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REMOTE MONITORING OF ECOLOGICAL STATE OF DISTURBED LANDS IN THE AREA OF TROJANOVO OPEN PIT COAL MINE IN BULGARIA

Trojanovo Open Pit Mine, Bulgaria is a known coal producer being among the top largest open pit coal mines in Europe. Started its history in the early 1960s, the open pit coal mine is now the only Bulgarian open pit mine that meets its own needs for power-generating coal. For the whole period of operation of the mine, the area of disturbed lands has made 15 thousand hectares. Mining has inflicted a large-scale damage to the natural landscape. In this connection, it has become of the theoretical and practical concern to carry out long-term monitoring of the disturbed land reclamation in the area of the open pit mine.

In recent years, the issues of the mining ecology become in spotlight for researchers on every continent. At the same time, as the review of the scientific literature shows, the open pit mining ecology issues have never been studied using resources of the remote sensing of different duration.

The article presents the results of the analysis of the disturbed land reclamation dynamics in the area of Trojanovo open pit mine using the freely accessible information resources of the remote sensing of the Earth.

Key words: *open pit coal mine, mining ecology, disturbed land reclamation, overburden dumps, recovered ecosystems*
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Introduction

Currently open pit coal mining has reached high levels in the Central and Eastern European countries. In Germany, Poland, Greece, Czech Republic, Serbia, Bulgaria, Romania, Bosnia and Herzegovina, there are 53 operating open pit coal mines. Among the ten largest coal companies in Europe, Trojanovo open pit coal mine has been producing coal since the 1960s in Bulgaria. Mining activities have brought an immense damage to natural landscape: total area of disturbed lands makes 15 thousand hectares. In this connection, it is of the theoretical and practical interest to arrange long-term monitoring and evaluation of efficiency of ecological equilibrium recovery in the area of the industrial infrastructure of the open pit mine.

The ecological issues of mining are recently of the intent concern, especially in terms of rehabilitation and reclamation of disturbed lands [1–12, 16–18]. On the other hand, the review of the scientific literature shows the lack of remote monitoring in the environmental research of open pit mines. In the meanwhile, remote monitoring is, in the point of fact, a framework for revealing long-term trends in generation and development of ecosystems in any area, including regions where hard mineral mining is carried out using the open-pit method. This gap in the knowledge is bridged by the joint school (Reshetnev Siberian State Aerospace University and Nauka Special Design and Technology Bureau at the Institute of Computational Technologies of the Siberian Branch, Russian Academy of Sciences) on open pit mining-disturbed land ecology research using remote sensing (RS).

Trojanovo Open Pit Mine: general information

The geological structure of Trojanovo lignite deposit with an area of 240 km2 developed using the open pit method is described below. Horizontal coal beds to 40 m thick with dirt beds are overlaid by sedimentary formation with the thickness from 50 to 80 m. The access to lignite is obtained via permanent trenches in the center and on the flanks of the deposit. Mining front is advanced in the meridional direction (**Fig. 1**).

The production bed is conventionally divided into two process blocks: Trojanovo-North and Trojanovo-South with the production benches 4.6 and 7.8 km long, respectively. The mining front advance is marked by the arrows in Fig. 1.

The current state of Trojanovo open pit mining is analyzed using free-accessible RS data [13].

Stripping is carried out with 19 bucket-wheel excavators (Russian analog ERP-2500). Overburden is conveyed to the internal and external dumps. Dumping is implemented by 13 stackers of the type of OShR-5000/100. The total length of the movable and stationary conveyor lines within Trojanovo-North and Trojanovo-South mines towards the dumps is 47.2 and 72.0 km, respectively. The number of stripping benches, 3–5, is conditioned by the ground surface relief.

Actual coal extraction employs 7 bucket-wheel excavators and 6 chain excavators. Bucket-wheel excavators operate mostly on benches, and downward digging chain excavators are utilized on the sites of depression of the bed.

The overall length of coal conveying lines within the mentioned production blocks is 19.1 and 18.3 km, respectively. A portion of coal is transported through the southern flank of Trojanovo-South mine to an on-site storage of thermal station no. 2 arranged on the pit wall. The rest of produced coal is conveyed to two handling points where coal is loaded to railway cars. The cars bring coal to thermal stations nos. 1 and 3 situated 10.2 km westwards and 10 km northeastwards the open pit mine, respectively.

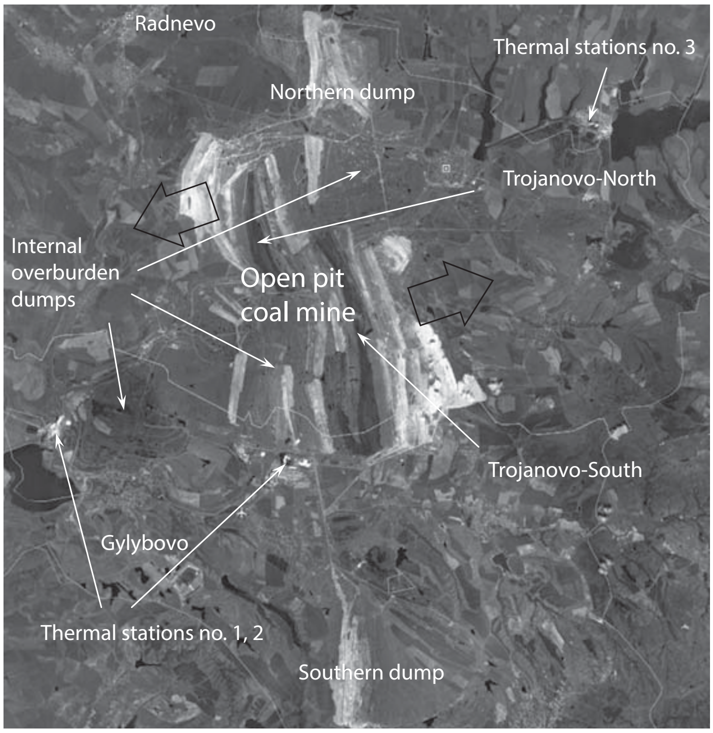

Fig. 1. Satellite sub-image showing location of industrial infrastructure objects: Trojanovo open pit coal mine, overburden dumps, thermal stations

Given the current flow chart of getting access to lignite and actual coal extraction expansion, in retrospect, the available shovels and stackers ensure annual coal production output at a level of 28–32 Mt. The annual volume of overburden and dirt removal is evaluated as 60–65 Mm^3 [14].

The mining area has a few climatic features. Annual precipitation makes 800 mm, and air temperature changes between −2 °C in winter and +30 °C in summer [15]. The ground surface relief above the coal deposit is a basin circled by small bold mountains to 500 m high on the south, west

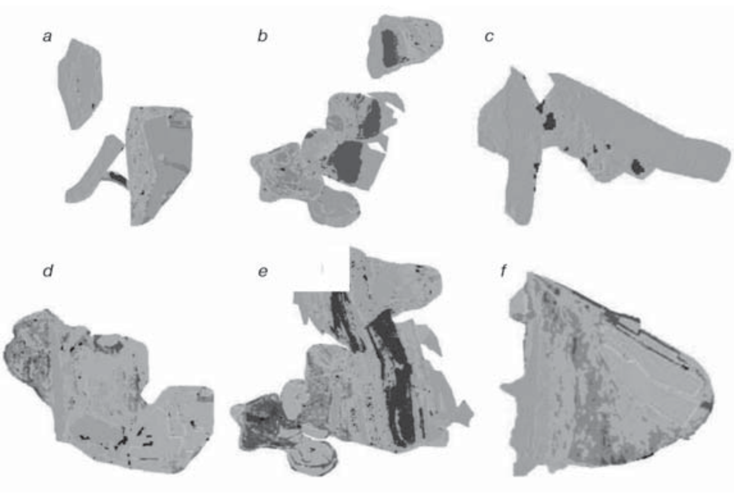

Fig. 2. Sub-images and decoding results:
***a*, *d*—Northern dump; *b*, *e*—Trojanovo open pit coal mine; *c*, *f*—Southern dump; *a*–*c*—1984; *d*–*f*—2016**

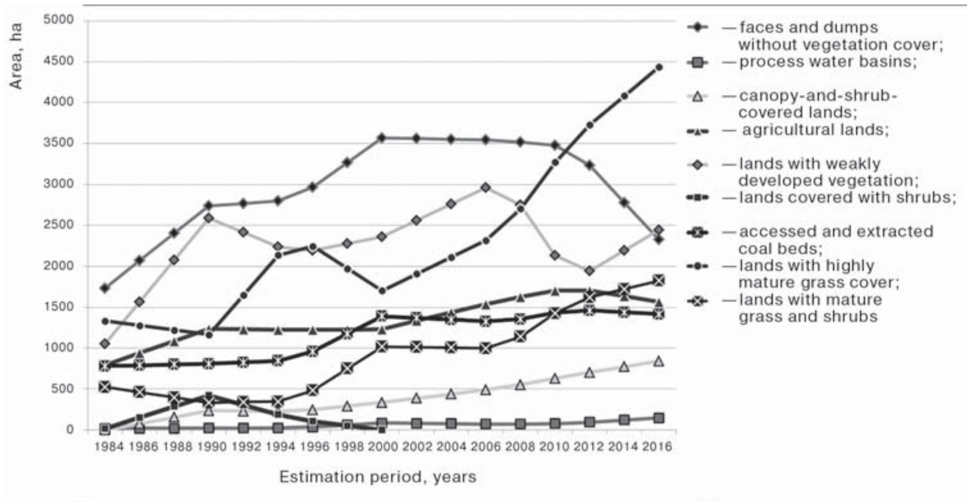

Fig. 3. Transformation of disturbed lands under mining and new ecosystems in the area of Trojanovo open pit mine by remote sensing data

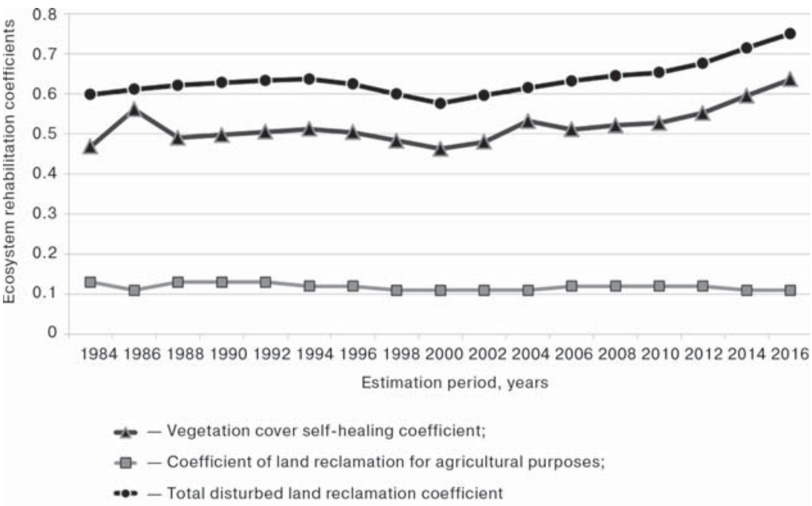

Fig. 4. Variation in the ecological recovery coefficients in the mining landscape in the area of Trajanovo open pit lignite mine

and north. The mountain shoulders are densely covered with trees and shrubs. Thanks to wind, winged seeds of aboriginal plant species efficiently settle on the adjacent areas.

Research findings

Hard mineral mining with the open-pit method always transforms natural ecosystems and the mining-adjacent landscape and results in the total absence of vegetation cover and the cardinally unnatural environment. A broad picture of the condition and trends in the plant ecosystems in such landscapes can be obtained from the studies of the local nature and climate together with the long-term remote sensing and the obtained data processing toward an objective result.

Based on the studies, the mining-affected landscape of Trojanovo open pit is divided into two categories: the open pit mine with the internal dumps and the Northern and Southern external dumps (Fig. 1). The data processing used 17 satellite images to reveal long-term trend in recovery of ecosystems on the mining landscape. **Fig. 2** shows the initial (1984) and final (2016) images with the decoding results. The images depict the boundaries of the analyzed areas; the mining-disturbed lands, plant ecosystems and water ecosystems are marked by different colors.

Inside the perimeter of the open pit mine, the dark color shows the accessed or extracted coal beds. The adjoined areas are the working sites of stripping benches or dumps. According to RS data over the period from 1984 to 2016, the lands under actual mining and external dumping have expanded from 6249 to 15001 ha. All in all 9 categories of disturbed and reclaimed lands are identified within this area: faces and dumps without the vegetation cover and coal beds; process water bodies and sites covered with vegetation without any dominating botanical level. In addition, disturbed lands after reclamation for the agricultural use were examined.

The revealed trends in transformation of disturbed lands under mining operations and under all ecosystems (water, plants) in the area of Trojanovo landscape are depicted in **Fig. 3**.

By the authors' estimation, in 32 years, the average annual rate of land withdrawal for mining and dumping totals 273.5 ha. In the mentioned time period, the area of accessed and extracted coal beds has nearly doubled: from 780 to 1416 ha due to the increased coal production capacity at the open pit mine from 15–16 to 28–30 Mt. This process was contributed to by the large-scale reconstruction of the mine transportation system taking 6 years from 1994 to 2000.

At the same time, the area without the vegetation cover only grew by 34 % (from 1733 to 2327 ha). A positive from the viewpoint of the ecological equilibrium recovery is a sharp enlargement in the area with the highly mature grass cover. The average annual rate of growth of this category area is 212.2 ha in the last 10 years. Total elimination of sites with the shrub cover between 1984 and 2000 is explained by the arrangement of new levels height-wise the dumps.

The area of process water basins changed by 8.1 times (from 18 to 146 ha). It is notable that the open pit mine rehabilitates disturbed lands based on primary and finishing layouts of dumps with a view to making the land suitable for agriculture. The area of such lands increased from 793 to 1565 ha in the specified period of time.

Forest recultivation was never undertaken at the open pit mine. The vegetation on the dumps, namely, the canopy and shrub cover—is a result of natural settling of aboriginal species of vegetable life under the influence of natural factors. The sustained upward trend is observed in the area of canopy-and-shrub-covered land from zero to 841 ha. Such situation becomes possible as the crown density is observed when trees are 18–20 years old, which implies that overburden is not placed in some areas of the dumps since the 1960s–70s.

It is a common practice in open pit mining to evaluate the rehabilitation efficiency using the disturbed land reclamation coefficient. When no reclamation is performed, the pit walls and dumps undergo spontaneous self-healing. This process takes much time than man-made land reclamation with sowing of grass and planting of trees and shrubs.

The present article authors offer another coefficient to characterize the mentioned process from the ecological viewpoint—vegetation ecosystem self-healing coefficient. Self-healing of the vegetation ecosystem in a mining landscape means the process of settling of aboriginal species of grass, trees and shrubs under the influence of natural biological factors, in particular, transition of seeds with wings with the wind. The change in the discussed coefficients between 1984 and 2016 is illustrated in **Fig. 4**.

The coefficient of disturbed land reclamation for the agricultural purposes in the discussed period of time is 0.11–0.13.

At the same time, the self-healing coefficient changes differently per different periods: from 0.46 to 0.55 in 1984–1986, from 0.49 to 0.51 in 1988–1994, from 0.46 to 0.52 in 2000–2004 and from 0.51 to 0.62 in 2006–2016. In the other time periods, the coefficient somewhat lowers. The wave-like behavior of the self-healing coefficient is to a certain degree explained by the lag of the aboriginal vegetation settling behind the enlargement in the mining lease area and vice versa.

Conclusion

The information sources of the modern tools offered by the remote sensing of the Earth open new opportunities to investigate the ecology dynamics in the areas under impact of mining. In terms of Trojanovo open pit coal mine, the authors have demonstrated and quantitatively evaluated the process of disturbed land reclamation for more than 30 years long period of mining activities.

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