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Concept for long-term geo-monitoring of the post-mining environment using the example of the Prosper-Haniel mine

Marcin Pawlik[1*], and *Tobias* Rudolph[1]

[1]Research Center of Post-Mining, Technische Hochschule Georg Agricola, 45 Herner St., 44787 Bochum, Germany

Abstract. The operation of a mining facility provides a wealth of data, starting from mining licenses, documentation of extracted deposits, tunnel reinforcement methods, to documentation regarding the termination of mining operations, which impacts the natural environment at the local, regional, and supra-regional levels. The results of projects conducted by the Research Center of Post-Mining at the Technical University of Georg Agricola in Bochum present the possibilities of integrating environmental geo-monitoring methods to understand the processes occurring both during and after mining operations. Among the research methods used, spatiotemporal multispectral analyses of satellite imagery and images from drone flights stand out, and these will be presented in this paper. Additionally, in-situ measurements using soil sensors, weather stations, the application of mobile GIS, and three-dimensional modelling of geological structures should be noted. A key aspect of mining process research is the implementation and integration of all available geospatial data, allowing the consideration of post-mining processes as a cycle of interconnected, independent values that, through data analysis and validation, enable a comprehensive understanding.

1 Introduction

According to Directive 2011/92/EU of the European Union [1], all changes resulting from mining activities that may affect the environment and people should be monitored. The activities of a mining company can significantly affect all spheres of the earth's shell: lithosphere, pedosphere, hydrosphere, biosphere, and atmosphere [2]. In particular, the extraction of mineral resources has an impact on water resources, soil, and air [3, 4]. The complexity of geo-monitoring results from many aspects that should be considered when interpreting mining processes [5, 6]. Environmental changes that occur both during and after mining activities are continuous and long-term [7 – 9], so integrated long-term monitoring is an important issue. Kretschmann [10] points out that these tasks have no fixed time frame and can therefore be called a perpetual task.

The concept for long-term geo-monitoring of the post-mining environment involves continuous assessment and surveillance of geological, environmental, and hydrological

* Corresponding author: marcin.pawlik@thga.de

factors [11, 12]. By employing advanced technologies such as remote sensing, GIS (Geographic Information Systems), and sensor networks, comprehensive data collection can be achieved. This approach facilitates proactive management strategies to mitigate potential hazards and ensure sustainable land use post-mining.

1.1 Research area

The study area is the Prosper-Haniel coal mine site, located in the western part of the Ruhr region (Fig. 1). Mining operations began there in 1976 [13]. In the area in question, the main exploitation of raw materials took place from the 1990s until 2014 [14]. The Prosper-Haniel mine ceased operations in December 2018 [13].

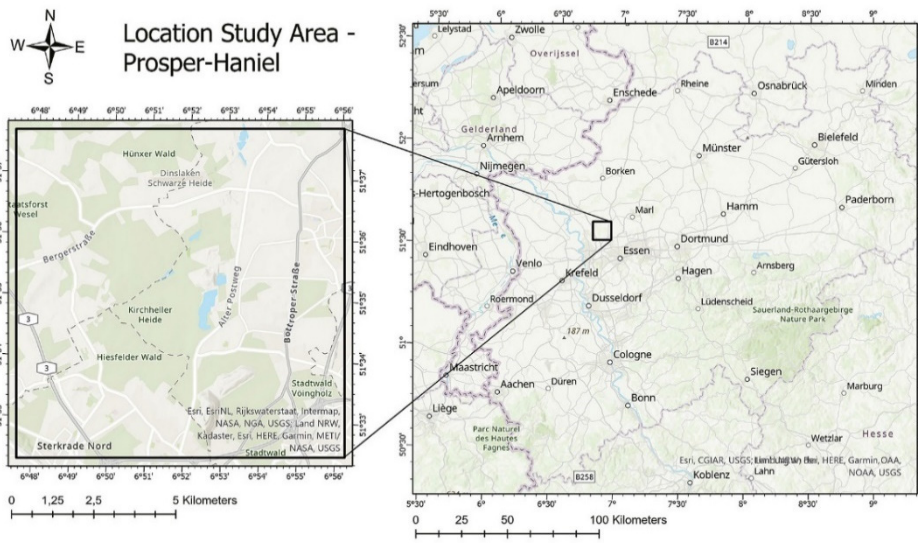

Fig. 1. Location of study area. Source: [15].

2 Methods

2.1 Geo-monitoring

Rudolph et al. [16] present environmental geo-monitoring as a process in which spatial and temporal changes and interactions in each geosystem/ecosystem are observed. The authors point out that to create an integrated understanding of the processes, it is advisable to conduct a primary measurement (zero measurement). Geo-monitoring analyses the interactions and changes occurring between the biosphere, the lithosphere, the hydrosphere, and the atmosphere. This process is carried out by coordinating results from various fields of natural and technical sciences, among which can be distinguished: remote sensing, climatology, geodesy, mining, biology, soil science, geology, hydro-(geo)-logy, hydro-(geo)-chemistry, geophysics as well as geo-informatics and data management. Multi-sensor, multi-temporal and multi-spatial environmental geo-monitoring is based on the establishment of thresholds and limit values, which are used to evaluate the results of monitoring, as these values enable appropriate measures (countermeasures) within the framework of risk management. An important aspect is social communication and transparent presentation of the obtained research results with the local community, so that the public is aware of the scientific research carried out in the area. Examples of geo-monitoring methods are presented in Fig. 2.

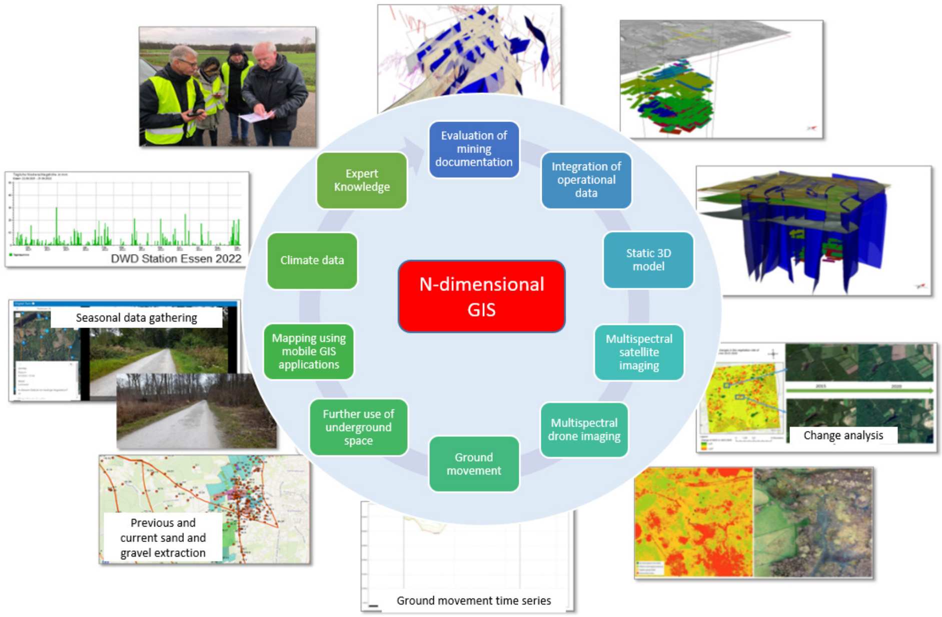

Fig. 2. Methods of geomonitoring in the project "Digital Twin". Source: based on [16].

2.2 Temporal-spatial multispectral analysis of satellite imaging

The evaluation of the quality of preliminary data, in the case of temporal-spatial multispectral analyses, applies among others to satellite imagery of space missions of NASA (Landsat) and ESA (Copernicus). Pawlik et al. [17, 18] point out possible criteria for their evaluation, among which can be distinguished: time series, survey area, spatial resolution, and spectral resolution. Understanding the different spectral ranges of satellites allows calculations of vegetation indices, which play a key role in observing post-mining processes [17, 19]. In the context of assessing plant health, chlorophyll plays an important role as an object for analysis. Chlorophyll absorbs energy in certain wavelengths (e.g., the red band) and reflects a band in the near-infrared range. Based on the above-described scheme, the most popular vegetation index – NDVI (Normalized Difference Vegetation Index) [20] was created, which, through the relationship between the near-infrared band and the red band, makes it possible to perform calculations for a time series and, consequently, to perform a temporal-spatial analysis, an example of which is presented in Fig. 3. The results of the analysis show that in the period 2002 – 2012 (the green lines define the given period in Fig. 3), the values of the NDVI index are decreasing, which, with the integration with other data (aerial photos, analysis of other remote sensing indicators), makes it possible to present conclusions that a lake was formed in the given study area.

2.3 Use of an unmanned aircraft

An unmanned aircraft, commonly referred to as a drone, could carry special sensors comparable to those on satellites. Drones equipped with multispectral cameras, typically recording in the red, green, blue, red-edge and near-infrared ranges, are therefore suitable for collecting data for precise vegetation index calculations. Thanks to the high (reaching several centimeters) resolution, it is possible to accurately distinguish singular plants. Thus, thanks to such flights, it is possible to record the phenomena occurring in a specific area very accurately. For example, it is possible to understand the effect of changes in soil moisture on vegetation indices before processing the less detailed, but available for large areas, satellite data. This understanding of the process can be visualized in both 2D and 3D space. A publication by Pawlik et al. [22] presented a summary of the characteristics of the spectral channels for the DJI Phantom 4 Multispectral and Sentinel 2 satellite missions, showing that the bands recorded by the drone fall within the bandwidth of the satellite sensor.

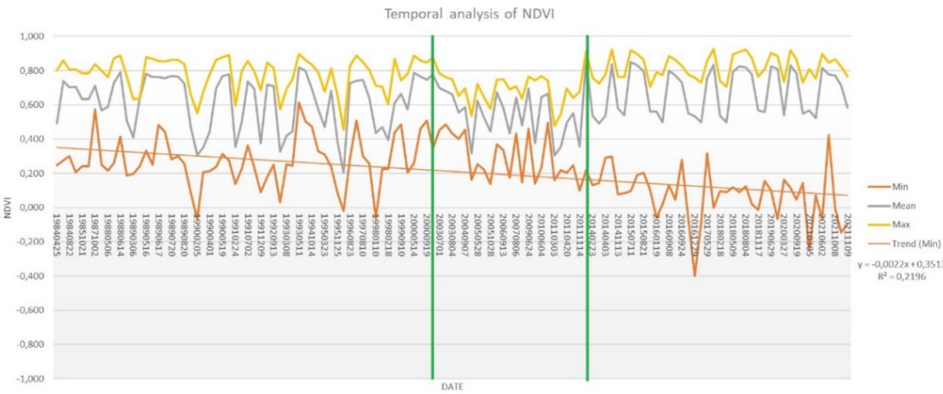

Fig. 3. Spatial-temporal analysis of the NDVI index in the period 1984 – 2021. Source: [21].

To conduct drone flights, especially in certain areas, it is necessary to obtain permission from landowners. In addition, the drone operator must comply with national and EU regulations, which clearly specify flight altitude, distance of the drone from roads or buildings, and caution when flying near groups of people. Conducting a drone flight also depends on the prevailing weather conditions [23].

3 Results

As part of the research conducted by the Post-mining Research Center, several drone flights were conducted to create orthophotomaps that are more accurate than satellite images. This included acquiring images using a drone with appropriate configurations regarding flight altitude, overlapping lateral and longitudinal ranges. For this purpose, a DJI drone equipped with a Phantom 4 Multispectral camera with a Real Time Kinematic (RTK) module function was used, which allows to receive signals from global satellite navigation systems (GPS, GLONASS, BeiDou, Galileo) and corrective data from the German Satellite Survey Service (SAPOS). This makes it possible to achieve a positioning precision of 2 – 3 cm.

3.1 GRWI – Green Red Water Index

GRWI (Green Red Water Index) is an index that allows for detection of water areas [24]. The authors note that many previous remote sensing indices have used combinations of SWIR (shortwave infrared) and NIR (near infrared) spectral bands [25 – 32], which have not previously been used as sensors in multispectral drone cameras [24]. Research on the development of the new indicator was based on drone flights using a DJI Phantom 4 drone equipped with a multispectral camera. The new GRWI index is based on the formula of the GRNDVI (Green Red Normalized Difference Vegetation Index) [30], considering the red-edge band (Equation 1). The index takes values from -1 to 1, where values for aquatic areas range from 0.2 to 0.6 [24].

$$GRWI = \frac{NIR - (Green - RedEdge)}{NIR + (Green + Red + RedEdge)}, \tag{1}$$

where *NIR* is the near-infrared band; *Green* is the green band; *Red* is the red band; and *RedEdge* is the red-edge band.

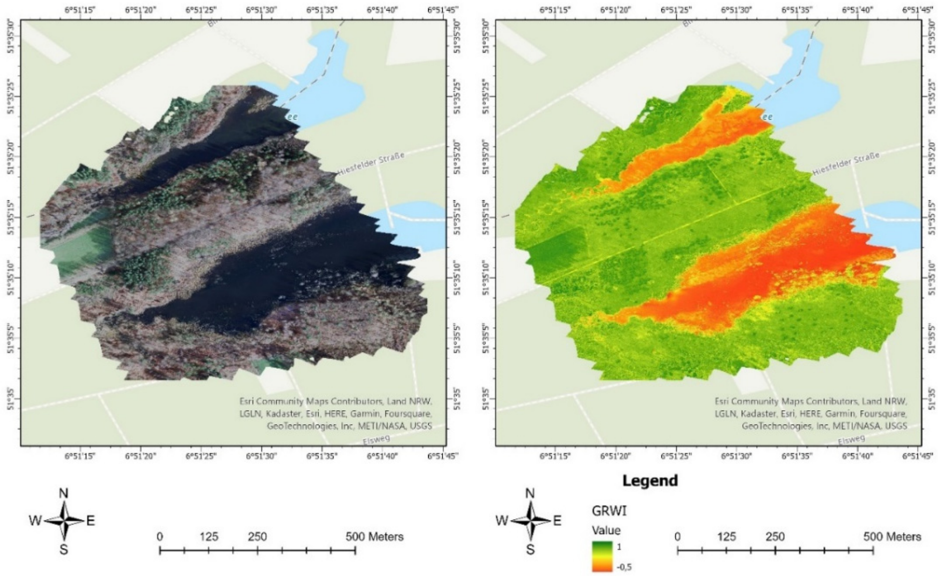

Fig. 4. Compilation of orthophotomaps (left) and GRWI (right) for lakes: Weihnachtssee and Pfingstssee, based on a drone flight – DJI Phantom 4 Multispectral on 28.03.2022. Source: [33].

4 Conclusions

The environmental geo-monitoring concept presented in this article exemplifies an innovative and interdisciplinary approach to integrating and fusing data to interpret and understand post-mining processes. It is worth noting that data derived from different sources pose a challenge due to their varying temporal, spatial, and spectral resolution during the fusion process. In interpreting environmental changes and their impact on the land surface, buildings, and infrastructure, mining operation data combined with the knowledge of mine surveyors are particularly important.

The integration of drones equipped with multispectral cameras and specialized indices like the Green Red Water Index (GRWI) presents a powerful tool for precise environmental monitoring. Drones, capable of recording various spectral bands including red, green, blue, red-edge, and near-infrared, enable accurate data collection for vegetation index calculations. This facilitates detailed monitoring and analysis of vegetation health and environmental changes in specific areas. Drone flights offer advantages over satellite imagery due to their higher resolution, enabling the accurate identification and monitoring of individual plants and phenomena such as changes in soil moisture. However, conducting drone flights requires permission from landowners and compliance with national and EU regulations regarding flight altitude, distance from infrastructure, and safety protocols. Additionally, weather conditions play a significant role in determining the feasibility of drone flights.

The utilization of drones equipped with specialized cameras, such as the DJI Phantom 4 Multispectral, combined with Real-Time Kinematic (RTK) positioning technology, allows for the creation of highly accurate orthophotomaps with positioning precision ranging from 2 to 3 cm. The development of indices like GRWI further enhances the capabilities of drone-based remote sensing by enabling the detection of water areas. GRWI, based on the GRNDVI formula, incorporates spectral bands such as near-infrared, green, red, and red-edge, offering a range of values from -1 to 1, with specific values indicating water areas.

Research conducted by the Research Center of Post-Mining showcases the practical applications of drone technology in environmental monitoring and research. By utilizing drone flights to create orthophotomaps and develop indices like GRWI, the center demonstrates how drones contribute to precise environmental monitoring, enabling the detection of vegetation health, water bodies, and other environmental phenomena with high accuracy and resolution.

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