SILESIAN UNIVERSITY OF TECHNOLOGY PUBLISHING HOUSE

SCIENTIFIC PAPERS OF SILESIAN UNIVERSITY OF TECHNOLOGY 2025
ORGANIZATION AND MANAGEMENT SERIES NO. 232

# ASSESSMENT OF ECOSYSTEM SERVICE POTENTIAL IN POST-MINING AREAS FOR SUSTAINABLE MANAGEMENT

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**Purpose:** The purpose of this study is to develop and apply an integrated algorithm for evaluating the ecosystem service potential of post-mining land and identifying the demand for such services in adjacent areas. The research addresses the growing need for sustainable spatial management of degraded industrial areas and aims to support evidence-based decision-making in post-mining land redevelopment.
**Design/methodology/approach**: The assessment was conducted across four distinct post-mining sites, considering variables such as land cover composition, landscape heterogeneity, presence of hydrological features, and anthropogenic infrastructure. The proposed methodology facilitates the identification of optimal land-use strategies, supporting sustainable spatial planning and redevelopment of degraded post-industrial sites.
**Findings:** The results demonstrate that applying ecosystem service-based valorisation enhances decision-making processes and aligns land reclamation with broader socio-economic and environmental objectives. The results indicate that the applied algorithm makes it possible to identify effective development directions for a studied post-mining area as well as support the decision-making process in the spatial management of sites that have lost their economic functions.
**Practical implications:** The value of the work lies in offering a replicable tool for planners and decision-makers seeking to align land reclamation with ecological and societal benefits. It contributes to bridging the gap between environmental science and strategic land-use management.
**Originality/value:** This paper presents a novel, integrated method for assessing post-mining land in terms of its potential to provide ecosystem services—a perspective that remains underexplored in current literature.
**Keywords:** spatial planning, environmental valorisation, land attractiveness, land cover analysis.
**Category of the paper:** Research paper.

# 1. Introduction

## 1.1. The Impact of Environmental Degradation on Ecosystem Service Provision

Sustainable land management plays a pivotal role in optimizing the environment's potential to deliver essential goods and services to society (Elmqvist et al., 2015; Ramirez, 2019). The expansion of anthropogenically transformed landscapes alters both the quantity and type of ecosystem services provided and modifies societal demands on the environment. For instance, areas with high levels of surface sealing intensify the need for rainwater and snowmelt retention systems. Similarly, high population densities elevate the demand for accessible recreational green spaces. Integrating ecosystem service considerations into development strategies is vital to enhancing human well-being and supporting sustainable economic growth (Ahirwal, Pandey, 2021).

Extractive activity leads to negative and often irreversible damage to ecosystems, both during coal deposit exploration as well as after mining is concluded (Neves et al., 2016; Rusche, 2019). Sanchez et al. (2014) state that aspects related to environmental protection and a lasting positive legacy for society as regards mine closure should be factored in at every stage of a mine's life cycle. This can be made possible with the engagement of broad groups of stakeholders across a mine's entire life cycle and the constant assessment of the influence that the mining activity exerts on the environment and society.

Numerous reports can be found in literature as regards the negative impact of extractive activity on: aquatic and terrestrial ecosystems (Mercado-Garcia et al., 2018; Beck et al., 2020), woodland areas (Obeng et al., 2019; Sonter et al., 2017; Zipper et al., 2011), microbial ecosystems (Orcutt et al., 2020; Tost et al., 2020) and biodiversity (Prach, Tolvanen, 2016).

The progressing growth of the economy and population leads to an increase in the demand for ecosystem services and the need for the sustainable management of post-industrial and post-mining land to restore its functions related to ecosystem services (Rosa et al., 2019).

## 1.2. Restoration Approaches

Ahirwal et al. (2021) state that mining activity leads to ecosystem service depletion through deforestation, topsoil and overburden displacement and the removal of significant bulks of waste and earth. However, they indicate that the appropriate reclamation measures, particularly planting plants resistant to climate change and stress conditions that are also native species, may enable the restoration of the ecosystem condition to a degree where it would be capable of providing ecosystem services and meeting the goals of international policies such as the UN Sustainable Development Goals.

Post-mining land reclamation towards reforestation may improve the resistance to climate change and alleviate its impact at a regional scale, while reclamation towards arable land and pastures may have a positive influence on local food production and the use of bioenergy (Larondelle, Haase, 2012).

On the other hand, Gwenzi (2021) reports the necessity to develop new guidelines for post-mining land reclamation. Currently the sole determinant for assessing the potential for restoring post-mining land to a useful state are the results of soil quality testing (e.g., pH, organic carbon content in the soil) (Bandyopadhyay et al., 2020; Agus et al., 2016). Post-mining land restoration should be performed using the results of tests conducted by means of innovative testing tools such as drones, laser cameras, genomics, big data analytics (Gwenzi, 2021) or satellite image analyses (McKenna et al., 2020). Such innovative tools can help unravel the complex relationships between biotic and abiotic components as well as ecosystem functions and services, which are currently difficult to investigate by means of conventional techniques.

### 1.3. Ecosystem Service Valuation

However, there are few literature reports concerning the transformation of post-mining areas in a manner that would enable benefiting from the ecosystem services provided by them (Boldy et al., 2021). Similarly, Boldy et al. (2021) report a lack of methodological cohesion in assessments of the post-mining land potential for providing ecosystem services.

Addressing this gap, the present study introduces a comprehensive algorithm for assessing ecosystem service potential and evaluating demand in surrounding areas. This approach leverages cutting-edge analytical tools to inform strategic planning and support evidence-based spatial management of post-industrial land.

## 2. Materials and methods

### 2.1. Characteristics of the study areas

The studies were conducted for 4 post-mining areas differing in the type of land cover as well as the presence of utilities and buildings. All the analysed areas were located in the Silesian Voivodeship in Poland. This region of Poland exhibits an industrial character based on traditional branches of manufacturing. It is currently undergoing an industrial restructuring process involving the total or partial decommissioning of mines, obsolete steelworks and associated processing plants. The closure of these sites leads to the generation of post-industrial and post-mining areas that require reclamation. The sites are characterised below:

Site 1 – “Borowa 2” waste dump located in Ruda Śląska, Poland

The former waste dump of the Bielszowice mine. The area is covered with dense vegetation and is located in the vicinity of green areas – woodland and agricultural – in the Kłodnica river valley. The site is currently used for recreational purposes. It exhibits significant height differences. It is undeveloped and no buildings or waste can be found there. The site has access to a public road.

Site 2 – Site of the decommissioned Rozbark coal mine encompassing railway siding, Bytom, Poland

The site of the decommissioned Rozbark coal mine encompassing former railway siding, stockyards and primary plant infrastructure. The area is flat, developed and covered with vegetation. Historical structures (railway siding) can be found in a part of the site. There are no buildings or access to infrastructure in the remaining, greater part of the area. In its vicinity are industrial sites as well as residential and service infrastructure. It has access to a public road.

Site 3 – Reclaimed site of the Powstańców coal mine, Bytom, Poland

Flat area with a regular shape, undeveloped and covered with low-growing vegetation. It is located in the immediate vicinity of green woodland areas as well as industrial sites. From the north it borders a manufacturing plant, whereas its west and south borders are by the Segiet stream bed and the Szarlejka river bed. The site has access to a public road.

Site 4 – Waste dump and transport infrastructure of the Michał coal mine, Siemianowice Śląskie, Poland

Settling ponds partially filled with water can be found at the top of the waste dump. Dirt coverage, with dense uncontrolled vegetation in the southern part. Visible unpaved traffic routes. Service, residential and recreational infrastructure can be found in the vicinity of the site. It has access to a public road.

Figure 1 displays images taken with a drone to present the varied structure of the land cover.

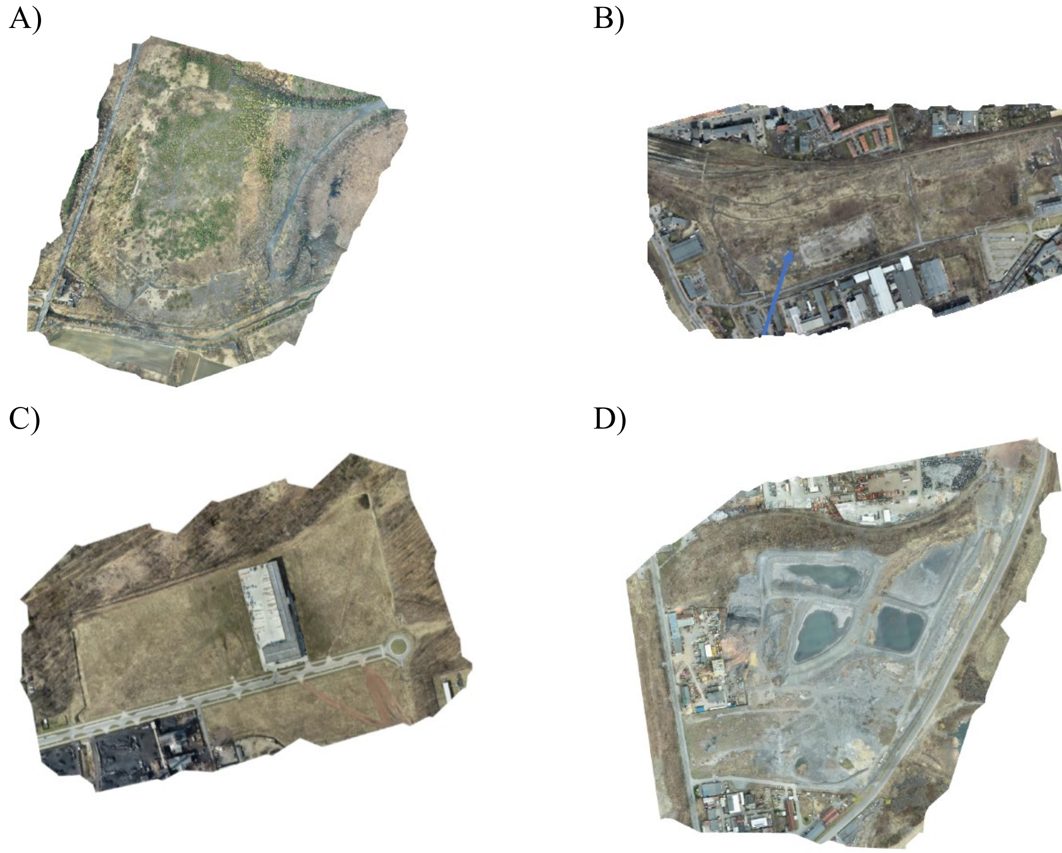


**Figure 1.** Analysed areas A) Site 1 – Borowa 2 waste dump in Ruda Śląska, Poland; B) Site 2 – Site of the decommissioned Rozbark coal mine encompassing railway siding, Bytom, Poland; C) Site 3 – Reclaimed site of the Powstańców coal mine, Bytom, Poland; D) Site 4 – Waste dump and transport infrastructure of the Michał coal mine, Siemianowice Śląskie, Poland.

Source: GIG-PIB.

The analyses were conducted for the 4 post-mining areas as well as for their vicinity within a radius of 1 km from the defined site borders and municipalities where the sites are located.

## 2.2. Assessment of the demand for areas with high recreational attractiveness at the municipality scale

In order to assess the demand for areas with high recreational attractiveness in a municipality that contains a post-mining area, the recreational attractiveness of the studied sites was analysed per the methodology proposed by Lupa (2016). This methodology was selected due to its proven effectiveness in evaluating recreational potential based on land cover, which directly influences the accessibility and perceived quality of natural areas.

The land cover type was defined based on the Corine Land Cover classification (Urban Atlas, 2018), which offers standardized, comparable, and spatially explicit data on land use across Europe.

The recreational attractiveness factor values ($WAR_{LULC}$) depending on the type of land cover are compiled in Table 1.

**Table 1.**
*$WAR_{LULC}$ values depending on the land cover type*

| Land type | Land description | Type per the Corine Land Cover classification | CLC type | $WAR_{LULC}$ |
|---|---|---|---|---|
| Developed and urbanized anthropogenic land | Continuous urban fabric | Continuous urban fabric | 111 | 37.12 |
| | Discontinuous urban fabric | Discontinuous urban fabric | 112 | 37.12 |
| | Industrial or commercial units | Industrial or commercial units | 121 | 37.12 |
| | Controlled vegetation | Green urban areas | 141 | 52.78 |
| | | Sport and leisure facilities | 142 | 53.78 |
| | Traffic infrastructure | Road and rail networks and associated land | 122 | 37.12 |
| | Mining grounds | Dump sites | 132 | 37.12 |
| | | Mineral extraction sites | 131 | 37.12 |
| | Other developed land | Construction sites, Port areas, Airports | 133, 123, 124 | 37.12 |
| | Urbanised undeveloped land[1] | Several types, mean value | | 51.64 |
| | Cemeteries | Green urban areas | 141 | 52.78 |
| Reclaimed land | Land transformed into woodland areas | Broad-leaved forest, Coniferous forest, Mixed forest | 311, 312, 313 | 76.26 |
| | Land transformed into agricultural areas | Non-irrigated arable land Permanently irrigated land | 211, 212 | 47.47 |
| | | Complex cultivation patterns | 242 | 48.65 |
| | | Land principally occupied by agriculture, with significant areas of natural vegetation | 243 | 56.48 |
| | | Agro-forestry areas | 244 | 47.47 |
| | | Pastures | 231 | 45.71 |
| | | Annual crops associated with permanent crops | 241 | 47.47 |
| Agricultural land | Arable land | Non-irrigated arable land | 211 | 47.47 |
| | | Permanently irrigated land | 212 | 47.47 |
| | Complex cultivation patterns[2] | Several types, mean value | 242 | 48.65 |
| | Land principally occupied by agriculture, with significant areas of natural vegetation[3] | Several types, mean value | 243 | 56.48 |
| | Orchards[4] | Several types, mean value | | 56.48 |
| | Permanent meadows | Pastures | 231 | 45.71 |
| | Permanent pastures | Pastures | 231 | 45.71 |
| | Developed agricultural land | Discontinuous urban fabric | 112 | 47.47 |
| | Ground under orchards | Water bodies | 512 | 73.23 |
| | Ground under ditches | Water bodies | 512 | 73.23 |

[1] Arithmetic mean for factors for arable land, pastures, moors and heathland, and built-up areas.
[2] Arithmetic mean for factors for arable land, pastures and controlled vegetation.
[3] Arithmetic mean for factors for arable land, pastures, forests, moors and heathland.
[4] Arithmetic mean for factors for arable land, pastures, forests, moors and heathland.

Cont. table 1.

| | | | | |
|---|---|---|---|---|
| Woodlands | Forests | Broad-leaved forest | 311 | 76.26 |
| | | Coniferous forest | 312 | 76.26 |
| | | Mixed forest | 313 | 76.26 |
| | Forests and shrubbery in transition[5] | Several types, mean value | 324 | 60.99 |
| | Moors and heathland | Moors and heathland | 322 | 76.26 |
| Tree-and shrub-covered land | Natural swards and pastures | Natural grassland | 321 | 45.71 |
| | Sclerophyllous vegetation | Sclerophyllous vegetation | 323 | 45.71 |
| | Dispersed vegetation | Sparsely vegetated areas Sparsely vegetated areas | 333 | 45.71 |
| Marshes | Inland marshes | Inland marshes | 411 | 45.71 |
| Water courses | | Water courses | 511 | 73.23 |
| Water reservoirs | | Water bodies | 512 | 73.23 |
| Ecological sites | | Several types, mean value | | 65.07 |
| Barren land | Naturogenic | Several types, mean value | | 65.07 |
| | Anthropogenic | Construction sites | 133 | 37.12 |

Source: Urban Atlas (2018).

These values reflect the assumed capacity of each land cover type to deliver recreational ecosystem services, based on empirical observations and prior valuation studies. For instance, forests and green urban areas are associated with higher attractiveness values due to their accessibility, biodiversity, and cooling effects in urban environments.

The weighted mean recreational attractiveness factor for the municipality was calculated using the following formula (1):

$$WAR_g = \frac{\sum_{i=1}^{n} S_i \cdot WAR_{LULC}}{\sum_{i=1}^{n} S_i} \quad (1)$$

where:

$WAR_g$ – weighted mean recreational attractiveness factor for given land unit cover,

Si – surface area of an i-th site,

$WAR_{LULC}$ – recreational attractiveness factor for an i-th site's land cover.

The classification of recreational attractiveness for each municipality was adopted as follows:

- A – High (61-80 pts).
- B – Medium (40-60 pts)
- C – Low (<39 pts)

The thresholds for classification were determined based on the natural distribution of WARg values obtained across multiple municipalities and on expert-based interpretation, ensuring consistency with previous studies (Lupa, 2016).

[5] Arithmetic mean for factors for pastures, forests, moors and heathland.

To assess demand, the inverse of the weighted mean recreational attractiveness factor was used, assuming that lower local attractiveness increases the demand for additional recreational spaces. The demand level was categorized as shown in Table 2, with threshold ranges derived from quartile-based distribution and sensitivity analysis conducted on a test sample of municipalities.

**Table 2.**
*Classification of the demand for areas with high recreational attractiveness*

| Score | Demand class |
|---|---|
| 1.2-1.4 | Very high (1) |
| 1.5-1.8 | High (2) |
| 1.9-2.2 | Medium (3) |
| 2.3-2.6 | Low (4) |

Source: GIG-PIB.

These classification thresholds were established to reflect meaningful differences in recreational demand levels across municipalities.

### 2.3. Assessment of the natural attractiveness of post-mining land

The natural attractiveness of post-mining land was assessed based on a modified version of the scoring method proposed by Jakiel (2015), which was adapted to the specifics of post-industrial terrains. The selected variables reflect key landscape features that influence the potential for recreational use and visual appeal, thus supporting the delivery of cultural ecosystem services.

Each component was selected based on its relevance to recreational and ecological potential:

- s1 – Lay of the land: Topographic variation enhances landscape diversity and is attractive for recreational use such as hiking.
- s2 – Presence of rock formations: Rocks provide aesthetic and geological interest.
- s3 – Type of land cover: Influences shade, biodiversity, and microclimate.
- s4 – Presence of water bodies: Water features are consistently valued in recreational landscapes.
- s5 – Landscape diversification: Heterogeneous landscapes are more attractive for users and better support biodiversity.
- s6 – Other anthropogenic objects: Certain features may either detract from (e.g., illegal dumping) or enhance (e.g., cultural heritage sites) recreational value.

Scoring for each criterion ranged from 0-3 points, calibrated based on expert knowledge, landscape guidelines, and previous empirical applications of the method. The criteria are presented in Table 3.

**Table 3.**
*Scoring criteria depending on the analysed terrain attractiveness factor*

| Component | Group of criteria | Detailed criteria | Landscape evaluation criterion with assigned number of scoring points | | | | |
|---|---|---|---|---|---|---|---|
| s1 | Vertical variation and lay of the land | Average sloping | 19-45° | 9-18° | 5-8° | <5° | |
| | Number of points | | 3 pts | 2 pts | 1 pt | 0 pts | |
| s2 | Visible rock formations | yes | 3 pts | | | | |
| s3 | Types of land cover | cover % | 1-25% | 26-50% | 51-75% | 76-100% | |
| | | Forests | 1 pt | 2 pts | 3 pts | 4 pts | |
| | | Meadows | 1 pt | 2 pts | 2 pts | 1 pt | |
| | | Arable land and orchards | 1 pt | 1 pt | 0 pts | 0 pts | |
| | | Developed land | -1 pt | -2 pts | -3 pts | -4 pts | |
| s4 | Presence of water bodies | Watercourse length | 50-250 m | | | <300 m | |
| | | | 1 pt | | | 2 pts | |
| | | Water reservoirs, rapids, waterfalls and karst springs (for their presence) | Per each water body | | | | |
| | | | 1 pt | | | | |
| s5 | Landscape diversification | Number of land cover types | 1 | 2 | 3 | 4 | |
| | | | 0 pts | 1 pt | 2 pts | 3 pts | |
| s6 | Other anthropogenic objects (undeveloped) | Anthropogenic objects | Power lines | Asphalt roads | Antennas and other objects | Illegal rubbish dumps | Historical and cultural sites |
| | | | -1 pt | -1 pt | -2 pts | -2 pts | 2 pts |

Source: Jakiel, 2015.

The total score for each post-mining site determined its attractiveness class, according to the scale in Table 4. The threshold values (0-4, 5-9, 10-14, 15-18 points) reflect natural breaks in scoring and ensure differentiation between sites of varying recreational quality.

Table 4 presents the method of classifying land attractiveness depending on the number of obtained points.

**Table 4.**
*Attractiveness classification for post-mining land and adjacent areas*

| Total number of points | Score | Attractiveness class |
|---|---|---|
| 15-18 | 3 | Very attractive |
| 10-14 | 2 | Attractive |
| 5-9 | 1 | Poorly attractive |
| 0-4 | 0 | Unattractive |

Source: GIG-PIB.

The final post-mining land attractiveness assessment ranges within 0-3 pts. The higher the score, the more recreationally attractive the analysed post-mining area.

### 2.4. Assessment of the natural attractiveness of adjacent areas within a 1 km radius of the post-mining land

The natural attractiveness of areas adjacent to post-mining land was evaluated using a simplified approach based on two key components:

- Type of land cover (s3): Reflects general recreational and ecological value.
- Landscape diversification (s5): Indicates the variety of land uses, linked to environmental heterogeneity and user experience.

These variables were selected for their ability to provide a rapid assessment while maintaining consistency with the criteria used in the assessment of the post-mining land itself. The scoring and classification followed the same principles as described above, ensuring methodological coherence across spatial zones.

## 3. Results and discussion

### 3.1. Assessment of the demand for areas with high recreational attractiveness at the municipality scale

CLC 112 (discontinuous urban fabric) is the dominant type of land cover in all the analysed municipalities. In Siemianowice Śląskie, the other dominant types of land cover are arable and agricultural land (CLC 211) and industrial sites (CLC 121), which constitute 24% and 22% respectively of the municipality's surface area. Green urban areas (CLC 141 and CLC 142) constitute 7% and 11% respectively of the Siemianowice Śląskie surface area, whereas forests (CLC 311) amount only to 1%. The significant industrial and minor forest coverage distinguishes this municipality from the other analysed locations. Forests constitute 16% of the land cover in the Bytom municipality, and 12% in Ruda Śląska. Meanwhile industrial land in these municipalities constitutes 7% and 9% of the land cover for Ruda Śląska and Bytom respectively (Figure 2).

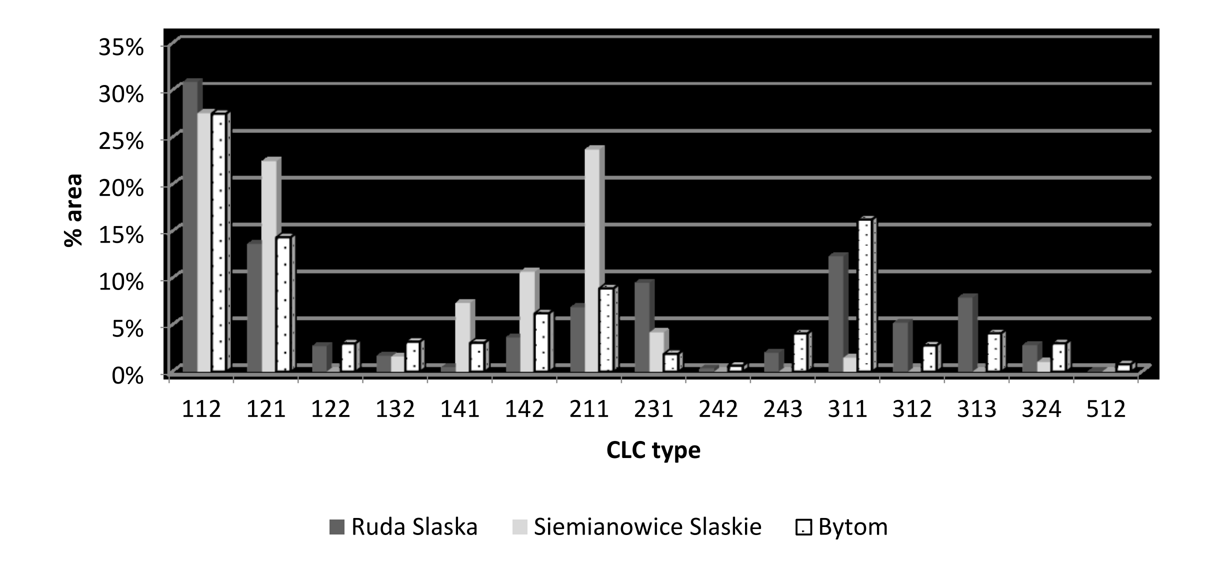


**Figure 2.** Land coverage for the municipalities of Ruda Śląska, Siemianowice Śląskie and Bytom with individual types of land cover per the Corine Land Cover (CLC) classification.

Source: GIG-PIB.

Further analysis demonstrated that the Siemianowice Śląskie municipality is characterised by the greatest demand for recreational areas among all the analysed locations (Table 5).

**Table 5.**
*Analysis of the demand for recreational areas*

| Municipality | Surface area (ha) | WARg | 1/WARg |
|---|---|---|---|
| Ruda Śląska | 6947 | 50.60 | 2.0 |
| Siemianowice Śląskie | 7764 | 50.38 | 2.0 |
| Bytom | 2551 | 43.68 | 2.3 |

Source: GIG-PIB.

The coefficient of recreational area demand in Siemianowice Śląskie was 2.3, whereas in the remaining municipalities it was 2.0 (Table 5).

### 3.2. Natural attractiveness assessment

Table 6 presents the ecosystem service demand assessment analysis results and the potential for providing ecosystem services within a 1 km radius of the analysed municipalities.

The greatest recreational attractiveness factor of 2.7 was obtained for the vicinity of the post-mining site in Ruda Śląska, which results from the local presence of green areas, significant terrain mosaicity and the presence of a watercourse. Furthermore, Site 1 itself (Borowa II waste dump) is characterised by very high recreational attractiveness, and its attractiveness factor is 2.5.

The vicinity of Site 2 (Rozbark coal mine) is characterised by medium recreational attractiveness (attractiveness factor of 1.7), while the site itself exhibits high attractiveness (attractiveness factor of 1.5), which results primarily from the local presence of historical sites.

Site 3 (Powstańców coal mine) and Site 4 (Michał coal mine) are located in an area characterised by low recreational attractiveness (attractiveness factor of 0.3). Given its flatness, only partial coverage with low-growing vegetation, very low terrain mosaicity and lack of historical sites, Site 3 is characterised by the lowest attractiveness factor among all the analysed areas, amounting to 1.0. On the other hand, Site 4 exhibits high recreational attractiveness (1.5) due to the presence of settling ponds. The study results are presented in Table 6.

**Table 6.**
*Recreational attractiveness assessment for post-mining land and its vicinity within a 1 km radius*

| Site | Site name | Municipality | Vicinity (r = 1km) | Site |
|---|---|---|---|---|
| 1 | Borowa II waste dump | Ruda Śląska | 2.7 | 2.5 |
| 2 | Site of the decommissioned Rozbark coal mine encompassing railway siding | Bytom | 1.7 | 1.5 |
| 3 | Reclaimed site of the Powstańców coal mine | Bytom | 0.3 | 1.0 |
| 4 | Waste dump and transport infrastructure of the Michał coal mine | Siemianowice Śląskie | 0.3 | 1.5 |

Source: GIG-PIB.

The study results demonstrate that the applied algorithm for assessing the demand for recreational areas in municipalities as well as assessing the potential of post-mining land and its vicinity for providing ecosystem services constitutes an important tool for decision-making as regards determining the directions of transforming post-mining land into areas with useful properties.

## 4. Conclusions

This paper has introduced a comprehensive algorithm for assessing the ecosystem service potential of post-mining land and evaluating service demand in surrounding areas. The findings highlight that key determinants of service provision capacity include land cover type, landscape heterogeneity, proximity to water features, and the presence of cultural or historical landmarks. Importantly, The study revealed that the potential of post-mining land for providing ecosystem services does not always coincide with the recreational attractiveness of the adjacent areas, indicating the need for tailored, context-sensitive redevelopment strategies.

The study further demonstrates that municipalities differ significantly in their demand for the transformation of post-mining land transformation in a recreational direction, which should be taken into account in strategic planning. Access to green spaces and the continuity of green infrastructure emerged as crucial factors in guiding sustainable land-use decisions.

The results indicate that the applied algorithm can supports spatial management by enabling planners and decision-makers to identify optimal redevelopment paths for economically obsolete areas. It offers a practical, scalable framework for integrating ecosystem service considerations into post-industrial land reclamation, contributing to both environmental resilience and socio-economic revitalization.

The following policy instruments and incentives can be helpful in integrating ecosystem services into spatial planning.

Incorporation of ecosystem service assessments into local and regional planning regulations,

- Financial incentives such as grants, tax reductions, or subsidies for projects that enhance ecosystem services, particularly those promoting green infrastructure, habitat restoration, and recreational development on post-mining lands.
- Development of cross-sectoral stakeholder platforms to foster collaboration between mining companies, local authorities, environmental organizations, and communities, ensuring participatory and transparent decision-making processes.

Implementing targeted policy measures and incentives will enable the effective achievement of sustainable development goals and improve the quality of life for local communities.

## Acknowledgements

This work was supported by the Regional Program European Funds for Silesia 2021-2027 under Grant FESL.10.11-IZ.01-07DA/23

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