mine and industrial area. Underground coal fires continue to burn and cause pollution as well as geotechnical instability. There is significant domestic pollution and poor sanitary infrastructure, partly a result of recent years of war, causing pollution of surface and ground water. Our work focused on making an inventory of hazards and risks, which will be used by local stakeholders to support cleanup actions and mitigate potential future catastrophes.
- Rosia Montana (Romania) (Baciu et al, 2012) is an area that has seen over two thousand years of gold mining. The last active (open pit) mine closed in 2006, but remediation measures

Plans to open a new mine in the near future will directly affect an area of more than 15 km<sup>2</sup>. Our work focused on characterizing the current situation and on the development of tools for future environmental monitoring.

This work can be used by local stakeholders as a baseline and as a future dataset for environmental monitoring

- Karabash and Mednogorsk (South Ural Mountains, Russia) (Aminov et al., 2017) These are two industrial areas with over 100 years of mining and smelting. Both areas are highly polluted up to distances of up to 30 km from the smelter. Pollution in the Karabash area is of disastrous proportions. Only 27% of the local population is considered healthy due to severe airborne pollution, large volumes of acid drainage and untreated sewerage discharge into a freshwater reservoir for the town of Chelyabinsk. A new smelter has recently been built in Karabash, but there are doubts about its effectiveness. Production is expected to double in the near future, and there is therefore concern that this will lead to greatly increased environmental impacts.

Our work focused on the development of tools that allow long-term monitoring of the impacts on soils and vegetation. The main stakeholders for this work should be the management of the smelters as well as government authorities and public health organisations. These stakeholders can use our work to monitor the large environmental effects of industrial activities in the area and the effectiveness of any new control measures

### 3. KRISTINEBERG TEST SITE

The Kristineberg area is heavily impacted by mining activities, though the full extent of these impacts is still not fully established. Large parts of the mining

operations are located in the Malmbergsgruvan (M) and Västana (V) open-pit mines. At 2.5 km downstream of the outlet

of the Kristineberg mine, the water enters the Kristineberg lake system (containing lakes and streams) and flows into the Kristineberg river. The riparian zone, i.e., the transition zone between water and land, of varying width. Riparian zones have important ecological and regulatory functions in aquatic systems. Quantifying plant biomass and related factors, such as geochemistry, has so far been a major challenge at the scale of entire riparian zones. Here, we applied high resolution (5 cm) remote sensing with an unmanned aircraft system (UAS) in combination with field sampling during the growing periods in 2011 and 2012. We performed the study at 10 locations (10

locations (river stretches of 320 m length) along the mining outlet. We estimated the amounts of metals (Cd, Cu and Zn) stored in the dominant species. At each location, we sampled 10

10-m-wide belts (M) parallel to the river bank. A vegetation map at the species level was derived from aerial images acquired with the UAS in combination with field sampling of species composition and cover. (Figure 2) Assessments of biomass (herbaceous and shrub vegetation) and metal contents were derived by combining the vegetation maps with results from field sampling.

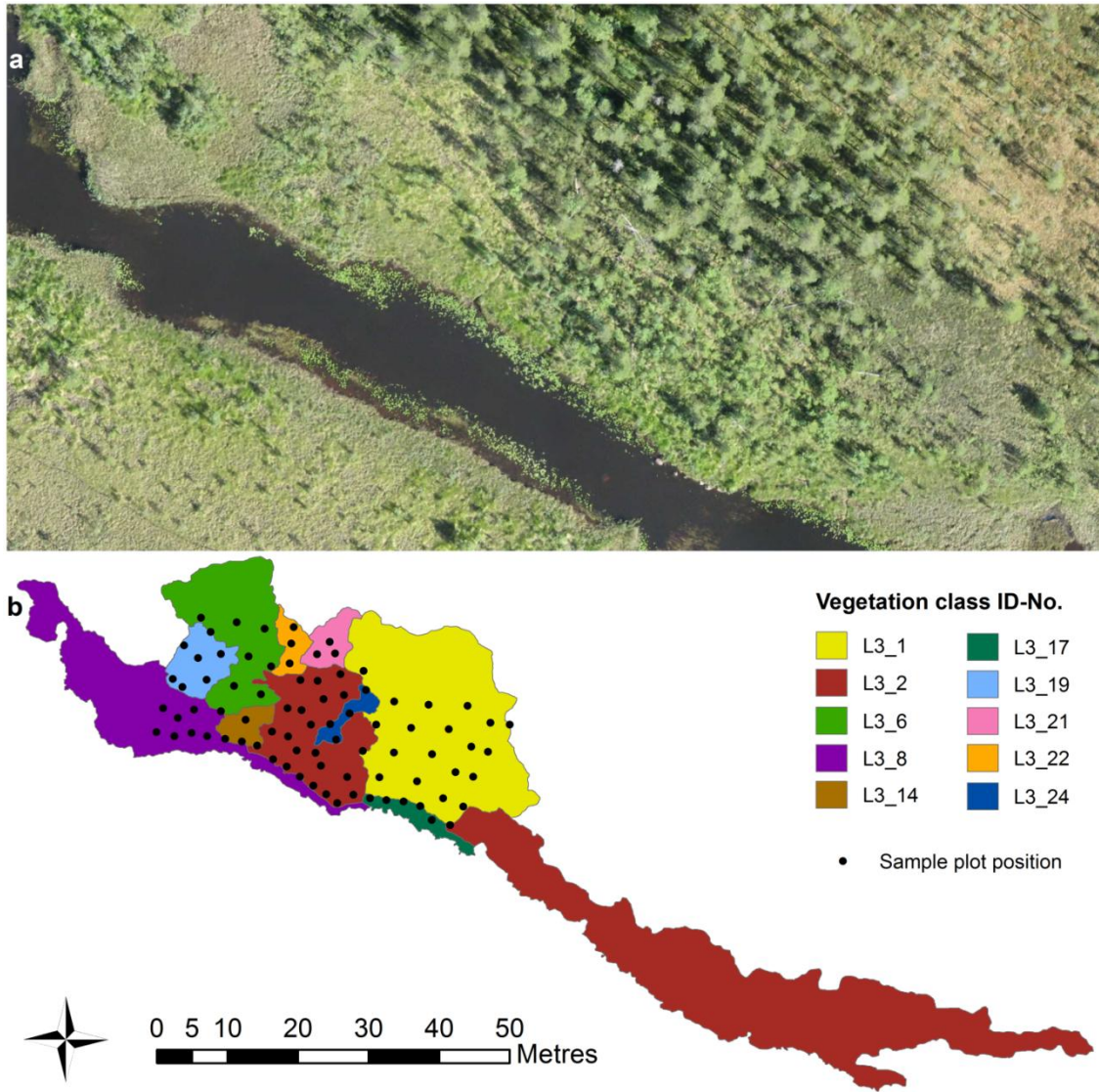


Figure 2 Core zone at location L3, a) orthoimage and b) vegetation map with sample plots

Concentrations of Cd, Cu and Zn decreased with increasing distance from the source of pollution. †  
 Cu concentrations ranged from high to moderate and Zn concentrations ranged from very high to moderate. †  
 concentrations remain constant.

May August 2011 ranged from 37 for Cd at L1 to 193 for Zn at L3.

Concentrations of Cd, Cu and Zn in riparian vegetation varied among species. Only *Salix sp.* contained the most Cd and Zn at all locations. Most pronounced was the difference between *Carex rostrata/vesicaria* which was significant in five of nine *Salix sp.* also differed from *Eriophorum angustifolium* for Cd at L3 and from *Molinia caerulea* and *Trichophorum cespitosum* for Zn at L3. Another significant difference was *Carex rostrata/vesicaria* *Carex nigra* *sp. juncella* for Cu at L1. †  
 concentrations were higher in vegetation from the river channel than in riparian vegetation that occurred in belt I. Cd, Cu and Zn concentrations, combined for all species in river channel vegetation, did not differ between locations.

The riparian zone at L1 was composed of 3 vegetation classes of which 12 were represented in the core zone. At L2, we identified 12 vegetation classes of which two were represented in the zone. Location L3 was similar to L1 in terms of vegetation types identified (27 vegetation classes which ten were represented in the core zone). The vegetation-specific biomass ranged from 0.32 to 2.22 kg m<sup>-2</sup>. L1 was the most productive location with 9.4 t ha<sup>-1</sup> followed by L2 (7.5 t ha<sup>-1</sup>) and L3 (5.2 t ha<sup>-1</sup>).

The total amounts of Cd, Cu, and Zn stored in the dominant species of riparian vegetation were 33, 801, and 13,620 respectively. Compared with the total amounts of Cd, Cu, and Zn transported by the river, this represents 0.7% of Cd (L1), 0.3% of Cu (L2), and 0.4% of Zn. The total amount of stored trace elements increased with increasing distance from the source of contamination. The maximum amounts of Cu and Zn were stored at L2.

*Salix* sp. which was dominant at only one location, contained only 3% of the total dominant biomass but 73% of all Cd and 24% of all Zn. *Zostrata/vesicaria* contained 85% of all Cu, 66% of all Zn, and 80% of the total dominant biomass. At L1, *Salix* sp. accounted for 99, 65, and 92% of the total amounts of Cd, Cu, and Zn, respectively, and for 61% of the total dominant biomass. At L2, *Zostrata/vesicaria* accounted for 99% of all Cd, Cu, Zn, and biomass. At L3, *Molinia caerulea* contained most Cd and Zn (56, and 41%, respectively). *Carex* sp. contained the most Cu (39%). *Salix* sp. was not among the dominant species. However, the amounts of Cd and Zn stored in *Salix* sp. were equivalent to 77 and 22% of the total amounts of Cd and Zn stored in dominant species at L3.

At most, there were 23 plant species (location L3). At location L2, there were in total only 10 plant species and two of the studied belts included only two species. *Zostrata/vesicaria* was present in both belts.

Our study supports previous studies showing that the closed mines upstream of the Kristineberg

The flexibility of the UAS (transportable and operable by a single person) permitted us to carry out remote sensing at exactly the desired locations and times, without being dependent on external image providers. The 5-metre resolution of the produced orthoimages allowed for detailed vegetation classification and accuracy mapping throughout the riparian zone. It was possible by visual interpretation to delineate vegetation stands on the images and to relate the specific optical appearance of the stands to species compositions derived from field visits, including tree, shrub and herbaceous species as well as submerged aquatic species. Because of the narrow spatial extent of riparian zones (often < 10 m wide), high spatial resolution has previously been found to be the main feature needed to improve riparian vegetation classification. Previous remote sensing approaches for riparian vegetation have been unable to resolve herbaceous and shrub vegetation at the species level, mainly due to the inadequate spatial resolution of available remote sensing data or limitations in automated image classification. Discrimination has so far been successful between various land cover/use classes such as agriculture, forest, grass, and shrub. Our study demonstrated that plant species differ significantly in their uptake of trace elements. In addition, the studied vegetation stands were generally characterized by multi-

species, single-species stands occurring mainly at L2. Biomass assessments conducted by sensing using satellite images of varying spatial resolution (30m) have successfully been applied to large-scale single-species stands in wetlands, and in assessing total wetland biomass. Applying such traditional remote sensing with satellites to the riparian zones studied here, however, would overlook the high spatial variation in vegetation stands, biomass, and trace element uptake. The method presented is suited for a more accurate assessment in terms of vegetation class species-specific biomass and trace element contents. This allows for detailed modeling of nutrient and trace element cycling in the riparian zone and of interactions with the adjacent aquatic system. Compared with the large areas covered by satellite wetland studies (3000 km<sup>2</sup>), the reach of our method is limited to river stretches of several hundred meters in length. Two reasons for this limitation are a) increasing uncertainty with increasing distance from the core zone, and b) the considerable time required for visual image interpretation, especially manual mapping, and fieldwork to train the interpreter and for biomass sampling. The first reason applies to areas with large spatial variation in vegetation. This variation leads to the definition of vegetation classes with species compositions that differ from those of any core zone vegetation class. However, this could be compensated for by distributing the sample plots over a larger area. Regarding the second reason, to make fieldwork more efficient could be divided into two steps. In the first step, species composition and cover could be investigated as a basis for vegetation mapping. After the validation of the vegetation map, biomass could be sampled by randomly selecting a certain number of points in each vegetation class, reducing the total number of samples needed. However, samples would then be distributed over a larger area, increasing the time needed for sampling. Biodiversity and species composition of vegetation appeared to be affected by potential

location is rather flat and hence probably more regularly flooded compared to the other two locations. Regular flooding results in the presence of plant species otherwise found in the riparian zone, e.g. *Molinia caerulea*, *Calamagrostis canescens* and *Andromeda polifolia*. In planning phytoremediation measures, it is crucial to know the extent to which contaminants accumulate in different plant species. Harvesting of selected riparian species before senescence could then be applied to prevent the release of the accumulated metals to the water. In particular, our study revealed that the removal of *Salix* sp. would be an efficient way to remove the vegetation-bound Cd and a considerable amount of Zn by only removing a small portion of the biomass. Similar results concerning the potential of *Salix* sp. to extract Cd and Zn from contaminated soils were obtained in other studies. However, it can only reduce the burden of metals to

studied 320 stretches

The application of UAS in addition to field sampling for riparian vegetation monitoring has great potential to improve the accuracy of assessments of biomass and trace element/nutrient content at the scale of entire riparian zones

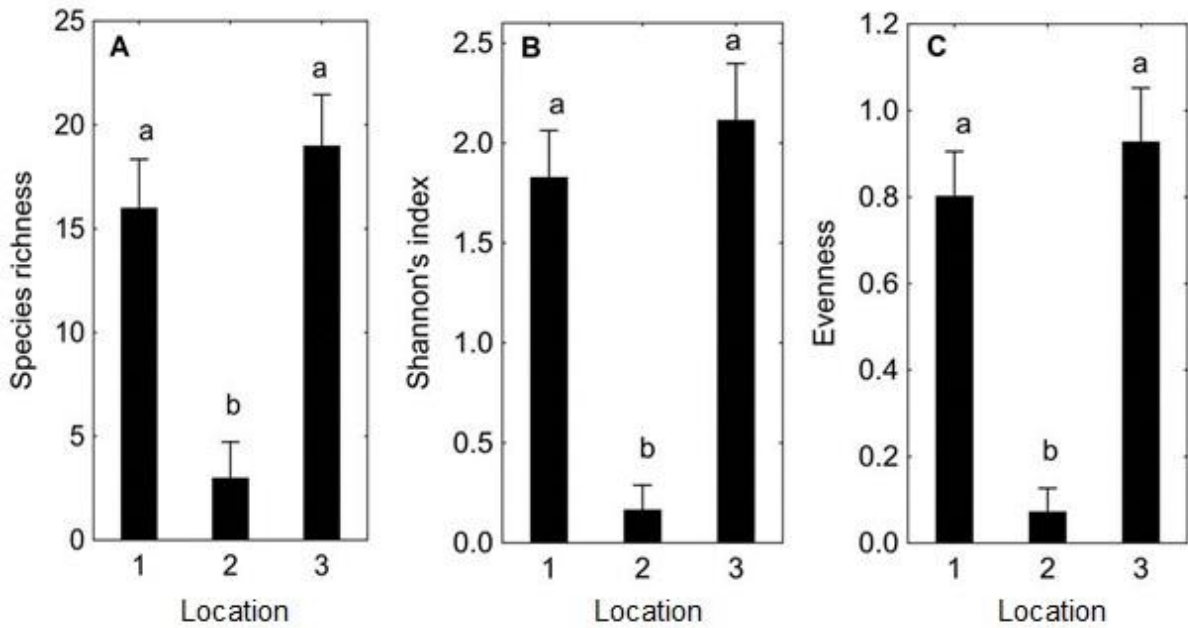


Figure 3. Diversity metrics (Species richness, Shannon's index, and Evenness) at three locations. Different letters indicate significant differences in diversity ( $p < 0.01$ ).

#### 4. MOSTAR TEST SITE

The City of Mostar, Bosnia and Herzegovina, situated along river Neretva in a mountain valley has been an important crossroad for thousands of years. Significant deposits of brown coal were discovered in the 19th century and the mining began soon afterwards to supply much needed coal for railroads and industry in Bosnia and Herzegovina in the Austro-Hungarian Empire. The mining of coal continued almost until the outbreak of hostilities in Bosnia in the 1990s. In addition to coal mining, Mostar was also a center of processing and aluminum-refining supporting the defense and aircraft industry in the former Yugoslavia.

Mostar Valley now contains at least three sites of possible environmental impact: the abandoned Vihovici Coal Mine, the abandoned waste ponds (mud depot) and the City of Mostar itself, rapidly expanding onto the former industrial lands. Industrial facilities have fallen into disrepair and the city itself remains much divided along ethnic lines as a result of the 1992 conflict resulting in continued degradation and lack of coherent vision. Of particular interest to the ImpactMin project are the coal mine and the waste ponds as the city of Mostar itself is situated in a karst environment with fragile aquatic ecosystem dependent on the river Neretva which is the main source of water for both Herzegovina as well as southern Croatia.

Near simultaneous acquisition of airborne hyperspectral (HS) and water quality measurements coupled with the high resolution imaging took place in Mostar during May/June of 2011, culminating almost 16 months of background research, identification of suitable detection technologies and mission planning. The primary goal was to correlate the various datasets to establish environmental impact and also to use various datasets to improve the overall quality of the acquired airborne data using the ground-based measurements.

#### 4.1. Site Goals

The acquired imagery and data were the first of its kind in Bosnia and Herzegovina and Western Balkans, in general and the first real empirical data collected in Mostar for over 20 years. The technology used in the course of the survey was considered and best suited for a complex network and relationship of water and ground targets. The active part of the Mostar Valley study locality were Photonics Faculty of Civil Engineering at the University of Mostar and Flemish Institute for Technology Research. Various levels of information towards the comprehensive document detailing the work performed at the Mostar Valley study site presented within the ImpactMin Report.

The main goals of the survey campaign within ImpactMin were:

1. Ascertain the success of 2009 remediation and current state at the Vihovici Mine site and point to the areas that are yet to be addressed or have been neglected from the first remediation attempt
2. Establish the baseline condition of the Neretva river, before Vihovici, after Vihovici Mine, below the city of Mostar and below the industrial area in the southern Mostar Valley (aluminium and agricultural areas).
3. Establish the current environmental baseline for the valley and preliminarily evaluate other sites that may have problematic occurrences in the future (for example, which was added as a topic during the project in the light of the Hungarian disaster).

The main advantages of the airborne approach are the abilities to resolve surface detail in high spatial and spectral resolution, over relatively wide area at moderate overall cost of acquisition. These qualities make it increasingly popular with industrial exploration and establishing types of surface cover, distribution of pollutants, anomaly identification and search/recovery. The spectral information provides a fairly robust approach in extrapolating composition of the particular imaged target and its classification from the background. Furthermore, by using the sheer quantity and redundancy of airborne data, it is possible to increase the level of confidence in target unmixing and detection, reinforcing the advantage over other sensing methods in terms of confidence, time and overall cost effectiveness. Therefore, the airborne component fills the important niche between in situ measurements and spaceborne EO sensing.

The Mostar case study is unique because it encompassed a variety of sites in an urban corridor with the satellite, airborne, lightweight and ground/water in situ sampling. All of the datasets had a particular role and niche to fill in the GEOSS compliant environment.

Vihovici Mine Site and mud storage facility are the two main areas of mineral impact concern in the Mostar Valley. Vihovici Mine is located close or within the urban zone, while the risks of the mud storage are yet to be fully appraised. The proximity of the sites to the urban zone and the important watershed of the river Neretva have called for a detailed study of both sites and their impacts on the environment. A combined campaign using variety of edge remote sensing assets and analysis tools have yielded the results presented below.



#### 4.2. Vihovici Mine Site (Figure 4)

*Figure 4. Mineral map and topographic model generated from UAS imagery showing surface mineral concentrations: most important are significant clusters of sulfate minerals (e.g. jarosite) on the northern*

§ The hyperspectral survey has been successful in detecting iron oxide, hydroxide and sulfate minerals that may have a negative effect on the environment. It was determined that hyperspectral data can detect the subtle changes in surface mineralogy caused by fires (Figure 5)

§ Satellite and airborne HSI data suggest that there are increased concentrations of Fe (hydroxide and sulfate) in the surface environment at the Vihovici mine site and storage facility, and most can be traced back to the resource extraction and/or processing activity.

§ Fe-minerals at Vihovici appear to be mainly related to the former burn area and waste piles, with the increased concentration of sulfates near the areas of former industrial waste (battery dismantling) and burn areas, but their overall impact appears to be moderate to the mine site (Figure 4)











































































