Analysis of the vegetation condition on the area of the closed Babina mine in 1989-2019 using multispectral satellite images

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Abstract. Technical and biological treatments, aiming at granting or restoring use/natural values of lands degraded by mining operations, are carried out already at the stage of mining works and continue after the end of exploitation. As a result of these activities, area of plant cover increases and condition of vegetation in the former mineral extraction is improved. However, monitoring of post-mining areas in various regions of the world indicates that in the sites of former exploitation local degradation of vegetation may occur, despite the completion of the reclamation process. Adverse changes in flora can be caused for example by water penetrating deep into the ground through the system of underground pavements or their collapsing. The purpose of this publication is to present the changes in the condition of plant cover within the Pustków mining field, one of the four fields of the closed lignite “Friendship of Nations - Babina Shaft” mine. The analysis of variation in the state of the plant cover health was carried out for the period of 1989-2019 based on NDVI, EVI and GNDVI spectral indices, developed using multispectral images of the Landsat TM/ETM+/OLI missions. The obtained results provide information about systematic improvement of the flora condition in the analysed region and indicate an increase in green areas. In 1989-2019, overgrowth of the shorelines of anthropogenic lakes and heaps was observed, as well as reservoir with a decreasing surface area due to vegetation succession was identified. In 2016, local degradation of the plant cover was also observed in the north-western part of the Pustków field. The obtained results prove the necessity of continuous monitoring of the flora health in the area of the analysed mine, but also in other post-mining areas.

1. Introduction

Mining activities lead to the significant and extensive metamorphosis of the natural environment. As a result of exploitation, changes of water regimes, as well as contamination of air and soil with heavy metals compounds are observed. Moreover, the natural landscape is transformed by the anthropogenic forms, such as waste heaps or large scale excavations. The effect of the open-cast mining works is also the destruction of indigenous vegetation, which is a consequence of the soil structure devastation, the occupation of a large area by the mine, and the settlement of dust pollution on the plants leaves [1, 2]. Restoration of use/natural values of areas degraded by mining occurs in the process of reclamation, which is understood as a technical and biological treatments aimed at relevant land forming of the post-mining area, adjusting water conditions, strengthening slopes, restoring soils, as well as improving the physical and chemical properties of lands [3]. As a result of reclamation process in areas of former mining activity, an increase in the green surfaces and an improvement in the vegetation condition are observed. However, it should be emphasized that adverse effects of ceased mining operations may occur. The reasons of plant cover degradation in the post-mining areas might be for example a substantial
drying of soils due to the lowering of the groundwater table (water penetration deep into the ground through the system of former underground pavements is one of the most common causes) or collapsing of the underground pavements. Therefore, monitoring of reclaimed areas is a significant issue. Periodic observations of the natural environment within these terrains may allow to the fast identification of places where vegetation is degraded, which in turn will contribute to the commencement of the research aimed at indicating its causes and reducing adverse effects in the plant cover. Taking into account of the dimensions of the areas that should be covered by cyclic monitoring, the use of classic measurement methods seems to be a time consuming and inefficient solution. For this reason, remote sensing data is increasingly used to monitor vegetation and other components of the natural environment in the post-mining areas.

A review of world literature provides information about wide spectrum of issues, in which remote sensing data was used to analyse changes in plant cover on post-mining areas. The subject of the most frequently undertaken research concerns monitoring of the reclamation process, including the development of vegetation in a degraded area. For example, Karan et al. [4] used the NDVI, EVI, NDMI and RVI spectral indices, developed on the basis of the Landsat program images, to assess the condition of the plant cover and to describe its changes in space over a period of 15 years. Similar studies using images of the Sentinel-2 mission and data obtained from Aerial Laser Scanning (ALS) were conducted in the area of former sulphur mining [5]. In turn, Raival et al. [6] based on Landsat TM images for the period of 2008-2012 has attempted to estimate biomass production in the reclaimed hard coal mining area Wise County (USA). Research concerning a monitoring of the post-mining areas reclamation process, in particular the time-space changes in the plant cover, using remote sensing data was also the subject of the publications [7-14].

Identification of undesirable changes in the reclaimed post-mining area was presented in the work of Padmanaban et al. [15]. Based on short-term changes in the NDVI time-series, developed using images of the Landsat ETM + mission, the authors indicated the location of two subsidence zones in which systematic vegetation degradation and wetland surface growth were observed. These phenomena were a consequence of rising groundwater table.

Another example of the remote sensing data usage in post-mining areas in the context of the plant cover research is the determination of flora restoration and self-regeneration indices. This issue was the subject of publications [16, 17].

The purpose of this study is analysis and presentation of spatial changes in the vegetation condition in 1989-2019 within the Pustków mining field, one of the four fields of the reclaimed lignite mine “Friendship of Nations - Babina Shaft” located in western Poland close to German border (Figure 1).

2. Study area
The Babina mine is located in the Żary poviat, which is a part of the Lubuskie Voivodeship (Western Poland). In terms of geomorphology, the area of former lignite mining is situated within a glaciotectonic structure called the Muskau Arch, having the form of a U-shaped horseshoe, that is a result of consecutive glacial periods. Geological processes occurring during subsequent glaciations were not only the reason for the metamorphosis of the terrain (formation of scales and folds), but also for the exposure of coal seams, which contributed to the commencement of raw material exploitation within the entire structure [20].
The mine, which is the subject of this research, was the largest mine in the Polish part of the Muskau Arch. Exploitation of lignite was begun in 1921 and it lasted over 50 years. The mineral was extracted both by underground and opencast methods, producing average of 225 thou. Mg of lignite before World War II and 380 thou. Mg after 1945. The Babina deposit consisted of four mining fields: Tuplice, Trzebiel, Żarki and Pustków, wherein only in the last two mentioned fields exploitation was carried out [21]. The mine was closed in 1973 due to unfavourable geological and mining conditions, and reclamation works in the forest direction was begun. However, it should be emphasized that the closure of mine has not completely terminated mining operations in this region. Until the end of the 90s, kaolin clays and clays were extracted in analysed area [22].

At present, the area of the closed mine is characterized by high forest cover. The dominant plant species are: pine, alder and riparian forests. In addition, due to the presence of the Chwaliszówka stream, the post-mining area is rich in species-diverse river, riverside and marsh systems. In the period of 40 years after the reclamation process, the originally poor and usually single-layer vegetation has been diversified by the lower trees and shrubs [23,24]. Since 2009, the former lignite mining area has been protected as part of the national geopark, which changed its name to UNESCO World Geopark - Muskau Arch in 2015 [21].

In this work, the analysis of changes in the vegetation condition in the period of 1989-2019 was carried out within the Pustków field. As a testing areas, four research polygons were selected, the location of which is shown in Figure 1. The choice of the indicated areas was dictated by the results of the previous field reconnaissance and information obtained from the local administration and the authorities of the Lipinki Forest District, indicating the lowering of the groundwater table, subsidence, intensive erosion processes and the occurrence of sinkholes within their borders.

Figure 1. Location of the test fields.
3. Materials and Methods

3.1. Satellite data
The analysis of changes in the vegetation condition located in the area of the former Pustków mining field in the period of 1989-2019 was carried out using multispectral images of the Landsat TM/ETM+/OLI (Landsat Collection Level-1) missions, obtained from the official website of distributor https://earthexplorer.usgs.gov/. All data used in the study were registered from May to the end of September. This selection of images was intended to analyse the plant cover health during its growing season. An additional criterion adopted during the data selection was cloud cover, which was set at less than 10%. Table 1. contains information about data used in this research, i.e. dates of the collected images and type of sensors that those images registered.

| Sensor name | Date of image capture |
|-------------|-----------------------|
| TM          | 18.09.1989, 04.08.1990, 07.08.1991, 10.09.1992, 08.05.1993, 31.08.1994, 18.08.1995, 20.08.1996, 01.09.1997, 10.08.1998, 14.09.1999, 11.05.2000, 14.05.2001, 18.06.2002, 25.09.2003, 10.08.2004, 29.08.2005, 26.09.2006, 19.08.2007, 29.07.2008, 24.08.2009, 12.09.2010, 24.09.2011 |
| ETM+        | 20.05.2012            |
| OLI         | 15.05.2013, 07.09.2014, 19.09.2015, 12.09.2016, 30.08.2017, 17.08.2018, 21.09.2019 |

3.2. Image pre-processing
The obtained images were subjected to procedures aimed at standardizing the material registered by different sensors in various atmospheric conditions. In the first stage of the collected data pre-processing, detector correction was performed by converting the radiometric values Digital Number (DN) into the values of the registered radiance $L_{SAT}$ according to the formula (1):

$$L_{SAT} = c_0 + c_1 \times DN$$

where: $c_0$ and $c_1$ are calibration constants for a specific type of sensor and spectral band, called offset and gain, respectively [25].

The influence of phenomena and processes occurring in the atmosphere was reduced by conducting atmospheric correction, taking into account the average height of the terrain in the area of the research, as well as aerosol (Tropospheric model) and atmosphere (Mid-Latitude Summer and Sub-Arctic Summer models) models. It should also be emphasized that the initial data processing included the removal of the scan line error for the images registered by ETM+ sensor using the landsat gapfill tool. Finally, the acquired data was cut to the borders of the Pustków mining field.

All the procedures described in this section were conducted using the ENVI 5.5 software and its modules (FLAASH, Radiometric Calibration, Raster Management).

3.3. Vegetation indices
The following spectral vegetation indices were used: NDVI, EVI and GNDVI. Selection of the EVI was dictated by the significant woodiness of the research area, for which land cover form NDVI may show irregularities (NDVI saturates in areas characterized by high biomass content). In addition, this index reduces the influences of the atmosphere and soils by using the blue band [26]. In order to increase the reliability of the results, it was decided to use the GNDVI, which is more sensitive to chlorophyll content than NDVI through a combination of green and near-infrared bands [27]. It should be pointed out that the literature review regarding the use of vegetation indices in the research of plant cover located in post-mining areas, presented in the Introduction section, indicates that NDVI and EVI are the most frequently chosen indices in this type of analysis. Combinations of spectral channels, i.e. SAVI, TSAVI, ARVI, NLI, MSR, DVI, SR and VARI, repeatedly used in publications, were rejected in this study. The
works of Zhang and Zhou [28] and Ma et al. [29] indicate that these indices do not reflect the real vegetation condition of former mining areas or are not suitable for research of high and species-diverse flora, which is the dominant form of Pustków field.

Table 2. presents mathematical formulas which were used to calculate the vegetation indices.

Table 2. A list of vegetation indices used in a research of the vegetation condition located in former Pustków mining field.

| Index   | Mathematical formula* | Reference |
|---------|------------------------|-----------|
| NDVI    | \[
\frac{NIR - RED}{NIR + RED}
\]                       | (2) [27]  |
| EVI     | \[
2.5 \times \frac{NIR + 6 \times RED - 7.5 \times BLUE + 1}{NIR + GREEN}
\]                     | (3) [5]   |
| GNDVI   | \[
\frac{NIR - GREEN}{NIR + GREEN}
\]                        | (4) [28]  |

* NIR, RED, BLUE, GREEN are the reflectance values in the near-infrared, red, blue and green bands, respectively.

4. Results

4.1. Analysis of the obtained vegetation indices values

A detailed analysis of the obtained average annual NDVI values indicates a systematic increase of coverage and denser vegetation in the area of the research in the 1989-2019 period. As Figure 2. presents, this index has not taken a value below 0.7 for over 10 years (it should be noted that Figure 2 does not include the average annual values of the NDVI for 2015, 2009, 2002 and 1997. Despite the adopted data selection criteria, these images are slightly cloudy, which significantly distorts the index values). In the analysed time period, the lowest NDVI value was observed in 1999 (0.63), and the highest in 2014 (0.79).

Figure 2. Average annual NDVI values in the area of the research in 1989-2019.

The graph in Figure 2. provides information about years of change of average NDVI value that can be translated into improvement or deterioration of the general condition of vegetation. On its basis, the 30-years study period was divided into shorter intervals, whose borders indicate significant changes of NDVI. Therefore, the following periods were distinguished: 1989-1999, 1990-1998, 1998-1999, 1999-2005, 2005-2006, 2006-2016, 2016-2018 and 2018-2019.
The first of the mentioned periods is characterized by a decrease of vegetation condition in the majority of the research area. An adverse change of flora, at a level not exceeding 20%, was observed in 75% of all image's pixels (25,116 pixels in total). Greater degradation (20-40%) was identified only along the shorelines of anthropogenic water reservoirs in the test fields no. 2 and 4. A slight improvement in the state of vegetation was noted in the southwestern part of field no. 4 and in the northern part of field no. 2. In turn, 1990-1998 period presents a development and growth of the plant cover. Improvement of flora (<20%) was observed in case of 24,180 image's pixels, with favourable changes exceeding 20% in the western part of field no. 1, north-eastern part of field no. 2, and south-western part of field no. 4. An inconsiderable decrease of vegetation condition in the analysed period was identified only in the northern parts of test fields no. 1-3. At the beginning of 1998, in the area of the former Pustków mining field, vegetation development was inhibited, and its condition deteriorated. The changes observed in 1998-1999 interval are analogous to those identified in the first analysed time period, however, the pixel's number presenting adverse changes was 21% lower.

In 1999–2005 period flourish of vegetation was observed in the research area. In the majority of the former Pustków mining field, the vegetation condition was strengthened by 20%. As in the period of 1990-1998, a slight decrease of flora health was identified only in the northern parts of test fields no. 1-3, as well as in the east of field no 4. In 2005, short-term deterioration of plant cover condition has occurred. Nevertheless, in 2005-2006 period significant positive or negative changes in the vegetation state were not identified.

The highest increase of average NDVI value was observed in the years 2006-2016. In this period the index value increased by 0.1. The analysed interval is also characterized by the greatest diversity of vegetation condition in the study area. An improvement in the state of flora at a level exceeding 40% was observed in the western part of field no. 1, while in the northern part of field no. 2 and in the western part of field no. 4 - at a level exceeding 20%. The maximum decrease of vegetation condition was noted in the field no. 1 (over 40%), which is a worth emphasizing fact, because no water reservoirs is located in this area. In turn, the years 2016-2018 are characterized by the deterioration of the plant cover state in the analysed post-mining area. However, terrain along the shorelines of anthropogenic lakes, the northern part of field no. 2, as well as areas where adverse flora changes were observed in the previous period, have considerable improved. In this interval, places of improvement in the vegetation condition at a level exceeding 20% were not identified.

In the last time interval, the flowering of vegetation and the improvement of its health was observed in fields no. 1 and 2 (below 20%), as well as locally in field no. 4 (mainly around water bodies). On the other hand, in the test field no. 3, the flora condition has decreased, except the neighbourhood of an anthropogenic lake.

The described changes in vegetation condition have been shown graphically in Figure 3.

The obtained values of EVI and GNDVI indices showed a strong, positive correlation with NDVI. The Pearson correlation coefficient was 0.89 for GNDVI, for EVI - 0.13. Therefore, it may be concluded that in the analysed study period the values of the indices changed in an analogous way. The correlation matrix between the determined indices is shown in Figure 4. On the other hand, Figure 5. shows the annual average values of the variables in the period of 1989-2019, which indicate years of significant divergences between the EVI and GNDVI indices and NDVI. For GNDVI, that example of period is 2018-2019, during which the NDVI increased by 0.4, while the GNDVI remained unchanged. The obtained values of EVI are characterized by a greater discrepancy in relation to NDVI. The substantial differences were observed in the periods: 1989-1990, 1993-1994 and 2018-2019.
Figure 3. Changes in the vegetation condition of the Pustków mining field between 1989-2019 based on the analysis of NDVI time series.
The last issue worth of an attention is the distribution of indices values among the image pixels. The analysis of the two most strongly correlated indices, GNDVI and NDVI, indicates that for both of these variables, majority of pixels were assigned value in the range of 0.6-0.7. The distributions of the obtained NDVI and GNDVI values, presented in the form of histograms, are also significantly similar. The Figure 6. presents histograms describing the distribution of mentioned indices values among image's pixels for two selected representative years of the analysed period (years 1998 and 2018).

![Figure 6. Distribution of NDVI and GNDVI values among pixels of the image: A) year 1998, B) year 2018.](image)
5. Identification of areas with significant changes in the condition of the plant cover
Areas of significant changes in the vegetation condition have been identified by integration of the obtained NDVI, EVI and GNDVI values. Thus, in the area of the former Pustków mining field the following changes have been observed:

- local decrease in the plant cover condition in the northern part of test field no. 1, which appeared in 2016,
- the systematic flora expansion in the western and central parts of field no. 4 and in the northern part of field no. 2,
- area decrease of the reservoir in the north-eastern part of field no. 1 as a result of the vegetation succession and shoreline overgrowing of other lakes located within this polygon,
- progressive vegetation coverage of the northern part of the reservoir shoreline in field no. 2.

Distribution of NDVI values in 1989, 1999, 2009 and 2019 within the former Pustków mining field shown on Figure 7. confirms the above-mentioned observations. In order to highlight the fact of the decreasing area of water reservoir situated in the north-eastern part of field no 4., the location of lake on the last graphic is shown in the form of shoreline contours. In this place two issues also need to be explained. An area of lower NDVI values located in the northern part of field no. 3 is the result of built-up areas of Nowe Czaple, while the central part of field no. 1 are agricultural lands.

The results obtained on the basis of spectral vegetation indices analysis, developed using satellite multispectral images, were verified during field reconnaissance. A detailed observation conducted in areas, where significant changes in the plant cover condition had been identified, confirms the results obtained from the processing of remote sensing data. The Figure 8. presents photos which show vegetation changes in the test sites, described in the first paragraph of this section.

6. Discussion
The results of this research indicate a systematic growth of vegetation in the area of the former Pustków mining field, at the same time providing information about its local degradation (it should be mentioned that research presented in this paper does not include the period between the mine closure and 1989, thus 16 years in total). Therefore, continuous monitoring of the plant cover condition in this region seems necessary. It should be emphasized that indices presented in the paper only assess the general health of the flora. According to the authors, more detailed analyses of the vegetation condition, concerning chlorophyll content in leaves, leaf surface and its compactness in tree canopies, amount of the radiation for photosynthesis process or water content, should be conducted in the future. The data obtained in mentioned analyses enable the determination of factors which have a significant influence on the development of the vegetation condition in the Pustków mining field, and thus may allow to forecast its changes in the following years. Furthermore, it seems to be important to combine the information resulting from the processing of remote sensing data with geological-mining conditions (e.g. depth of seams, location of mining excavations, hydrogeological conditions, etc.) to determine whether and to what extent former mining activities have an impact on the plant cover.
Figure 7. Distribution of the NDVI values within the testing fields in 1989, 1999, 2009 and 2019.
Another issue that should be emphasized is a pixel size of the images used in this study. Landsat mission satellites register data with a spatial resolution of 30m, which proved to be insufficient value after field reconnaissance. The obtained results did not reflect local decreases in the vegetation condition resulting from smaller sinkholes. The Figure 9. is shown the plant cover degradation caused by the above mentioned process, which was observed in the test fields no. 1 and 4. These changes were not identified for any of the analysed spectral indices. Therefore, the authors suggest conducting measurements in a shorter time period using higher resolution images (e.g. Sentinel-2), which allow to the identification of sinkholes occurring in recent years or using sensors placed on board of Unmanned Aerial Vehicles (UAV). The aim of the Landsat images selection was analysis of vegetation changes in longer period of time, which is not possible with using higher resolution satellite systems that are in operation since recently.

Finally, it is worth to point out that this research comprised only one mining field of the former lignite mining area and does not present a complete view about the state of vegetation in the closed Babina mine. Thus, in order to describe all changes taking place in the analysed area, it seems necessary to carry out similar analyses in the other three fields.

The issues indicated above will be the subject of further research that the authors plan to conduct on the site of the former Babina mine.
7. Summary

The research, which was the subject of this paper, indicates that despite the reclamation process carried out in post-mining areas, adverse changes in plant cover may occur. The impact of former exploitation on components of the natural environment may be seen even many years after the cessation of mining works. However, periodic monitoring of these areas may allow to identify the sites where the degradation of vegetation occurs and thus contribute to the initiation of studies which will indicate the causative factor. As a consequence, it will be possible to eliminate the cause of the decreasing plant cover condition and to reduce its effects.

As the obtained results demonstrate, both the remote sensing data and developed on its basis spectral vegetation indices can be a proper tool for monitoring of post-mining areas. These simple combinations of spectral bands allow to detect changes in the vegetation condition in large regions. In the case of the Pustków mining field, the spectral indices enabled to identify the local decrease in the plant cover state and to monitor its succession in majority part of the analysed area in 1989-2019 period. After 40 years from cessation of mining work the vegetation condition in former Babina mine improved significantly and covered majority of the terrain. Moreover, growth of flora is a reason of decreasing area of water reservoir in north-eastern part of field no. 1 and shoreline overgrowing of other lakes located in this region. Despite the limitations of satellite imagery usage, such as cloud cover or spatial resolution, it seems to be an appropriate tool for this type of research, due to the cost-effectiveness, availability and short time of satellite revisits.

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