Comparative Analysis of Waste Material Distribution between Remote Sensing Data and a Geochemical Map

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Abstract A comparative analysis of the waste material distribution between remote sensing data and a geochemical map was carried out in and around the Bor mine located in Eastern Serbia in Southeastern Europe. Remote sensing data were obtained by analyzing Lansat-8 images based on surface materials collected as ground truth data. Based on the mineral components of the surface materials, the Landsat-8 images were analyzed to make distribution maps of the surface materials. The maps indicate that the pollution from the Bor mine has diffused downstream and to the floodplains. The distributions of the surface materials are also associated with a geochemical map made using the river water quality.

Key words Remote sensing, waste material, XRD, geochemical map, Bor mine, Serbia

Introduction

Mine wastes are the largest volume of waste materials handled in the world (ICOLD, 1996). These waste materials are diffused via environmental cycles. River water and other surface water are their main means of transportation. Waste materials are transported by river water, and then river channels and floodplains become contaminated by metal-rich waste in concentrations that may pose a hazard to human livelihoods and sustainable development. Because ~90% of metal contaminants are physically transported in sediment-associated forms (Martin and Maybeck, 1979), knowledge of long-term sediment deposition and remobilization is required to accurately assess contamination levels and dynamics (Coulthard and Macklin, 2003). Meanwhile, dissolved metals from these wastes generate acidic drainage and the release of this water is an environmental problem at international scales (Blowes et al. 2003).

Methods to assess the spread of these pernicious, passively toxic elements have traditionally been geochemical, hydrologic, and geophysical in nature, and therefore have required the collection of numerous samples followed by laboratory measurements. The amount of data can be bound using GIS techniques (e.g., Ishiyama et al. 2015). While remote sensing at optical wavelengths cannot directly detect trace metals, it can be used to map the minerals that host these metals. In recent years, remote sensing has been successfully used to aid this process (e.g., Fenstermaker and Miller, 1994; Ferrier, 1999; Farrand, 1997; Farrand and Harsanyi, 1997).

In the present study, distributions of waste materials were analyzed using remote sensing techniques and then compared with a geochemical map to interpret and prevent environmental problems caused by metal mining. The geochemical map was created in Ishiyama et al. (2015) using the chemical contents of river water and river sediment samples. Conversely, the distributions of the waste materials were analyzed using ground truth data and multispectral images (Landsat-8).

Study area

The town of Bor is located in a mountainous and forested area in Eastern Serbia (Southeastern Europe) close to the Bulgarian and Romanian borders and approximately 200 km from the capital city of Belgrade. The climate in the Bor area is moderately continental. Bor and its surroundings are well known in Europe for copper deposits. The mining exploitation of Bor started in 1903 and has continued until the present (Serbula et al. 2013). The mining in Bor consists of two open pits, underground mining, and two plants for mineral processing (Fig. 1a, EIA Study, 2010). A copper smelter is also located at the mine. In addition, an old-flotation pond, tailing dam, and overburden are located near the mine. The river system in this area has become severely contaminated by the extraction and processing at the mine. The Bor River flows around Old Bor area. The Krivelj River flows around the Veliki Krivelj open pit. After the confluence of the Bor and Krivelj Rivers, the two rivers flow as the Bela River, which then joins the Timok River and the Danube River. Contaminated sediment particles are deposited within river channels and on floodplains (Fig. 1).

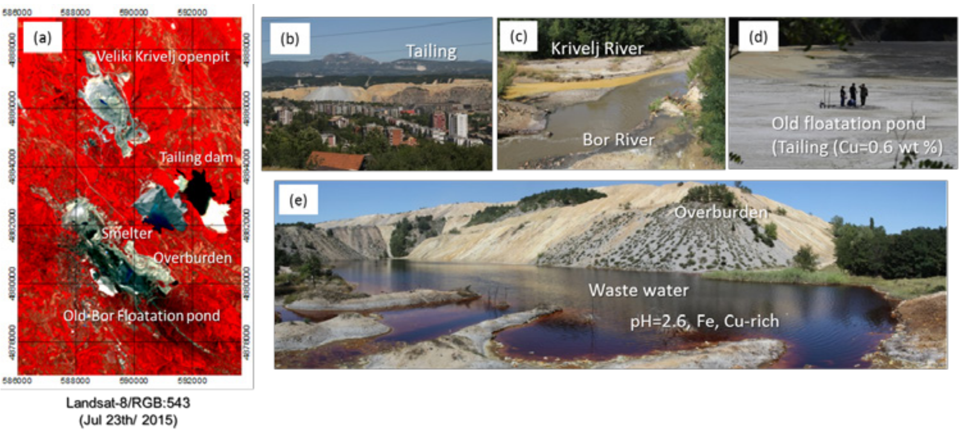

Figure 1. *Location of the Bor mine and photos of the polluted area.*

Ground truth data

Surface materials, rock, and soil samples were collected from around the Bor mining area. A total of 22 samples were collected from Old-Bor flotation pond, the tailing dam, and the floodplains along the Bor River, Krivelj River, Timok River, and Danube River. The samples were analyzed to identify their mineral components using XRD (MiniFlexII). Their reflectance spectrums were captured in the laboratory using a spectro-radiometer (Fieldspec). The XRD data indicated the existence of quartz, alunite, jarosite, kaolinite, and illite. Based on the mineral components, the 22 samples were divided to four groups as follows.

- Group 1 consists of Danube River samples that contain no jarosite (samples 1501, 1502, 1503, 1504, 1505, and 1506).
- Group 2 consists of floodplain sediments from the Bor River, Krivelj River, and Timok River that contain jarosite, gypsum, and alunite (samples 1507, 1703, 1704, and 1706).
- Group 3 consists primarily of samples from the tailing dam of the Veliki Krivelj open pit (Dam 3) that contain jarosite, gypsum, and chlorite (samples 1508, 1608, 1601, 1602, 1603, 1604, and 1605).
- Group 4 consists of Old-Bor flotation tailing and Vrazogranac samples. Jarosite, kaolinite, and alunite are contained in these samples (samples 1606, 1607, 1701, 1702, and 1705).

The reflectance spectrums were compared and used to evaluate if the groupings were correct. The spectral features of each group nearly coincided with each other (Fig. 2). Two data points (samples 1608 and 1706) were anomolous.

Data and image processing

Landsat-8 images were primarily used in this study. Landsat-8 has two optical sensors: an Operational Land Imager (OLI) and a Thermal Infrared Sensor (TIRS). The OLI measures nine spectral bands between the visible and short-wave infrared regions. The TIRS measures two long-wave infrared regions.

First, the Normalized Difference Vegetation Index (NDVI) was measured using the Environment for the Visualization of Images (ENVI) Version 5.2 software package. Four seasons of NDVI data were used to estimate the land use, i.e., the temporary vegetation area (agricultural fields), forest area, and the non-vegetation area. Four images were selected from four seasons of 2015: March 17, May 20, July 23, and November 12. Near the Bor mine, the path and row of the images are 185 and 29, respectively. These four NDVI datasets were overlaid (Fig. 3a); then an unsupervised classification was performed using the Iterative Self-Organizing Data (ISODATA) analysis technique. To analyze satellite images in non-vegetation areas in the present study, a mask image was made from the classification to remove the vegetation areas (Fig. 3b). In Fig. 3b, the Danube River is recognized as a non-vegetation area and analyzed with the other areas in the following; however, in the future, the river area will be removed.

The grouping determined from the ground truth data was used for the classification as supervised data. To make supervised data, pixel data corresponding to the sampling point of each group was collected from the Landsat-8 image of July 23, 2015. Based on these supervised data, a classification of the non-vegetation areas was performed using the Spectral Angle Mapper (SAM) method (Fig. 4) for the Landsat-8 image of July 23, 2015. Figure 4 represents the false color Landsat-8 image and the classification map around the Bor mine.

***Table 1**. Mineral existence and groupings.*

No.	Location	Alunite	Calcite	Chlorite	Kaoli-nite	Dolo-mite	Gyp-sum	Jaro-site	Illite	Classifi-cation
1501	Danube R.		○	○	○	○			○	
1502	Danube R.		○	○	○	○			○	
1503	Danube R.		○	○	○	○			○	Group 1
1504	Danube R.		○	○		○			○	
1505	Danube R.		○	○		○			○	
1506	Danube R.		○	○		○			○	
1507	Timok R.	○			○		○	○		
1703	Vrazogra-nac	○				○	○	○	○	Group 2
1704	Krivelj R.	○			○		○	○		
1706	Bor R.	○		○	○		○	○		
1508	Timok R.				○		○	○	○	
1608	Old-Bor mine				○		○	○	○	
1601	Dam3			○			○	○	○	
1602	Dam3			○				○	○	Group 3
1603	Dam3			○			○	○		
1604	Dam3			○			○	○	○	
1605	Dam3			○					○	
1606	Old-Bor mine	○			○			○		
1607	Old-Bor mine	○			○			○		
1701	Vrazogra-nac	○			○			○	○	Group 4
1702	Vrazogra-nac	○			○			○	○	
1705	Bor R.	○			○			○		

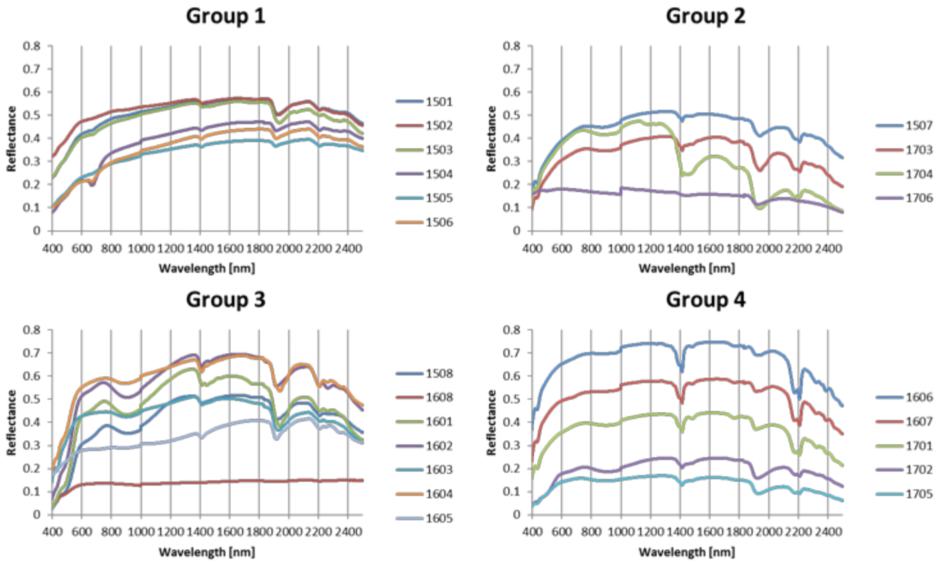

***Figure 2**. Spectral data of the samples.*

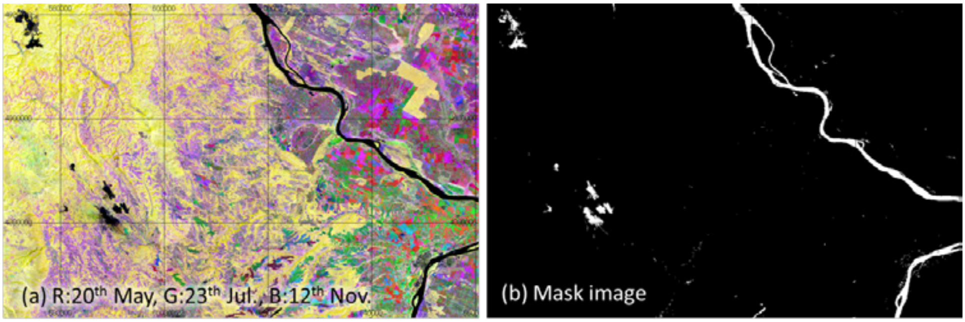

***Figure 3**. (a) Four overlaid seasons of NDVI data and (b) the mask image extracting the non-vegetation areas.*

Figures 4b and 4c show the area around the Bor mining area. All four surface material groups exist around the Bor; however, this area primarily consists of groups 2 and 4. Figures 4e and 4d show the confluence between the Bela and Timok Rivers. This area primarily consists of groups 2 and 4, as does the Bor mine area. Figures 4f and 4g indicate the river mouth of the Timok River. This area primarily consists of group 1 and small amounts of groups 3 and 4. This indicates that the confluence of the Bela and Timok Rivers, and the Timok and Danube Rivers, are contaminated by mine waste material.

The quality of the river water has been measured near the study area to make many kinds of geochemical maps (Ishiyama et al. 2015). The distribution map of the surface material map made in the present study was overlaid with some of the geochemical maps (Fig. 5).

The result of the overlay indicates the relationship between the source of the pollution and the diffusion of that pollution.

Conclusions

In the present study, a distribution analysis was performed using remote sensing techniques to examine the diffusion of polluted surface material in and around the Bor mine, located in Eastern Serbia in Southeastern Europe, which has been exploited for the last 100 years. Multispectral images, Landsat-8 images, were analyzed using ENVI software and ground truth data were collected in the study area. Non-vegetation areas were extracted using NDVI seasonal differences. In addition, 22 surface materials were collected as ground truth data. The collected samples were analyzed using XRD and their mineral components were identified. Based on the mineral components, these 22 samples were divided into four groups. Landsat images from the summer of 2015 were analyzed to make distribution maps of the surface materials from the supervised data associated with the four groups. The results of the analysis indicate that the pollution from the Bor mine has diffused to the downstream floodplains of the Bela River, Timok River, and Danube River. The distributions of the surface materials are associated with the geochemical map made using the river water quality. In future studies, ground truth data need to be added and high-resolution and hyperspectral images need to be adopted.

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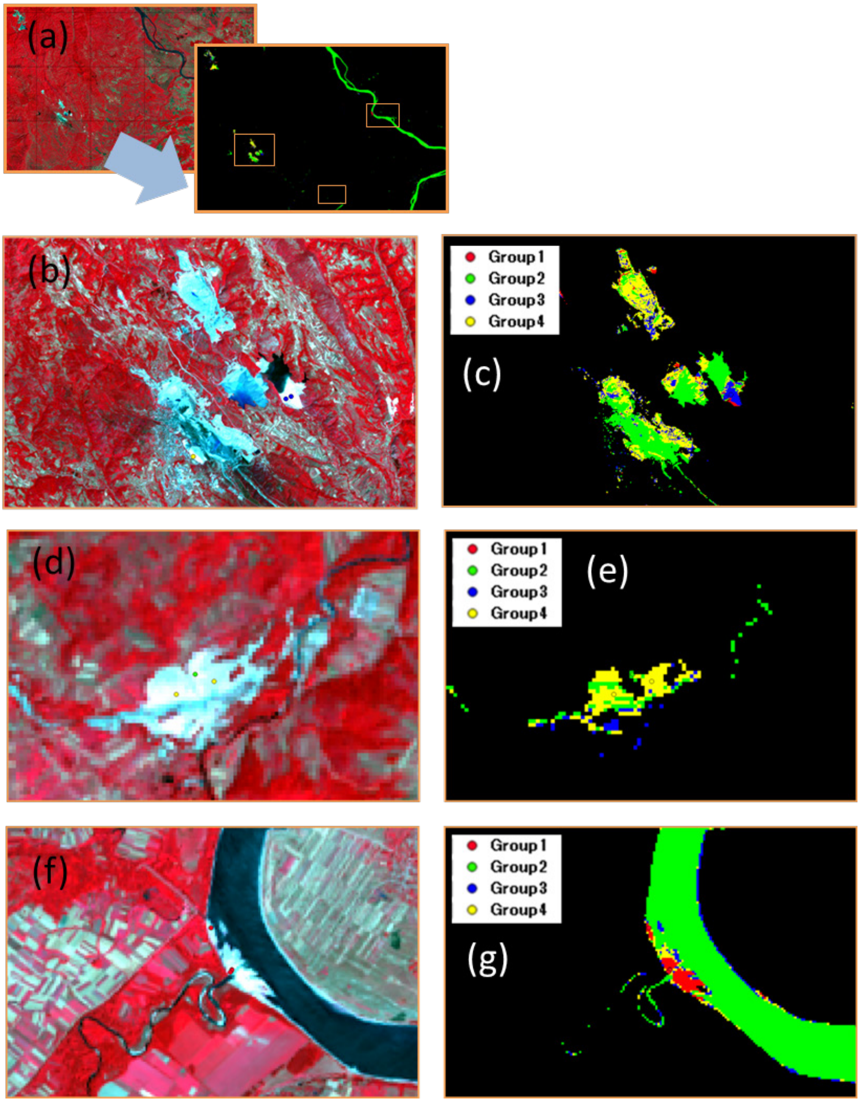

Figure 4. *False color images (left side) and classification maps (right side).*

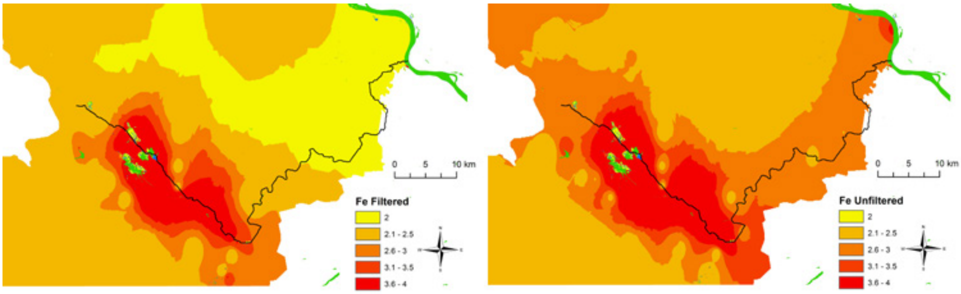

Figure 5. *Overlaid maps of the distribution of surface materials and geochemical maps of Fe.*