Call	RFCS-2022
Project number	101112657

REECOL Ecological rehabilitation and long term monitoring of post mining areas

Deliverable 3.1

Document on classification of ecosystem degradation including of degraded land maps

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Version | Date	VERSION 1 **|** 31.05.2024
Dissemination level	PU

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1. INTRODUCTION

The REECOL project is a significant initiative focused on enhancing environmental sustainability in coal regions undergoing transition. This collaborative effort includes eleven partners from five European countries, encompassing research institutions and key industry stakeholders such as coal mining companies. The core aim of the project is to significantly improve post-mining ecological rehabilitation methods. By integrating a comprehensive understanding of ecosystem degradation, intended future land uses, and the economic viability of various rehabilitation strategies, the project addresses the immediate and long-term needs of these regions.

Integral to the REECOL project are the activities centred on classifying ecosystem degradation and mapping degraded lands. These processes are essential for assessing the extent and nature of damage caused by mining activities and providing a baseline for recovery and rehabilitation efforts. Effective classification and mapping are critical as they enable the identification of specific ecological rehabilitation needs and the tailoring of approaches to address varied degrees of soil and ecosystem degradation. This not only aids in restoring ecological functionality but also supports the broader goal of sustainable land use post-mining.

One of the key outputs of the project is Deliverable 3.1, titled "Classification of ecosystem degradation and mapping of degraded land". This document focuses on the systematic classification of post-mining areas, taking into account the degree and nature of land degradation and evaluating soil characteristics such as fertility, texture, moisture levels, chemical contamination, and organic matter content. These soil conditions are crucial as they can significantly constrain revegetation efforts and plant survival. By linking degradation classes with physical, biological, and geochemical indicators, Deliverable 3.1 aims to establish a comprehensive framework for monitoring ecosystem rehabilitation. The insights gained will be instrumental in developing innovative, tailored solutions for land reclamation and ecosystem rehabilitation that meet the specific needs of coal regions in transition. This cohesive approach underscores the interconnected objectives of the REECOL project, fostering a sustainable future for areas impacted by coal mining.

2. THE IMPACT OF COAL MINING ON ECOSYSTEMS

Coal mining, a critical component of global energy supply chains, primarily employs two specialized methods based on the geology of the coal deposit: underground mining and open-pit mining. Underground mining, or deep mining, is implemented for accessing coal seams located deep beneath the Earth's surface, utilizing sophisticated techniques to create and maintain tunnels and shafts that ensure safe and efficient extraction. This method is particularly adapted to environments where surface mining is unfeasible due to the depth of the coal seam. Conversely, open-pit mining, also referred to as surface mining, is preferred for coal seams that lie close to the surface. This method involves the mechanized removal of vast quantities of overburden to expose the coal seam for extraction, utilizing advanced earth-moving equipment to manage the large-scale environmental alterations inherent to the process.

Coal mining, encompassing both underground and open-pit methods, significantly impacts the environment, though its effects can vary based on the technique used. While these mining practices are essential for energy production, they introduce a range of environmental challenges that need careful management. The principal environmental effects of coal mining can broadly be classified into two categories: environmental changes and landscape alterations (Fig. 1.).

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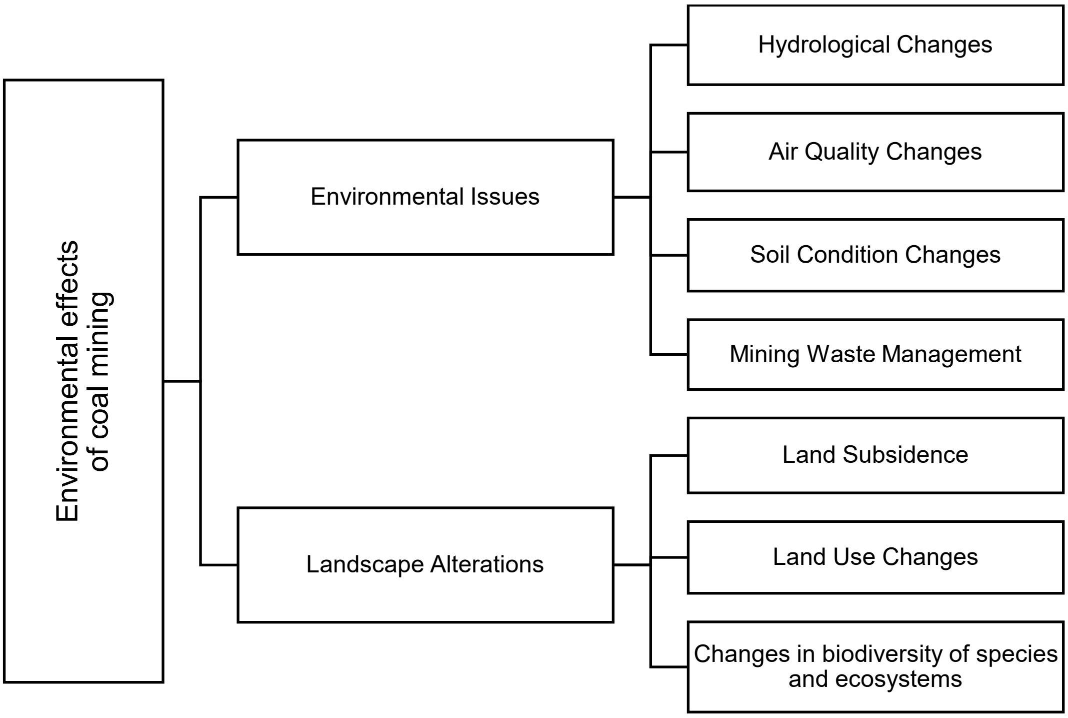

Fig. 1. Environmental effects of coal mining framework

Building on the previous discussion of environmental changes caused by both underground and open-pit mining methods, it becomes evident that the impact on ecosystems is profound and multifaceted. These mining techniques not only alter the landscape but also affect the underlying and surrounding ecological dynamics.

An **ecosystem** is understood as a community of living organisms interacting with their non-living environment, forming a complex network where each component is interdependent. This system involves a delicate balance of biological, chemical, and physical interactions that sustain life across various habitats. The stability and functionality of these ecosystems are crucial for maintaining biodiversity and ecological health, yet they are highly vulnerable to disruptions. Recognizing this vulnerability is essential when considering **ecosystem degradation**, a concept that is extensively discussed in the literature (Delgado, Marín, 2020). Although various definitions of ecosystem degradation exist, common denominators among them include the reduction in the ecosystem's ability to maintain its structure, function, and capacity to provide essential services. Degradation typically results from disturbances that compromise the natural processes and resilience of ecosystems, often leading to diminished biodiversity and altered ecosystem productivity.

Given this context, **ecosystem degradation in post-mining areas** can be broadly defined as the significant reduction in an ecosystem's ability to maintain its structural integrity, functional capacity, and ecological services, resulting from human activities. This degradation typically manifests through extensive alterations to landscapes, soil properties, water systems, and air quality. These changes include disruptions in soil structure, contamination of water bodies, air pollution, and landscape fragmentation, which collectively compromise the natural regenerative processes and biodiversity of the ecosystem.

However, for the purposes of the REECOL project and its objectives, subsequent sections of this document will primarily consider the soil and landscape aspects of ecosystems. These components have been identified as most critical for the ecological rehabilitation related to the reintroduction of vegetation in the studied areas. This focused approach allows for a more targeted analysis of degradation degree and the development of effective restoration strategies that are essential for restoring ecological functionality and promoting sustainable land use in post-mining landscapes.

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3. CRITERIA FOR ECOSYSTEM DEGRADATION – INDICATORS SELECTION

In the context of environmental restoration and sustainable management, accurately classifying ecosystem degradation is crucial. This chapter establishes the criteria for assessing degradation in post-mining areas, detailing the indicators used to measure the health of the ecosystem across various dimensions, including terrain, soil geochemistry, and geotechnics.

The classification system integrates diverse indicators that reflect both the physical and chemical properties of ecosystems. Each indicator is selected for its ability to provide specific insights into the degradation processes, facilitating a nuanced analysis that can guide remediation strategies effectively. By discussing how these indicators are measured and interpreted, the chapter aims to provide a robust framework for stakeholders to evaluate and address the impacts of mining.

To assist in the understanding and application of these indicators, Appendix I contains a comprehensive table summarizing all the indicators discussed in this chapter. This table serves as a quick reference to aid in the classification process. Further, Appendix II presents a table with example values for these indicators, providing practical examples that illustrate how different levels of degradation are defined based on empirical data.

The subsequent sections will explore each indicator in depth, clarifying their scientific basis and practical implications in the context of post-mining ecosystem recovery. This approach not only aids in the thorough understanding of current conditions but also in the planning and implementation of effective restoration practices.

3.1.LANDSCAPE INDICATORS

Mining, although constituting a huge industry, allowing the extraction of raw materials impossible in any other way, causes a number of negative effects with its activities. These include landscape changes, which in addition to visual values also strongly affect water management, or the degradation of habitats for living organisms. Within the framework of reclamation activities, these changes are leveled, although not always to an adequate degree. Thus, within the framework of this document, the following subsections will present indicators to assess the degree of degradation of rehabilitated areas, in the context of post-mining facilities.

3.1.1. Standard Deviation of Elevation (SDE)

The Local Standard Deviation of Elevation (SDE) is an important metric for evaluating the microrelief and topographic variability of a landscape, which is particularly valuable in assessing reclaimed post-mining areas. By measuring the variability in elevation within small, localized areas, SDE provides insights into the terrain's heterogeneity, which can significantly influence hydrological processes, soil stability, and vegetation patterns.

The concept of SDE revolves around analyzing the variation in elevation within a specific window or neighborhood around each pixel in a Digital Elevation Model (DEM). A DEM is a representation of the Earth's surface and is typically obtained through remote sensing technologies such as satellite imagery, aerial surveys, or LIDAR. The primary advantage of using a DEM is its ability to provide comprehensive and detailed elevation data across large areas, which is essential for thorough landscape analysis.

To compute the Local SDE, elevation data from the DEM is processed to calculate the standard deviation within a defined window around each pixel. This window size, often a few pixels across (e.g., 5x5 or 3x3), determines the scale of the local variability being measured. The standard deviation within this window reflects how much the elevation values vary from the mean elevation of the window. High standard deviation values indicate areas with significant elevation changes, such as steep slopes or rugged terrain, while low values suggest relatively flat and uniform areas.

The standard deviation (σ) is a measure of the amount of variation or dispersion in a set of values. In the context of elevation data within a defined window around each pixel in the DEM, the formula for standard deviation is:

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \mu)^2}$$

where:

σ – is the standard deviation.

N – is the number of valid (non-NaN) elevation values within the window.

x_i – are the individual elevation values within the window.

μ – is the mean (average) elevation value within the window

The Local SDE is particularly useful in post-mining landscapes where reclamation efforts aim to restore ecological balance and stability. Variability in microrelief can affect water drainage patterns, potentially leading to erosion or waterlogging if not properly managed. By identifying areas with high topographic variability, land managers can implement targeted interventions, such as erosion control measures, drainage systems, or specific planting strategies to stabilize the soil and promote vegetation growth. In addition to its role in hydrological and soil management, Local SDE is also crucial for understanding vegetation dynamics. Areas with diverse microrelief may support a variety of plant species, each adapted to different microhabitats created by the varying terrain. This diversity can enhance the ecological resilience of the reclaimed area, making it more robust against environmental stresses. Moreover, the Local SDE can be used to monitor changes over time, providing a means to evaluate the effectiveness of reclamation efforts. By comparing SDE values from different time periods, stakeholders can assess whether the terrain is stabilizing and becoming more uniform, or if further interventions are needed to address ongoing variability. The use of advanced remote sensing technologies, such as high-resolution satellite imagery and drone-based sensors, enables precise and consistent measurement of SDE across large and often inaccessible areas. This capability is vital for regular monitoring without disturbing the site, ensuring that accurate and up-to-date data is available for effective landscape management.

3.1.2. Topographic Wetness Index (TWI)

The Topographic Wetness Index (TWI) is an essential indicator used to assess the potential for water accumulation in a landscape, which is particularly relevant in post-mining rehabilitation projects. TWI is derived from Digital Elevation Model (DEM) data and helps to understand the spatial distribution of soil moisture, which directly influences vegetation growth, soil stability, and habitat conditions. To calculate TWI, elevation data for the area must first be obtained. A Digital Elevation Model (DEM) is preferable as it provides comprehensive coverage of the area, limited only by its resolution. DEMs can be acquired through satellite imagery, aerial surveys, or LIDAR technology.

Once the DEM data is available, the slope (β) of the terrain is calculated. The slope is the angle of the steepest descent at each point in the landscape. Mathematically, the slope in radians can be calculated using the gradient in the x and y directions:

$$\beta = arctan\left(\sqrt{\left(\frac{\partial Z}{\partial x}\right)^2 + \left(\frac{\partial Z}{\partial y}\right)^2}\right)$$

where $\frac{\partial Z}{\partial x}$ and $\frac{\partial Z}{\partial y}$ are the partial derivatives of the elevation Z in the x and y directions, respectively. Next, the Specific Catchment Area (SCA) represents the upslope area contributing flow to a given point, per unit contour length. It can be computed as:

$$SCA = \frac{A}{w}$$

where,

A – is the upslope contributing area, and

w – is the contour length, which is often approximated as the grid cell width in DEM data.

Finally, TWI is calculated using the formula:

$$TWI = \ln\left(\frac{SCA}{\tan\beta}\right)$$

TWI provides insights into soil moisture distribution, which is crucial for various environmental and land management applications, particularly in post-mining landscapes. Understanding the spatial distribution of potential water accumulation areas helps in designing effective drainage systems and preventing waterlogging, which can degrade soil quality and hinder vegetation growth. Areas with high TWI values are likely to have higher soil moisture content, which can support more robust vegetation growth. Conversely, areas with low TWI values may require additional interventions such as irrigation or soil amendments to promote vegetation establishment. TWI helps in identifying areas suitable for the restoration of wetlands and other moisture-dependent habitats. This information is vital for biodiversity conservation and enhancing ecosystem services in reclaimed mining areas.

By identifying areas prone to water accumulation, TWI aids in implementing erosion control measures such as planting vegetation or constructing barriers to stabilize soil and prevent erosion. Advanced remote sensing technologies, including high-resolution satellite imagery and drone-based sensors, enable precise and consistent measurement of TWI over large and inaccessible areas. This technology is crucial for regular monitoring of soil moisture conditions without disturbing the site, providing accurate data essential for long-term ecological management.

3.1.3. Normalized Vegetation Difference index (NDVI)

NDVI is an index that shows the condition of flora in the surveyed area. It is ratio of difference between red- and red-light reflectance and sum of infra-red and red light reflectance (formula below), which is due to the properties of chlorophyll contained in plants - vegetation absorbs more visible light (especially red due to chlorophyll) and reflects more near-infrared light (fig. 2). This spectral data are acquired using the appropriate research instruments, such as handheld spectrometer and spectral cameras on drones or satellites. The NDVI is normalized and expressed on a scale of -1 to 1, so it is easy to read and determine the degree of vegetation condition based on it. In general, this indicator - because the intensity of chlorophyll varies depending on the class of greenery, allows to distinguish between for example tree canopies NDVI > 0.4 and low vegetation 0.2 < NDVI < 0.4 (Rizvi et al., 2009).

$$NDVI = \frac{NIR - RED}{NIR + RED}$$

Using the NDVI indicator, knowing the area of the land under reclamation, it is possible to calculate its degree of vegetation cover, divided into vegetation classes.

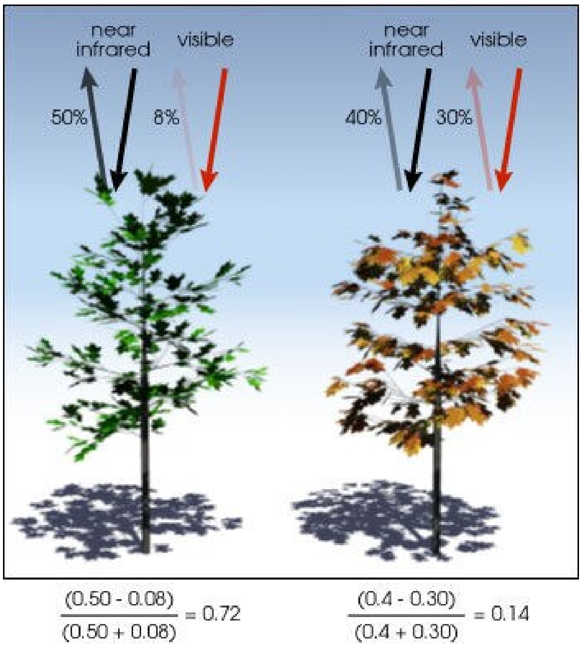

Fig. 2 Example of the working of the NDVI indicator on the example of plants with good condition and bad condition (Illustration by Simmon, 2014)

This indicator can help to quantify the extent of vegetation cover. This is crucial for ensuring that land reclamation projects are successful in terms of biomass accumulation and habitat restoration. One of the primary uses of %NDVI is in the longitudinal monitoring of vegetation recovery in reclaimed lands. By comparing %NDVI values over time, changes in vegetation density can be tracked, providing insights into the success of ecological restoration efforts and the need for further interventions. The %NDVI can also be applied to differentiate between types of vegetation, such as grasslands, shrubs, and forests, which may have distinct roles in an ecosystem and different requirements for conservation efforts. This differentiation helps in planning targeted actions for different vegetation zones, enhancing the ecological value and stability of the area. By providing a clear measure of vegetative cover, %NDVI assists in tailoring restoration practices to the specific needs of an area. For instance, areas with low %NDVI values may require more intensive restoration efforts such as planting, soil amendment, or protection from erosion.

The use of advanced remote sensing technologies, including high-resolution satellites and drone-based sensors, enables the precise measurement of NDVI across large and inaccessible areas. This technology is vital for regular monitoring without disturbing the site, providing consistent and accurate data essential for long-term ecological management. With the rise of big data analytics in environmental science, %NDVI data can be integrated with other ecological indicators in comprehensive models that predict the outcomes of various restoration strategies. These models can help in optimizing resource allocation and enhancing the ecological outcomes of reclamation projects. By integrating %NDVI into regular environmental monitoring and management practices, stakeholders can enhance the effectiveness of land reclamation and ensure the sustainability of ecosystems. This approach not only supports biodiversity but also promotes a healthier environment through the successful establishment of robust vegetative cover.

3.1.4. Normalized Difference Water Index (NDWI) and Modified Normalized Difference Water Index (MNDWI)

The Normalized Difference Water Index (NDWI) and the Modified Normalized Difference Water Index (MNDWI) are vital tools for detecting surface water in remote sensing applications. These indices prove particularly useful during the wet season, characterized by high rainfall and minimal green vegetation.

NDWI, as described in McFeeters (1996), utilizes the Near-Infrared (NIR) and Green bands of the electromagnetic spectrum. The formula for NDWI is:

$$NDWI = (GREEN\ -\ NIR)/(GREEN +\ NIR)$$

While NDWI effectively highlights water features, it can sometimes mistakenly identify built-up areas or dense vegetation as water due to its sensitivity to moisture in these elements.

To address this limitation, MNDWI (Xu, 2006) modifies the approach by replacing the NIR band with the Mid-Infrared (MIR) band. This adjustment enhances the distinction between water bodies and other surfaces such as built-up land, soil, and vegetation. The formula for MNDWI is:

$$MNDWI = (GREEN\ -\ MIR)/(GREEN +\ MIR)$$

MNDWI is particularly effective in enhancing the contrast between water bodies and the surrounding environment, making it a more reliable index for accurately identifying surface water. This attribute makes MNDWI invaluable for applications requiring precise water mapping, such as in urban and semi-urban areas where buildings and vegetation can obscure accurate water detection. Utilizing MNDWI allows for more precise assessments of water extent and distribution, crucial for effective water resource management and environmental planning.

NDWI (Normalized Difference Water Index) and MNDWI (Modified Normalized Difference Water Index) are primarily utilized in the monitoring of aquatic environments to track changes in water bodies. These indices are essential for real-time assessments of water extent in lakes, rivers, and wetlands, facilitating the detection of variations that may be due to environmental or anthropogenic factors. Beyond just monitoring, the analysis of historical NDWI and MNDWI data can provide insights into long-term trends and patterns of ecosystem degradation. For example, a consistent decrease in the indices over time could indicate a reduction in water body surface area, suggesting possible degradation processes such as sedimentation or pollution. By examining historical changes through these indices, researchers and conservationists can identify and quantify the impacts of human activities on aquatic ecosystems, thereby contributing to more informed and effective conservation and restoration efforts. This dual application of NDWI and MNDWI makes them invaluable tools in the comprehensive study and management of water-dependent ecosystems.

3.1.5. Angle of slope

The Angle of Slope as an indicator is crucial in assessing the potential environmental impacts of mining activities on ecosystems. The slope of a terrain affects water runoff, soil erosion, and the stability of the land, which in turn influence the habitat quality and biodiversity of the area. Mining operations often alter the natural landscape, increasing slope gradients, which can accelerate erosion processes, lead to loss of topsoil, and subsequently degrade the ecosystem.

Effective land management in post-mining landscapes must consider the slope of the terrain to mitigate environmental degradation and promote sustainable land use. By categorizing land based on its slope, restoration efforts can be more targeted and effective, promoting ecological stability and recovery. The classification system as suggested by the studies of Paulo (2008) and Chodak (2013) provides a structured approach to determine the suitability of land for various uses post-mining. Here's how the classification translates into practical guidelines for land use:

- **Slopes less than 5°** are generally flat enough to support most forms of agriculture, making them ideal for arable farming.
- **Slopes under 15°,** while too steep for traditional farming, can still support less intensive agricultural uses such as pastures for grazing.
- **Slopes under 35°** are typically suitable for forestry. Trees can help stabilize these slopes, although care must be taken in managing such areas to prevent erosion.
- **Slopes up to 60°** can still support forestry, but the risk of soil erosion increases significantly, requiring more careful management and possibly engineering interventions to stabilize the soil.
- **Slopes steeper than 60°** present severe challenges for any type of land use and require extensive reclamation efforts, such as slope stabilization and soil restoration, before they can be effectively utilized.

Furthermore, the slope stability assessment recognizes steep slopes as a prime indicator of erosion risk. High-slope areas, especially those altered by mining, are often identified as having a high degree of degradation. It is crucial to note that steeply sloping escarpments, particularly those facing south, can foster valuable dry grassland communities, which are beneficial for biodiversity.

For agricultural reclamation on post-mining spoil heaps, areas with moderate slopes—typically less than 4.0% and no more than 7.0%, depending on the subsoil structure—are preferred. Gentle slopes facilitate adequate water infiltration and drainage, reduce water stagnation, and prevent severe erosion, thereby mitigating drought effects.

By applying these slope-based classifications, mining companies and land reclamation professionals can strategically plan restoration activities that are aligned with the natural capacity of the landscape, thus enhancing the recovery of ecosystems disrupted by mining operations. This comprehensive approach ensures that the land's ecological stability and its potential for varied land uses are effectively maintained for future generations.

3.1.6. Area of thermal processes

Thermal processes in mining areas, especially in coal dumps, are a major concern due to their potential to cause spontaneous combustion. This phenomenon not only leads to the emission of hazardous gases like carbon monoxide and sulfur dioxide but also contributes to persistent fires that can degrade soil quality, pollute air and water resources, and destroy local ecosystems. The area of thermal processes typically refers to regions within and around mining dumps where heat is generated and retained, leading to higher temperatures than the surrounding environment.

The presence of endogenic fires or high thermal activities in mining waste areas can severely impact the ecological balance:

- **Soil Degradation:** Elevated temperatures can alter soil chemistry, reduce microbial activity, and degrade soil organic matter, leading to diminished fertility and increased erosion.

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- **Air Pollution:** Combustion processes release a variety of pollutants, including particulate matter and volatile organic compounds, which can affect air quality and pose health risks to nearby populations.
- **Water Contamination:** The leaching of pollutants from heated waste materials can contaminate groundwater and surface water, affecting water quality and aquatic life.
- **Vegetation Loss:** High temperatures and toxic emissions can inhibit plant growth and lead to the loss of vegetation cover, further exacerbating soil erosion and habitat loss.

Spontaneous heating and fire in coal mines represent a global issue that is of significant concern both to the industry and to researchers focusing on this problem. The majority of fires currently active in various coalfields are attributed primarily to the spontaneous combustion of coal. This phenomenon, known as "spontaneous heating" or "auto oxidation," occurs when coal interacts with oxygen in the air at ambient temperatures, releasing heat. If this heat is not adequately dissipated, it can accelerate the oxidation process, potentially leading to spontaneous fires (Singh, 2013).

The "Area of Thermal Processes" indicator is suitable in evaluating the thermal conditions of an area, particularly in mining environments where spontaneous combustion and thermal anomalies are prevalent. Land Surface Temperature (LST) plays a crucial role in this context as it directly impacts the heat exchange between the Earth's surface and the atmosphere. LST can be effectively measured using remote sensing data from satellites like Landsat 8, which offers the advantage of monitoring at global, regional, and urban scales, essential for studying thermal processes such as urban heat islands and mining-related thermal activities. Remote sensing technology provides a systematic approach to monitoring and detecting areas susceptible to thermal processes. Satellites equipped with thermal sensors, like the Thermal Infrared Sensor (TIRS) on Landsat 8, capture data that can be analyzed to identify heat anomalies associated with environmental hazards or industrial activities, such as mining. This data is processed using various algorithms to calculate the LST, providing a detailed thermal profile of the surface (Wang et al., 2019).

- **Data Collection:** Satellites continuously capture multispectral and thermal imagery, providing periodic data essential for monitoring changes over time.
- **Image Processing:** Algorithms such as the Mono-Window Algorithm (MWA), Split Window Algorithm (SWA), and Single-Channel Method are used to convert raw thermal infrared data into actionable temperature measurements.

While remote sensing is a powerful tool for monitoring large areas systematically, several limitations must be considered:

- **Time of Satellite Overpass**: The satellite's observation schedule around noon may not capture all thermal events, especially those that develop or change significantly at different times of the day.
- **Weather Dependency**: Accurate thermal data collection requires clear weather conditions; clouds can obscure the thermal signatures of the surface, reducing the reliability of the data.
- **Spatial Resolution**: The resolution of satellite images (10mx10m in the case of Landsat 8) might only identify broad and intense thermal phenomena, potentially missing smaller scale or less intense anomalies.

To overcome the limitations of satellite data and ensure comprehensive monitoring of thermal processes, direct field measurements are necessary:

- **Thermal Cameras:** Using thermal cameras on the ground or mounted on drones can provide high-resolution temperature data, crucial for detailed analysis and verification of satellite-derived observations.
- **Manual and Drone Surveys:** These methods allow for targeted investigation of specific areas of interest, especially in regions where satellite data suggests potential thermal activity.

3.1.7. Land Surface Albedo

Land Surface Albedo (LSA) is a critical biophysical parameter in ecological climatology that measures the proportion of sunlight reflected by the Earth's surface relative to the total sunlight it receives. This parameter is vital for understanding the Earth's climate system, as it influences the surface energy balance and, consequently, climate modeling at global, regional, and urban scales.

Albedo varies significantly across different surface types and conditions, which affects biophysical processes and ecological dynamics. For example, surfaces with low albedo absorb more solar energy, leading to higher temperatures, whereas surfaces with high albedo reflect more sunlight, contributing to cooler surface temperatures. This variation in surface temperature can affect local weather patterns, water cycles, and even global climate phenomena.

Human activities that alter the land surface, such as deforestation, urbanization, or agricultural practices, can change the albedo. These changes are crucial in the study of environmental degradation, such as desertification. Research indicates that surface characteristics like soil moisture and salt crusts significantly affect surface reflectance, and thus albedo. For instance, exposed soil surfaces typically have a higher albedo, serving as an indicator of desertification processes. This is because they reflect more sunlight compared to vegetated areas, which typically absorb more light and have a lower albedo (Liu et al., 2017).

In conclusion, land surface albedo not only serves as a fundamental parameter for climatic studies but also as a sensitive indicator of ecological changes induced by human impacts. Its ease of measurement from satellite data makes it an invaluable tool in environmental monitoring and management, helping researchers and policymakers understand and mitigate the effects of land degradation and climate change.

3.2. GEOCHEMICAL INDICATORS

Soil chemistry is fundamental to the success of reclamation efforts in post-mining areas, particularly when it comes to restoring vegetation. The presence of heavy metals and hydrocarbon compounds in soil can severely inhibit plant growth due to their toxicity. These contaminants may also become absorbed by plants grown for food, potentially harming human and animal health.

Beyond these contaminants, factors like salinity, acidity, organic carbon content, and microbial activity significantly influence soil recovery and vegetation success. Mining operations can increase soil salinity, which in turn causes osmotic stress in plants, reducing their ability to absorb water and nutrients (Zhao et al., 2020). Additionally, the exposure of sulfide minerals to air and water can generate sulfuric acid, leading to soil acidification (Kölbl et al., 2021). A lower pH can mobilize toxic metals and alter the availability of nutrients, further challenging plant growth (Bojórquez-Quintal et al., 2017).

Organic carbon is crucial for maintaining soil fertility and structure, affecting water retention and nutrient availability. Unfortunately, mining can deplete the soil of organic carbon by disrupting soil structure and reducing vegetative inputs. Moreover, the disturbance from mining activities often adversely affects soil microbial populations, which are vital for nutrient cycling, organic matter decomposition, and maintaining soil structure. Reduced microbial diversity and activity can severely degrade soil health, impacting its capacity to support plant life (Stefanowicz et al., 2012).

Geochemical indicators are also essential for determining the future use of these areas. Soil geochemical quality must be compatible with the intended uses. Metallic and organic contamination must not pose any health problems, especially if the soil is to be used by sensitive populations (children, pregnant women). In terms of landscape quality, organic matter and clays will ensure adequate fertilization. With a view to integrating these areas into a wider biodiversity management system, the quality of the ecosystems must be able to be integrated on a broader scale. Geochemical indicators can provide guidance as to the type of biodiversity that can develop depending on the geochemical quality of the soil.

3.2.1. Heavy metals contamination

Heavy metals contamination remains a critical environmental issue, posing significant threats to ecosystems, human health, and agricultural productivity globally. These contaminants, including metals and metalloids such as arsenic, cadmium, chromium, copper, mercury, lead, zinc, nickel, and cobalt, originate from both natural geological sources and anthropogenic activities like mining, industrial processes, waste disposal, and the use of metal-containing products.

These contaminants and their impacts are usually represented on conceptual site models (CSMs) that are refined iteratively with the various pollution and risk assessment studies carried on the site (following figure).

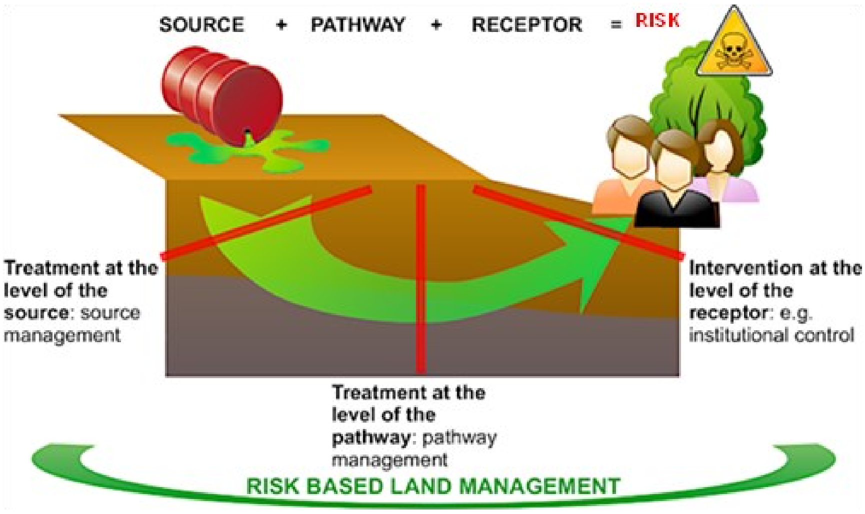

Fig. 3. Conceptual Site Model for risk based land management (from Tack and Bardos 2020)

In the European context, the challenge of heavy metals in soils is particularly acute due to the long history of industrialization and intensive agriculture. This has led to widespread distribution of metal pollutants, often exceeding natural baselines and necessitating extensive remediation efforts estimated to cost billions annually. The interaction of heavy metals with the soil matrix, their bioavailability, and potential for bioaccumulation up the food chain complicates their impact, making the situation more perilous as these elements infiltrate terrestrial and aquatic ecosystems.

Research efforts, including extensive soil surveys like the LUCAS Topsoil Survey, have begun to provide a more detailed mapping of soil contamination across Europe, highlighting areas at risk and the varying degrees of heavy metal concentrations. These efforts are crucial as they inform policy-making and remediation strategies, aiming to mitigate the adverse effects of these pollutants. The importance of such monitoring is further underscored in the proposed Directive of the European Parliament and of the Council on Soil Monitoring and Resilience (Soil Monitoring Law), which mandates monitoring for a comprehensive list of elements including Arsenic (As), Antimony (Sb), Cadmium (Cd), Cobalt (Co), Chromium (total) (Cr), Chromium (VI) (Cr VI), Copper (Cu), Mercury (Hg), Lead (Pb), Nickel (Ni), Thallium (Tl), Vanadium (V), and Zinc (Zn).

In the complex landscape of soil contamination regulations, a variety of thresholds for heavy metals have been established across many countries, reflecting the diverse environmental and public health priorities of each nation. Soil Screening Values (SSVs) are one such type of threshold, generally rooted in comprehensive risk assessment methodologies that aim to safeguard human health and the soil ecosystem. These SSVs often also take into account the impacts on groundwater, drinking water, and surface water, making them integral in wider environmental protection efforts.

Nationally, the approach to setting these values can differ significantly. For instance, the United Kingdom, Germany, and the Netherlands have developed SSVs that focus on human health risks and the protection of ecosystems. Furthermore, when addressing ecosystem protection, these countries utilize species sensitivity distributions to establish risk-based thresholds that can protect the most vulnerable fractions of organisms. The variability in SSVs across different countries reflects the diverse environmental conditions, soil types, climate variations, and land uses prevalent in Europe. This diversity necessitates that each country's SSVs are tailored to their specific circumstances yet are robust enough to ensure effective management of soil contamination risks. Some country like France do not set any soil values and evaluate health risk according to the current or targeted uses. However background soil values are used to evaluate if the industrial activities are responsible of the impact on soil quality.

Outside Europe, as part of the Ecological Risk Assessment (ERA), the US EPA developed ecological thresholds for soil called Ecological Soil Threshold Values (ECO - SSLs) for 17 inorganic substances and 4 organic substances frequently encountered on remediated sites. These values are set for different types of target group: plants, soil invertebrates, mammals and birds.

As depicted in the conceptual schema (Figure 4.), 'thresholds' in soil pollution risk assessment are broadly categorized into background values and SSVs. This schema serves as a guideline, offering a standardized

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framework that can be adapted by individual countries to suit their unique environmental assessment needs. This approach ensures that despite the inherent complexities and variations, there remains a cohesive strategy towards managing soil pollution within the EU.

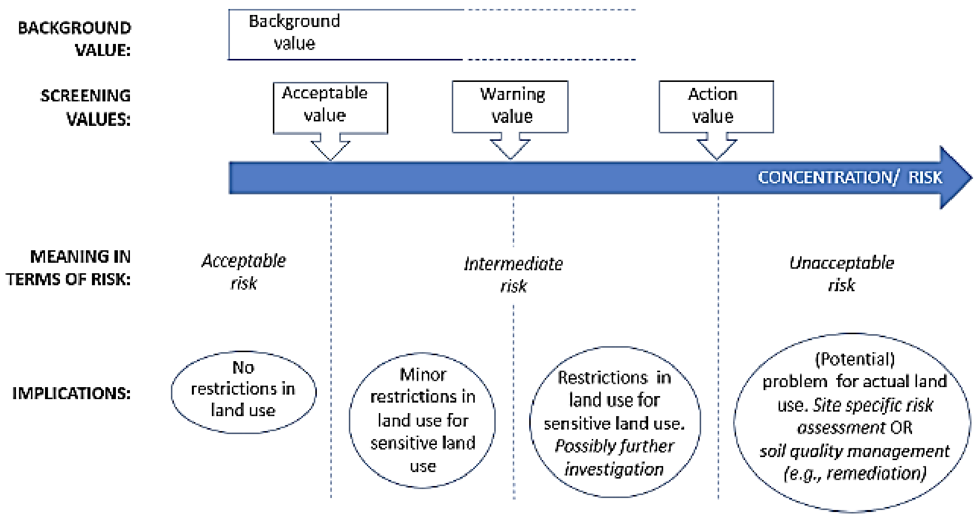

Fig. 4. Schematic overview of soil pollution risk assessment thresholds (EEA Report 08/2022)

When evaluating the risks posed by metals in the soil, the derivation of background, warning, and action values plays a crucial role, a method extensively applied across EU Member States. The work of Carlon et al. (2007) provides a foundational overview of the varying intermediate and critical risk levels for an array of metals, with a detailed update in this publication that specifically examines cadmium, copper, lead, and zinc. Over 444 individual screening values, ranging approximately from 50-60 per metal and risk level, were identified. These values were initially gathered from various technical reports or policy documents at European, national, or regional levels and were recently updated for Bulgaria, Czechia, Denmark, and Germany.

The array of SSVs, as depicted in Table 1., showcases extensive variation that reflects different stratification strategies, including considerations for protection targets (such as human health, ecosystem health, and arable crop quality), the underlying risk limits at various endpoints, methodologies to convert these risk limits to screening values in soil, and specific approaches to adjust for land use or soil type. For instance, in regions like Wallonia, Belgium, only critical risk levels are available, referred to as action values (EEA Report 08/2022).

Tab. 1. Current Screening Values (SSVs) for Cadmium, Copper, Lead and Zinc in soil (mg/kg) (EEA Report 08/2022)

Country/Region	Cadmium				Copper			
	Warning Value		Action Value		Warning Value		Action Value	
	Stratum ([a])	SSV	Stratum	SSV	Stratum	SSV	Stratum	SSV
Austria	LU	1-40	-	10	LU	100-1,500	-	600
Belgium/Brussels	-	1	LU	2-30	-	40	LU	145-800
Belgium/Flanders	-	-	LU	2-30	-	-	LU	200-800
Belgium/Wallonia	-	-	LU	1.8-20	-	-	LU	53-600
Bulgaria	LU, pH	1.5-3.5	-	12	LU, pH	80-300	-	500
Czechia	LU, pH, text.	1.5-20	-	-	pH	150-300	-	-
Denmark	LU	5	-	-	LU	1,000	-	-
Finland	-	1	LU	10-20	-	100	LU	150-200
Germany	LU	2-20	LU	0.1-20	LU	1 (b)	LU	1,300
Hungary	-	1	-	10	-	75	-	1,000
Italy	-	-	LU	1.5-15	-	-	LU	100-600
Lithuania	-	-	-	0.75-3	-	-	-	35,200
Netherlands	-	-	SOM, clay	13	-	-	SOM, clay	190
Poland	-	-	LU, SHC, z	1-20	-	-	LU, SHC, z	30-1,000
Slovakia	LU, text.	0.4-10	LU	20-30	LU, text.	300-500	LU	600-1,500
Slovenia	-	2	-	12	-	100	-	300
Sweden	LU	0.4-12	-	4	LU	100-300	-	1,000

Country/Region	Lead				Zinc			
	Warning Value	Action Value	Warning Value	Action Value	Warning Value	Action Value	Warning Value	Action Value
	Stratum	SSV	Stratum	SSV	Stratum	SSV	Stratum	SSV
Austria	LU	100-300	-	500	-	300	-	-
Belgium/Brussels	-	120	LU	200-2,500	-	120	LU	300-3,000
Belgium/Flanders	-	-	LU	200-2,500	-	-	LU	600-3,000
Belgium/Wallonia	-	-	LU	120-1,840	-	-	LU	196-3,000
Bulgaria	LU, pH	60-150	-	500	LU, pH	200-450	-	900
Czechia	LU	300-400	-	-	-	400	-	-
Denmark	-	40	-	400	-	500	-	1,000
Finland	-	60	LU	200-750	-	200	LU	250-400
Germany	-	(b)	-	-	-	2	-	-
Hungary	-	100	-	750	-	200	-	2.500
Italy	-	-	LU	100-1,000	-	-	LU	150-1,500
Lithuania	-	-	LU	50-500	-	-	LU	75-1,200
Netherlands	-	15-590	SOM, clay	530	-	150-720	SOM, Clay	720
Poland	-	-	LU, SHC, z	50-1,000	-	-	LU, SHC, z	100-3,000
Slovakia	-	150	-	600	LU	2-500	-	3,000
Slovenia	-	100	-	530	-	300	-	720
Sweden	LU	80-300	-	800	LU	350-1,050	-	3,500

Notes:
(a) Stratified according to: LU, land use, text., texture; SOM, soil organic matter; SHC, saturated hydraulic conductivity; z, soil depth.
(b) Analysis based on concentrated ammonium nitrate (commonly, extraction with aqua regia is used).
The references for this table are available on request from the EEA; they are contained in a database of European SSVs (EEA and Eionet Thematic Group Soil, Working Group on Soil Contamination)

The comparability of SSVs across Member States is also influenced by analytical differences. Generally, intermediate or critical risk levels for metals are determined after extraction with strong acids, typically aqua regia. However, in Germany, SSVs for soils intended for arable crops are based on extraction with concentrated ammonium nitrate, aimed at assessing metal bioavailability specifically to plants. This variation in extraction methods signifies that SSVs aimed at protecting arable crop quality cannot be directly compared due to methodological differences alone. The levels of SSVs among countries also differ due to varying soil conditions, which may include factors like soil organic carbon class, texture, parent material group, land use, and acidity (pH). The lack of a uniform classification system further complicates the direct comparability of SSVs.

In the context of post-mining area degradation, the presence of pollutants, particularly heavy metals, significantly impacts ecosystem health and the quality of soils and groundwater. These areas, often affected by years of exploitation, exhibit varying levels of contaminants that can greatly exceed norms established for less impacted regions. **This heterogeneity in pollution levels underscores the necessity for detailed risk assessments and the application of locally tailored threshold values that consider the specific characteristics of the area.** The restructuring and rehabilitation of post-mining landscapes thus require a thorough understanding of the interactions between existing pollutants and their effects on local ecosystems. Without such knowledge, planning and implementing effective remediation actions is challenging. The introduction of harmonized assessment procedures, based on current research and adherence to newly established standards, can contribute to better management of risks associated with heavy metals presence.

3.2.2. Soil Organic Carbon Content and Composition

Soil organic carbon (SOC) and soil organic matter (SOM) are critical indicators of soil health, influencing a wide array of environmental functions and processes. SOC refers specifically to the carbon component of SOM (55 to 60%; Lehmann and Kleber, 2015). SOM includes a continuum of organic compounds at different decomposition level since it is constantly nourished by plants and animals on the one hand and decomposed by soil organisms on the other. This continuum also results from different forms of protection of SOM against decomposition by soil organisms: physicochemical protection of SOM and the influence of environmental conditions on the activity of soil organisms. Depending on the degree of protection, SOM is considered more or less “labile” or “stable” over time in the face of the action of soil organisms (Lehmann and Kleber, 2015). Chemical protection refers to the complexity of the molecule considered: a simple sugar like glucose is more easily metabolized by soil microorganisms than a complex polymer like cutin, for example. Although this form of protection has long been considered the main explanation of this continuum, it is in reality far from explaining it entirely. Indeed, the physical and chemical protections of SOM play a major role in its decomposition speed. The first corresponds to the adsorption of SOM on the mineral surfaces of the soil and/or its interaction with metal ions (e.g. iron, aluminium) found in the soil. Physical protection, for its part, refers to the trapping (or inclusion) of this SOM in soil aggregates.

The speed of decomposition of SOM by soil organisms is strongly influenced by pedoclimatic conditions, the plant cover of the soil and human activities. First, physical and chemical protections are closely linked to the type of soil considered, and in particular to its grain size/texture (clay, silt and sand contents. The SOC/clay ratio has emerged as a crucial indicator for assessing soil health, particularly focusing on the interaction between soil organic carbon (SOC) content and clay content. The presence of clay in the soil tends to stabilize SOC by protecting it against decay and enhancing its resistance to decomposition. This relationship suggests that soils with higher clay content can sustainably support higher levels of SOC. A significant study by Johannes et al. (2017) built upon earlier research by Dexter et al. (2008), who initially proposed that the optimal SOC content should be approximately 10% of a soil's clay content. This concept was refined to focus more specifically on dispersible clay rather than total clay content. In their research, Johannes et al. utilized data from 161 samples across Swiss agricultural lands, particularly cambic luvisols, and determined a vulnerability limit expressed as %SOC = 0.1×%clay. This limit indicates the threshold at which soil begins to show signs of degradation, marking a critical point for maintaining soil health and structure. Further studies, such as those by Prout et al. (2020), have suggested a vulnerability limit of less than 1/13 for the SOC/clay ratio, identifying soils below this threshold as potentially degraded. This ratio has been validated across various land uses, including arable land, grassland, and woodland, demonstrating its applicability for monitoring soil health across a broad spectrum of soil types and conditions. This ratio not only helps in tracking the structural stability of soil but also serves as an effective tool for understanding and managing soil resilience. Increases in the SOC content are positively correlated with the recovery of soils from degradation processes like compaction, which further underscores the importance of monitoring and maintaining adequate SOC levels relative to clay content. Such insights are crucial for developing strategies to enhance soil health and ensure sustainable land use practices. In the European Union's recent proposal for a directive on soil health, the SOC/clay ratio has been introduced as a key indicator for monitoring the loss of soil organic carbon (SOC). This reflects a growing recognition of the importance of maintaining SOC levels as a measure of soil health and resilience. In terms of establishing a healthy state for this parameter, the proposal of soil directive specifies distinct targets for different soil types:

- For organic soils: respect targets set for such soils at the national level.
- For mineral soils: a SOC/clay ratio greater than 1/13 is considered healthy, indicating adequate organic carbon relative to clay content to maintain soil function and structure.

On the other hand, soil temperature and humidity greatly influence the speed of SOM mineralization by soil microorganisms. Indeed, a 10°C increase in soil temperature can increase the speed of SOM mineralization by two or three. Increasing soil humidity also accelerates mineralization but only up to a certain threshold of between 20 and 50% volume humidity (Pellerin et al. 2019). From this threshold, conditions become anoxic (i.e. without oxygen) and the speed of mineralization decreases, this is the case in peatlands in particular. Finally, an increase in fresh SOM inputs following, for example, a greater production of biomass by plants or the spreading of manure by humans can stimulate the speed of decomposition of SOM by organisms (Burke et al. 1989). All these mechanisms lead us to speak of the “dynamics” of SOM degradation because all its constituents are constantly transformed/renewed. Indeed, via the action of decomposers, fragments or organic residues of animals or plants are transformed into smaller molecules (the ultimate reaction being mineralization into CO2) while other organisms use the small molecules to synthesize them. larger ones. In addition, when their size decreases, the solubility and reactivity of these compounds increase, leading to perpetual association/dissociation of the latter with the aggregates and the mineral fraction of the soil (Lehmann and Kleber, 2015).

The debate within the soil science community about whether there is a universal optimal or critical minimum level of SOM or SOC is ongoing. This discussion highlights the challenge of setting generalized thresholds for SOC that ensure soil fertility, water retention, and structural integrity to support adequate crop yields under various nutrient management conditions. However, most studies on the characterization of SOM and the different forms of SOC are based on agricultural land management practices (e.g. field crops, cover crops, silviculture, type of tillage, etc.). The majority of studies therefore concern the upper arable layer (the first 30 centimeters of soil). In

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this context, the analytical methods classically used by the soil science community, manufacturers and design offices, such as the elementary analysis of atomic emission spectrometry – inductively coupled plasma (ICP-AES), and physical fractionation methods, are methods developed related to the needs of agricultural soils. These methods are often not suitable for other types of soils and, in particular, soils rich in mineral carbon and with a low SOC content or very degraded soils. For these soils, traditional methods such as ICP elemental analysis are not sensitive enough to assess the presence of SOC and do not reflect accurate information related to the form of SOC. Recently, new methods based on the SOM combustion (method RockEval®) have been developed and adapted to quantify and qualify the composition of SOM in soils with very low SOC (> 1%), such as very degraded soils (Sebag et al, 2016 and 2022).

Identifying site-specific SOC thresholds that reflect local environmental conditions and management practices is crucial. These thresholds are used to determine whether soils are SOC-depleted and to establish benchmark values for healthy soils, typically set at 75% of the observed SOC levels under optimal management conditions. However, while these benchmarks help guide sustainable soil management, they do not directly measure specific soil functions (EEA Report 08/2022), and complementary approaches based on the quantification and characterization of the meso- and micro-fauna and flora are needed.

3.2.3. Soil nutrient loss: nitrogen and phosphorus

Soil nutrient loss, specifically nitrogen (N) and phosphorus (P), is a critical factor influencing biomass production and crop yields in both natural and agricultural soils. While fertilized soils may show less impact, maintaining an appropriate nutrient status remains crucial for optimizing biomass production and crop yield. This involves ensuring adequate levels of both macronutrients—nitrogen, phosphorus, calcium, magnesium, potassium, sulfur—and micronutrients like boron, zinc, manganese, iron, copper, and molybdenum. The diversity of soil microorganisms, soil animals, and plant species is also significantly affected by the nutrient status, with nitrogen often reducing diversity, whereas variations in other nutrients can have either a positive or negative effect. Increased nutrient status enhances carbon storage due to the higher input of crop residues and may lead to reduced water quality, especially with high phosphorus levels which escalate the risk of runoff into surface waters. Nitrogen and phosphorus are pivotal, together with soil pH, in determining soil fertility. These nutrients, affected by inputs from both fertilizer and atmospheric deposition, play a key role in soil productivity and ecological balance.

In soils, **nitrogen** is typically derived organically rather than from inorganic minerals. Unlike phosphorus, nitrogen does not undergo dissolution or precipitation processes and has limited sorption capabilities, except on positively charged soil particles for ammonium. Biological processes predominantly govern nitrogen availability in agricultural contexts, where it is added through fertilizers and manures. Added nitrogen is utilized by plants and soil organisms, with any surplus being lost to the atmosphere as various nitrogen oxides or to water bodies primarily as nitrate, contributing to potential eutrophication.

Contrary to nitrogen, **phosphorus** levels in the soil are buffered by the stock of reactive or available phosphorus. This buffering capacity means that changes in phosphorus inputs from fertilizers affect crop yields less significantly in soils already rich in phosphorus. Soil phosphorus availability is influenced by the content of aluminum and iron oxides, which can bind phosphorus, reducing its availability for plant uptake.

Monitoring the status of nitrogen and phosphorus in soils is crucial for managing soil health and agricultural productivity. While total nitrogen and phosphorus content provide a basic measure, the availability of these nutrients for plant uptake is more indicative of soil fertility. For nitrogen, indicators include the total mineral nitrogen content, which influences nitrogen mineralization and availability. For phosphorus, both target and critical levels are established to enhance crop growth where phosphorus is limiting or to mitigate negative impacts on water quality at high levels of soil phosphorus.

3.2.3.1. Indicators and thresholds for Nitrogen

N_{min} in Agricultural Soils

In agricultural soils, the delineation of critical limits for total nitrogen (N) or available nitrogen (mineral N content) is complicated due to its dynamic nature within soil systems. While total N and available N are pivotal for crop growth in unfertilized soils through the process of N mineralization, establishing a fixed critical limit is challenging.

This is because nitrogen fertilization practices generally ensure an ample supply of N, overriding the natural variability and potential deficits in soil nitrogen status.

Moreover, excessive nitrogen does not typically limit crop growth if soil acidification—another side effect of high nitrogen input—is counteracted through liming practices. However, a high concentration of mineral nitrogen (Nmin) can negatively impact soil biodiversity. Such impacts are less about the absolute nitrogen content and more about how nitrogen additions via fertilizers alter soil ecological dynamics. The primary concern with nitrogen is its role in the broader environmental context—excess nitrogen contributes to air and water quality degradation through processes such as denitrification and nitrogen leaching, which are influenced by soil properties such as clay content and groundwater levels, rather than the inherent nitrogen status of the soil.

A practical approach to managing nitrogen involves minimizing the nitrogen surplus at the farm level—balancing the nitrogen inputs from fertilizers and feed against the nitrogen outputs in harvested plant and animal products. This management strategy aims to reduce the nitrogen losses to the environment, thus mitigating its broader ecological impacts.

Critical Limits for C/N Ratio in Forest Soils

The nitrogen retention capacity in forest soils, particularly within the organic layer, is highly influenced by the C/N ratio—a critical metric for understanding nitrogen dynamics in forest ecosystems. High soil C/N ratios indicate robust microbial immobilization of nitrogen, thereby reducing its availability for plant uptake and minimizing the risk of nitrogen leaching. Conversely, lower C/N ratios suggest increased nitrogen availability, raising the potential for nitrogen leaching into surrounding ecosystems.

The critical ranges for C/N ratios in forest soils have been empirically determined to assess the risk of nitrogen leaching (EEA Report 08/2022):

- **High N retention and low leaching potential:** C/N ratio > 30
- **Moderate to high N retention and low to moderate leaching potential:** C/N ratio between 25 and 30
- **Low to moderate N retention and moderate to high leaching potential:** C/N ratio between 20 and 25
- **Low N retention and high leaching potential:** C/N ratio < 20

These thresholds help differentiate forest sites by their nitrogen processing characteristics, indicating how well nitrogen is retained within the soil matrix and its potential impact on forest ecology and water quality. The understanding of these dynamics is crucial for managing forests sustainably, ensuring that nitrogen inputs do not exceed the ecological capacity of the forest soil, thereby preventing adverse environmental effects such as eutrophication and biodiversity loss.

3.2.3.2. Indicators and thresholds for Phosphorus

Phosphorus (P) is a critical nutrient for crop growth and plays a significant role in maintaining soil fertility and environmental health. To manage P effectively and minimize its environmental impact, it is essential to maintain soil P levels within specific target and critical thresholds.

Target levels for available phosphorus for crop yields in agricultural soils

The management of soil phosphorus focuses on maintaining levels that support optimal crop production without causing environmental degradation. This concept is often implemented through a "build-up and maintenance" approach, which ensures that P application does not exceed the soil's capacity to bind phosphorus, thus preventing leaching into water systems. This approach involves:

- **Avoiding P application** in soils where available P exceeds the threshold for P leaching.
- **Matching P input** with crop uptake when soil P levels are between the critical level for crop yield and the critical level for P leaching.
- **Increasing soil P** levels with additional P fertilizer if levels fall below the critical level for crop yield, aiming to elevate P to adequate levels for crop production.

This strategy is depicted in Figure 5., illustrating the various stages from high environmental risk to optimal levels for crop yield based on soil P status.

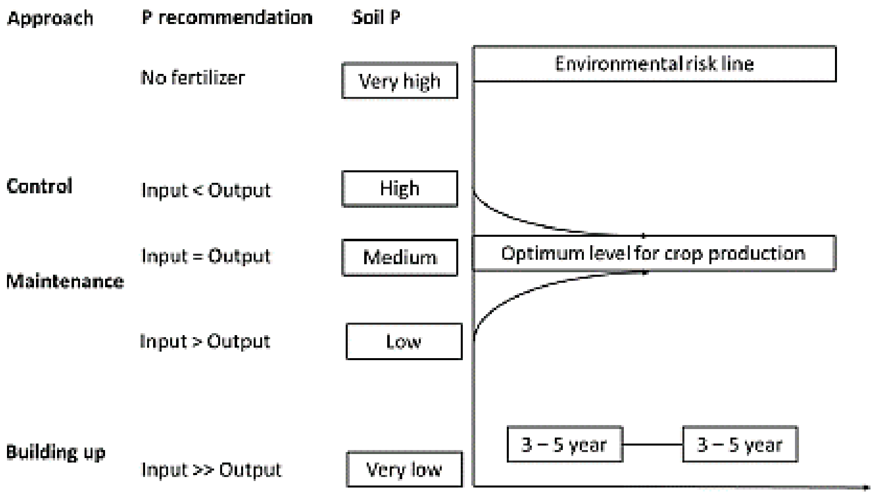

Fig. 5. Phosphorus management approaches (EEA Report 08/2022)

Critical levels for crop yield and environmental health

Critical levels for phosphorus in agricultural soils are determined through both short-term pot experiments and long-term field studies, which help define the specific soil P levels at which crop yield response plateaus (no further response to added P) and the levels at which environmental risks, particularly leaching, become significant.

- **Critical Level for Crop Yield:** Research, such as that conducted by Bai et al. (2013), has identified specific critical Olsen-P values for various crops like maize, wheat, and rice. These values range from 7mg/kg to 18mg/kg, depending on crop type and soil properties. These thresholds are crucial for determining when additional P fertilization is unlikely to increase crop yields.
- **Critical Level for P Leaching:** The risk of phosphorus run-off increases significantly when soil P levels exceed certain thresholds. This leaching potential is linked to the soil's P saturation index and the concentration of P in soil water (Pw). Effective management aims to keep soil P levels below these critical points to prevent eutrophication of water bodies.

The relationship between crop yield, P leaching risk, and soil P fertility status is illustrated in Figure 6., highlighting the balance needed between enhancing crop yield and minimizing environmental risks.

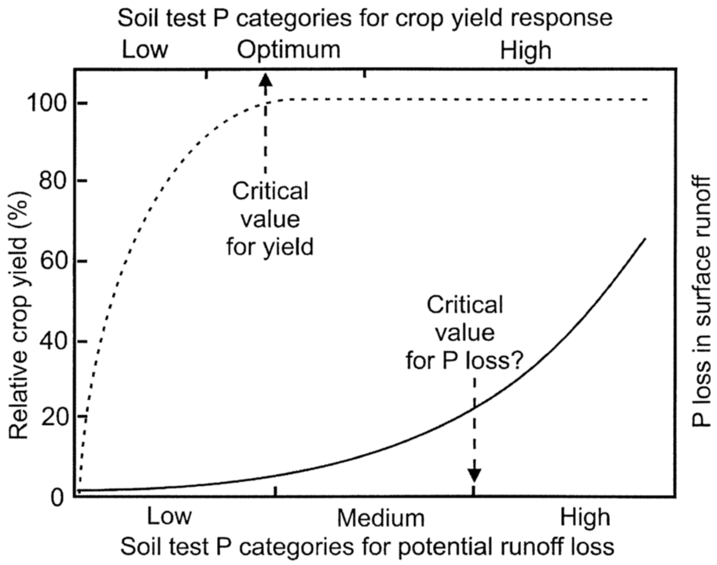

Fig. 6. Relationship between soil Phosphorus levels, crop yield, and surface runoff risk (Hart et. al., 2004)

Indicators for soil phosphorus status include (EEA Report 08/2022):

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- **Total and Available Phosphorus:** These indicators assess the total and plant-available phosphorus in the soil, which are critical for understanding the nutrient's role in crop growth and environmental impact.
- **Soil P Saturation Index (PSI):** This index measures the proportion of phosphorus that is bound to soil particles relative to the soil's total binding capacity. A critical PSI is often set at about 15%, indicating a balance between availability for crop uptake and risk of leaching.

In summary, managing soil phosphorus involves maintaining appropriate levels to support crop growth while preventing excessive leaching that could lead to environmental degradation. This dual focus is supported by indicators and thresholds that guide agricultural practices and environmental protection efforts. In line with the European Union's proposal for a directive on soil health, the extractable phosphorus "maximum value" must be defined by each Member State within the range of 30-50 mg/kg, ensuring that soil management strategies are tailored to local conditions while addressing broader environmental concerns.

3.2.4. Salinization

Soil salinity is recognized as a crucial soil degradation issue, particularly prevalent in semi-arid regions, areas with shallow groundwater, and coastal deltas. Soil salinity is often described using three primary categories: saline soil, sodic soil, and alkaline soil. Each type presents unique challenges and mechanisms of impact on soil health and plant viability (E. Bloem, et al., 2012).

- **Saline Soil:** Characterized by high concentrations of soluble salts, these soils impede plant transpiration due to the high osmotic pressure of soil water, making it difficult for plants to absorb moisture effectively.
- **Sodic Soil:** Dominated by high concentrations of sodium ions, sodic soils suffer from structural degradation, which affects water infiltration and root penetration.
- **Alkaline Soil:** Although not the primary focus here, these soils are disturbed chemically towards high pH levels, often leading to toxicity and nutrient deficiencies for plants.

Saline soils are often considered easier to remediate quickly compared to sodic soils, which may develop slowly but are challenging to restore once affected. This distinction in remediation complexity is crucial for effective management strategies (E. Bloem, et al., 2012).

Electrical conductivity (EC) is a critical measure used to assess the salinity of soil and water. It is quantified in deci-Siemens per meter (dS/m) at a standard temperature of 25°C to minimize temperature variation effects, which can be linearly compensated if needed. This measure is crucial because it reflects the concentration of all soluble salts within a sample. Additionally, salinity can be estimated from soil samples by creating a standard saturation extract (ECe), where water is added to dry soil to simulate saturation conditions. This method is particularly useful for comparing salinity across different soil types and conditions (Daliakopoulos, et al. 2016). The importance of EC as an indicator lies in its ability to classify soils based on the salinity hazard and predict potential impacts on the yield of various field crops (tab. 2). This classification follows the general scheme proposed by Richards in 1954, which remains a cornerstone in salinity assessment practices today. The use of EC is integral to managing salinity risks in agricultural and environmental settings, providing a robust basis for interventions aimed at mitigating salinity's adverse effects on crop productivity and soil health.

Tab. 2. Classification of Soil Salinity Levels and Their Effects on Crop Yield Based on Electrical Conductivity (ECe) Measurements (Richards, 1954)

ECe [dS m^{-1}]	Class	Effect
0-2	Non saline	Negligible
2-4	Slightly saline	Yield reduction of sensitive crops
4-8	Moderately saline	Yield reduction of many crops
8-16	Strongly saline	Normal yields for salt tolerance crops only
>16	Very strongly saline	Reasonable crop yield for very tolerance crops only

At the conclusion of the discussion on soil salinity indicator, it is pertinent to consider regulatory frameworks such as the directives proposed by the European Union regarding soil health. Specifically, the directive outlines a criterion for soil salinity assessment, suggesting a threshold for salinity as less than 4 deci-Siemens per meter (dS m−1) when measuring electrical conductivity using the saturated soil paste extract method (eEC). Alternatively, an equivalent criterion is recommended if another measurement method is employed.

3.2.5. Soil pH

Soil pH is a critical measure reflecting the acidity or alkalinity of soil, providing essential insights into the soil environment's chemical balance. Defined as the negative logarithm of the hydrogen ion concentration, pH values range from about 0 to 14, with 7 considered neutral, values below 7 acidic, and those above 7 alkaline (Fig. 7). The pH scale is logarithmic, meaning each whole number change represents a tenfold increase or decrease in acidity; for instance, a soil with a pH of 6 is ten times more acidic than one with a pH of 7. This property of soil is significantly shaped by the presence of acid and base-forming ions. Acidic conditions are primarily contributed by cations like hydrogen (H+), aluminum (Al3+), and iron (Fe2+ or Fe3+), while alkalinity is encouraged by the presence of base-forming cations such as calcium (Ca2+), magnesium (Mg2+), potassium (K+), and sodium (Na+). Understanding soil pH is crucial because it affects the solubility of nutrients and contaminants, thereby influencing plant growth, microbial activity, and soil structure (McCauley at.al, 2009).

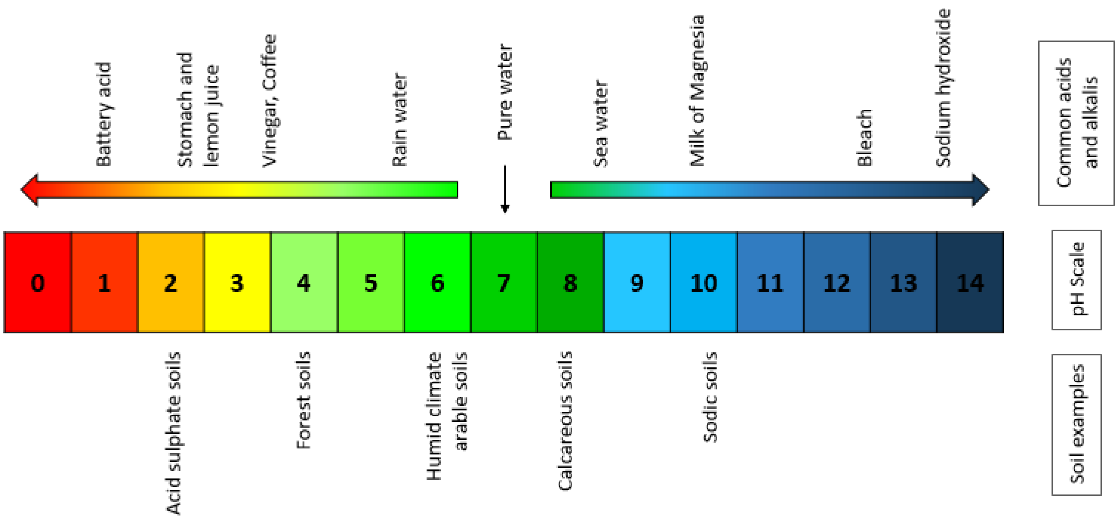

Fig. 7. pH scale (based on Nutrient Manager, 1996)

The optimal pH for plant growth generally falls between 6 and 7.5, which aligns with the needs of most agricultural and garden plants. However, plant adaptation allows for thriving across a broader spectrum of pH values, with some species specifically suited to more acidic or more alkaline conditions. The relationship between soil pH and plant health isn't merely about tolerance; many plants actively modify the pH of their immediate root environment to improve nutrient uptake. For example, certain plants lower the pH around their roots to solubilize and absorb nutrients more effectively (Fabian et al., 2014). Detailed descriptions of pH ranges and soil characteristics are provided in Table 3.

Tab. 3. Descriptive pH Range and Soil Characteristics

Descriptive Term and pH Range	Description of Soil pH Effects
Very Acid pH < 4.9 H_2O, pH < 4.5 KCl	Represents extreme soil acidity that can significantly limit the growth of most plants and microbial activity, leading to severe degradation of the ecosystem. Such acidity may necessitate substantial liming and other soil amendments to mitigate toxicity and restore ecological balance.
Acid pH 5.0 – 5.9 H_2O, pH 4.6 - 5.5 KCl	Indicates moderately acidic conditions that might restrict the diversity of plant species and microbial functions. While not immediately toxic, this level of acidity may hinder certain agricultural uses and require moderate soil conditioning.
Lightly Acid pH 6.0 – 6.9 H_2O, pH 5.6 - 6.5 KCl	Slightly acidic soil conditions that generally support a broader range of plant life but may still pose mild restrictions on certain sensitive species or crops. Minor adjustments such as light liming might be beneficial.

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Neutral pH 7.0 H_2O, pH 6.6 - 7.2 KCl	Ideal for most agricultural and natural ecosystem functions, indicating no degradation related to acidity. This range is typically targeted in reclamation efforts to ensure the maximum functionality of the soil.
Lightly Alkaline pH 7.1 – 8.0 H_2O, >7.2 KCl	These conditions are generally favorable for many types of plant life and microbial populations but may begin to restrict the availability of certain nutrients such as iron, manganese, and phosphorus.
Alkaline to Very Alkaline pH 8.1 – 9.4 H_2O and >9.4 H_2O	High alkalinity can lead to significant challenges in nutrient uptake for plants, potentially leading to degradation if not managed properly. Reclamation may involve soil acidification processes to reduce pH to more suitable levels.

In terms of crop production and environmental impacts, such as enhanced metal uptake and leaching, maintaining soil pH above critical levels is essential to avoid limiting crop yield and controlling heavy metal availability. Critical pH levels can be established through:

- **Short-term manipulation experiments** where soil pH is adjusted by adding H+ or OH-, allowing for controlled studies on crop responses. These experiments offer the advantage of isolating soil pH as the sole variable while maintaining constant conditions such as soil type, temperature, water, and nutrient availability. However, they may not accurately reflect field conditions, and adjustments in pH can significantly impact soil microbial communities and nutrient dynamics.
- **Long-term field experiments** that assess the effects of declining soil pH on plant growth and crop yields. These provide insights under actual field conditions but are complicated by other variables like climate changes, pests, and diseases, which necessitate careful data interpretation.

For example, results from both short and long-term studies on cereals such as wheat, maize, and rice have shown a significant non-linear relationship between soil pH and relative crop yield, which is defined as the fraction of the maximum yield attainable without acidification impacts. The critical pH value, where a 5% yield loss is expected, typically ranges between pH 4.5 and 4.7 in short-term studies, aligning closely with the onset of aluminum release. However, long-term observations suggest higher critical pH values between 5.0 and 5.9. Lime application recommendations often target maintaining soil pH within specific ranges suitable for various crops, as indicated in Table 4., to optimize plant health and yield while minimizing environmental risks associated with soil acidification (EEA Report 08/2022).

Tab. 4. Optimal soil pH values for various crops (Teagasc, 2022)

Crop	Optimum pH
Beet, beans, peas and oilseeds	7.0
Cereals and maize	6.5
Grassland	6.3
Grassland (high molybdenum)	<6.2
Potatoes	6.0

3.3. GEOTECHNIC INDICATORS

It is important for the rehabilitation of post-mining areas to take care of the proper physical and mechanical properties of the soil. Open-pit mining, due to the way surface mining is carried out, makes it possible to carefully plan appropriate soil mixtures that have the desired properties in this regard. The indicators proposed below allow a comprehensive analysis of the degree of degradation of such sites.

3.3.1.1. Soil porosity

Soil consists of solid particles (minerals and organic matter) of varying sizes, bound together into aggregates. The gaps between them create a network of pores that enable the exchange of water and air, as well as the flow of heat and nutrients. The number and size of pores vary based on organic matter content, texture, and structure (Hao et al., 2006). Soil porosity refers to the fraction of the total soil volume occupied by pores. It's crucial for understanding how soil retains and transmits water, air, and nutrients.

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Porosity directly influences the soil's water-holding capacity, allowing it to store and supply water to plants. Adequate porosity ensures proper gas exchange, crucial for oxygen and carbon dioxide movement. It also affects root penetration, enabling roots to grow and explore the soil for water and nutrients. Furthermore, soil pores provide habitats for microorganisms essential for nutrient cycling. These aspects highlight the vital role porosity plays in soil health and and is an important indicator of the degree of environmental degradation in post-mining areas (Eden et al., 2011).

3.3.1.2. Soil density

Soil density is a measure of soil mass relative to its volume and is expressed in g/cm³. Bulk density represents the mass of dry soil divided by the total soil volume, including pore spaces. It is determined using the formula:

$$\rho = \frac{mass\ of\ dry\ soil}{total\ soil\ volume}$$

Bulk density is influenced by soil texture, structure, and organic matter content. Sandy soils generally have higher bulk densities due to fewer aggregates and lower organic matter. Fine-textured soils, such as clays, often have lower bulk densities due to better aggregation and higher organic matter content. Compaction increases bulk density by reducing pore space.

Bulk density is crucial for understanding soil compaction, porosity, and overall soil health. High bulk density can impede root growth, reduce infiltration rates, and limit water and nutrient availability. Conversely, low bulk density indicates good soil structure and favorable conditions for plant growth (Assouline, 2006).

3.3.2. Soil erosion

Soil erosion refers to the process by which soil particles are detached and transported by natural forces such as water, wind, and gravity. It is a significant environmental issue, particularly in reclaimed post-mining areas where soil stability and health are paramount. The rate and extent of soil erosion depend on various factors, including climate, topography, soil characteristics, vegetation cover, and land management practices. Understanding and managing soil erosion are critical for the successful rehabilitation of mining sites.

3.3.2.1. RUSLE

The RUSLE (Revised Universal Soil Loss Equation) is an enhancement of the Universal Soil Loss Equation (USLE) that provides an estimate of the annual soil losses due to erosion caused by rainfall and runoff. RUSLE is used to predict average annual erosion by rain and associated runoff for specific areas, which is crucial in soil conservation planning and water resource management.

The Revised Universal Soil Loss Equation (RUSLE) serves as an effective method for classifying the degree of soil degradation on reclaimed mining sites. This application of RUSLE facilitates the evaluation and management of soil erosion risks on landscapes that have been disturbed by mining activities, which are often susceptible to accelerated erosion due to exposed soil surfaces and altered topography.

The RUSLE model is often integrated with Geographic Information Systems (GIS) and remote sensing, allowing for accurate and efficient erosion modeling over large areas. Technological advancements in these areas have significantly enhanced the precision and utility of RUSLE in various applications such as land use planning and natural resource management.

When discussing the values of the RUSLE index, the focus is on the comprehensive output that the model provides, which is the annual rate of soil loss expressed typically in tons per hectare per year (t/ha/yr). This numerical output reflects the integrated effect of all contributing factors and allows for a detailed understanding of erosion dynamics on a given landscape.

- The RUSLE model incorporates five primary factors, which will be described in detail in the following subsections:
- Rainfall Erosivity (R Factor): This factor assesses the impact of rainfall intensity and amount on soil loss.
- Soil Erodibility (K Factor): Indicates the inherent vulnerability of soil to erosion, essential for understanding how different soil types found in reclaimed mining areas respond to erosive forces.
- Topographic Factor (LS Factor): Evaluates how changes in slope length and steepness, common in mining landscapes, influence erosion rates.

- Cover and Management (C Factor): Assesses the effectiveness of vegetation cover and land management practices in reducing erosion, a key component in the successful reclamation of mining sites.
- Support Practice Factor (P Factor): Focuses on the role of conservation practices such as contour farming and terracing, which are often employed in reclaimed areas to stabilize soil and reduce runoff.

Based on the above components, the RUSLE index is calculated with the following formula (Phinzi & Ngetar, 2019):

$$A = R \times K \times LS \times C \times P$$

Each of these factors has its own calculation method, taking into account local climatic conditions, soil types, site topography, vegetation types and applied land management practices. RUSLE is a flexible tool that can be adapted to different environmental conditions, making it extremely useful for soil conservation planning and erosion management. Individual indicators will be described in detail in the following subsections.

3.3.2.1.1. R Factor

The R factor represents the rainfall erosivity factor and plays a crucial role in modeling soil erosion caused by precipitation. It quantifies the impact of rainfall on erosion based on data regarding the intensity and amount of precipitation over a given period, typically measured annually. This factor is expressed in units of MJ·mm/ha/hr/yr (megajoules per millimeter per hectare per hour per year), reflecting the energy of rainfall capable of causing erosion.

The R-index in the Revised Universal Soil Loss Equation (RUSLE), which determines the erosivity of rainfall, is calculated from data on the intensity and amount of rainfall. This process requires the collection of meteorological data from local stations or global databases such as the European Soil Data Center (ESDAC) (Fig 8., next page). The kinetic energy of each rainfall is calculated from the kinetic energy equation, taking into account the mass of the rain and its impact velocity, and the erosivity is represented by the maximum 30-minute rain intensity (I30). The R-index is ultimately calculated as the sum of the kinetic energy products and I30 for all rainfall in a given year. It is also possible to directly derive R-values from converted rain erosivity values available in databases, which is useful when local data are unavailable or incomplete.

In such cases, the following are useful global databases that offer both historical and current rainfall erosivity information for different regions of the world. For example, one available data source is the European Soil Data Portal (ESDAC) managed by the European Commission, which provides R-factor values for RUSLE. The data available on the European Soil Data Center (ESDAC) website (https://esdac.jrc.ec.europa.eu/) can be used to obtain R-factor values without the need to conduct time-consuming and expensive measurements yourself. Access to such data makes it possible to quickly and efficiently analyze the erosivity of rainfall over large areas, which is particularly useful for planning conservation measures in erosion-prone areas.

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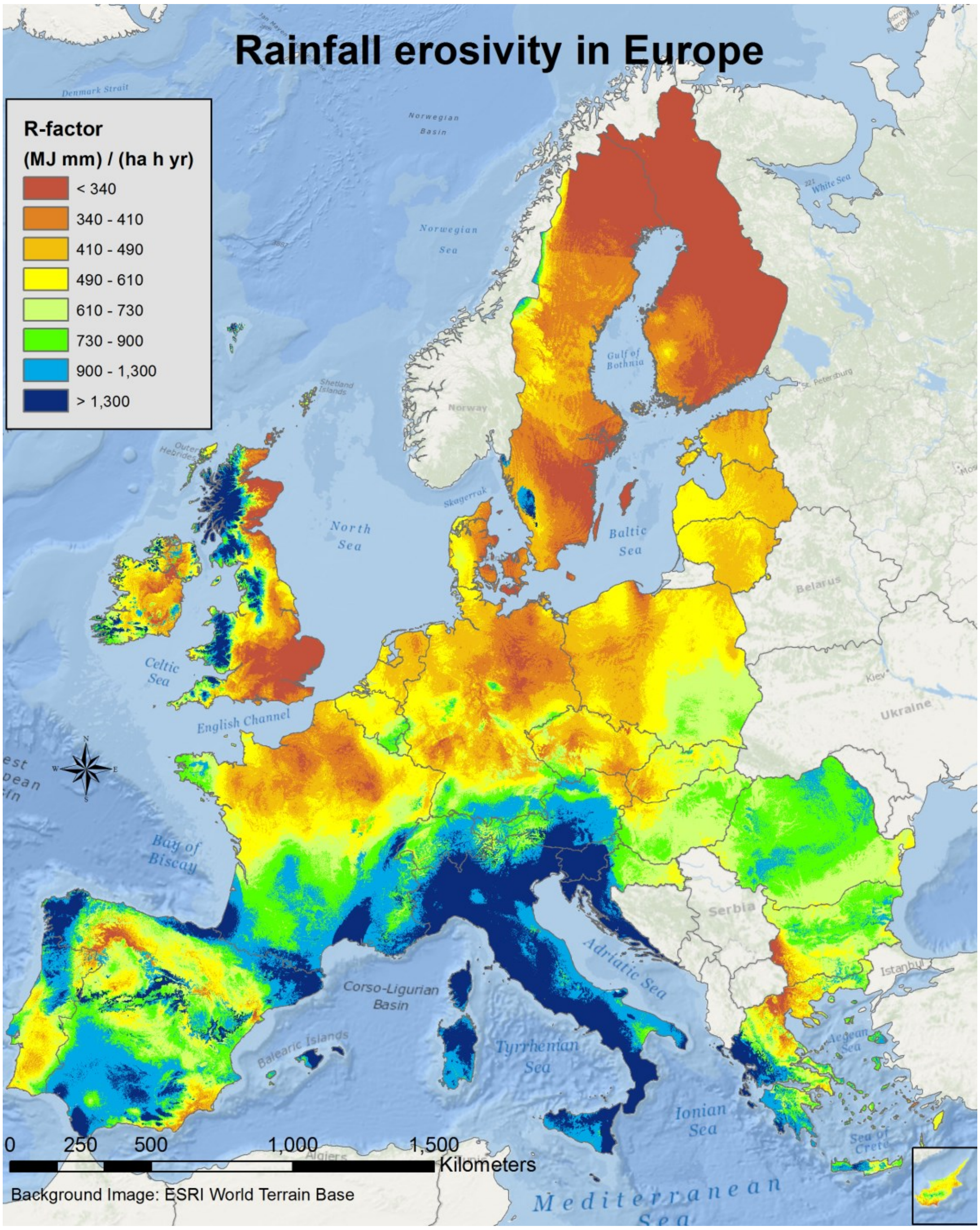

Fig. 8. Map of rainfall erosivity in Europe
https://esdac.jrc.ec.europa.eu/tags/rusle

3.3.2.1.2. K-Factor

The K factor represents the erodibility of a soil, or its susceptibility to erosion caused by water. It is a parameter that takes into account the physical and chemical properties of the soil, such as texture, structure, organic matter content and permeability. The K-index is crucial because different types of soils have different abilities to resist erosion. To calculate the K index, soil data is used, such as the percentage composition of sand, silt and clay fractions and organic matter content. The formula for this indicator is as follows:

$$K = \left[\frac{2{,}1 \times 10^{-4} \left(12 - OM\right) M^{1{,}14} + 3{,}25(S-2) + 2{,}5(P-3)}{7{,}59} \times 100 \right]$$

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Where:

$OM - soil\ organic\ matter\ content,$
$M - product\ of\ the\ primary\ particle\ size\ fractions,$
$S - soil\ structure\ code\ (tab.5),$
$P - permability\ class\ (tab.6),$

variable M is calculated by the formula:

$$M = (\%silt + \%very\ fine\ sand) \times (100 - \%clay)$$

Where very fine sand means particles means grain size 0.063 mm – 0.1 mm.Access to precise and up-to-date soil data is crucial for accurate calculation of the K factor. In practice, these data can come from direct field surveys, soil maps, or databases such as those maintained by research institutions or government agencies. Accurate determination of the K-factor enables effective assessment of environment degradation level.

Tab. 5. Classification of Soil Structure Types

Soil structure code	Description
1	Very fine granular
2	Fine granular
3	Moderate or coarse granular
4	Blocky, ploty or massive

Tab. 6. Classification of Soil Permeability

Permeability class	Description
1	Rapid
2	Moderate to rapid
3	Moderate
4	Slow to moderate
5	Slow
6	Very slow

3.3.2.1.3. LS-Factor

The LS factor (Moore and Burch 1986; Moore and Wilson 1992), calculates the soil erosion based on the slope length (L) and steepness factor (S), which are computed based on the DEM. This index determines the effect of topography in a specific area and how intense the erosion is (Louloudis et al. 2023).

In the context of the Revised Universal Soil Loss Equation (RUSLE) refers to the combined influence of slope length and steepness on soil erosion. The LS factor is a mathematical expression that combines the slope length (L) and the steepness (S) to produce a single value that characterizes the impact of topography on erosion rates. Slope length refers to the distance that runoff travels over the surface before reaching a stable channel or deposition area, directly influencing the potential acceleration and erosive power of water. Slope steepness measures the angle of the slope, affecting the velocity of surface runoff and its capacity to transport soil particles (Phinzi & Ngetar, 2019).

3.3.2.1.4. C-Factor

The C-factor, or cover management factor, is a crucial component in soil erosion modeling, particularly within the Revised Universal Soil Loss Equation (RUSLE). It represents the ratio of soil loss under specific cropping conditions to soil loss that would occur if the soil were left bare. This factor quantifies the impact of various land management practices on soil erosion rates, reflecting the influence of vegetation cover and management on erosion.

The C-factor is defined as the ratio of soil loss under specific cropping and management conditions to the loss that would occur on bare soil. It considers several sub-factors: prior land use, soil cover by plant canopy, soil cover by crop residues, soil surface roughness, and soil moisture. Each sub-factor contributes to the degree of protection the soil surface receives from erosion processes.

Modern techniques prefer remote sensing and GIS over traditional field experiments due to their cost-effectiveness and accuracy. Land use/land cover (LULC) classification from satellite imagery is often used to assign C-factor values. Spectral indices like NDVI (Normalized Difference Vegetation Index) and other vegetation indices are utilized to estimate vegetation cover, which directly influences the C-factor. However, these indices primarily measure photosynthetic vegetation, which may not account for non-photosynthetic (dry or dead) vegetation that also affects erosion.

A significant challenge in using spectral indices is their variability across different climatic conditions and their inability to fully capture the protective effect of non-photosynthetic vegetation. The accuracy of C-factor estimation is highly dependent on the quality of the remote sensing data and the chosen methods for image classification and analysis.

Various empirical relations have been developed to relate vegetation indices to C-factor values. For instance, equations by De Jong (1994) and Van der Knijff et al. (1999, 2000) are commonly used to derive C-factor values from NDVI. Despite the popularity of these methods, they have limitations, such as low correlation in certain regions, which has led to the development of improved equations like the rescaled NDVI method by Durigon et al. (2014).

The C-factor is a critical element in soil erosion modeling, reflecting the effectiveness of land cover and management practices in mitigating soil loss. Its estimation has evolved from field experiments to sophisticated remote sensing and GIS-based techniques, enhancing the accuracy and efficiency of soil erosion assessments. However, challenges remain, particularly regarding the variability in vegetation cover and the accurate representation of non-photosynthetic vegetation.

3.3.2.1.5. P-Factor

The P-factor (support practice factor) in the Revised Universal Soil Loss Equation (RUSLE) represents the impact of conservation practices that reduce the amount and rate of water runoff, thereby mitigating soil erosion. It is one of the five factors in the RUSLE model used to predict the average annual rate of erosion on field slopes.

The P-factor measures the effect of support practices on erosion control, particularly how these practices influence the pattern, direction, and speed of water runoff. It accounts for practices such as contour farming, strip cropping, and terracing, which are designed to slow down water flow and reduce erosion.

Historically, the P-factor has been estimated through field observations and interpretation of aerial photographs. Modern methods involve the use of high-resolution satellite imagery and GIS-based land use/land cover (LULC) maps to assign P-factor values.

The P-factor is calculated using the widely used formula: $0{,}2 + 0{,}03 \times S$

where *S* is the slope steepness in percent.

4. CLASSIFICATION

Following a detailed examination of the indicators used to assess ecosystem degradation in post-mining areas, this chapter introduces a structured classification system designed to categorize the levels of degradation based on their impact on future land usability. Utilizing the insights gained from the indicators, this classification system delineates the conditions of the terrain and soil into four distinct classes, each reflecting a different potential for recovery and reuse.

Class 1 encompasses areas where ecosystems show no signs of degradation and maintain their original condition. These ecosystems retain their full functionality and are capable of supporting both existing and planned land uses without any need for intervention. This class signifies that the ecosystems have either naturally preserved their vitality and ecological processes or have successfully undergone reclamation to meet or exceed the original environmental standards. As a result, these areas can sustain biodiversity, natural resource cycles, and ecosystem services seamlessly, contributing positively to the surrounding environment. **Class 2** represents areas where the parameters are degraded compared to the optimal condition, but these areas do not require reclamation intervention as the degradation does not significantly restrict the land's utility for intended purposes. **Class 3** includes areas that are not phytotoxic, excluded, or hazardous; however, they may benefit from reclamation of the upper horizon of the terrain or application of reclamation additives to enhance usability. **Class 4** encompasses areas with severe degradation to the point of being phytotoxic, excluded, or hazardous, requiring fundamental modifications to the terrain or soil structure, such as overlaying with suitable reclamation additives to restore land usability.

This classification framework (Tab. 7) is essential not only for guiding remediation and management strategies but also for prioritizing areas based on the severity of degradation and the complexity of restoration required. By categorizing the degree of impact on future land use, stakeholders can more effectively allocate resources and implement targeted interventions that promote ecological recovery and sustainable development.

Tab. 7. Classification of Ecosystem Degradation

Ecosystem element		Class 1 (No Degradation or Achievement of Reclamation Goal)	Class 2 (Degradation without Need for Reclamation)	Class 3 (Recommended Reclamation Intervention)	Class 4 (Necessary Fundamental Modification)
LANDSCAPE		The landscape retains its natural form and functionality, showing no signs of degradation. It continues to support the original ecosystem processes and biodiversity as intended or has been restored to achieve these conditions through successful reclamation practices.	Landscape shows slight alterations but retains functionality without needing reclamation.	Landscape changes suggest minor disrupt-tions; reclamation of terrain shape or appli-cation of reclamation additives can be recommended.	Significant landscape degradation requiring fundamental modifica-tions, such as overlaying with suitable reclamation additives to restore functionality.
SOIL	Geochemistry	The soil maintains its original chemical properties without any contamination. It supports natural biological processes and fosters a stable environment for plant growth and wildlife, reflecting a successful avoidance of degradation or effective reclamation	Soil shows minor chemical alterations not requiring intervention.	Soil chemistry indicates non-phytotoxic levels, but enhancement through additives could improve conditions.	Soil contamination reaches phytotoxic levels, necessitating extensive soil treatment or replacement to mitigate hazards and restore quality.
	Geotechnics	Soil structure and stability are intact, ensuring continued support for natural processes and land use without any alterations. This stability indicates that the soil has either remained undisturbed and preserved its ecological integrity or has been effectively restored to match or improve upon its original condition.	Minor geotechnical variations present; no immediate reclamation needed.	Moderate geotechnical disruption suggests benefits from corrective measures like soil amendment or contouring.	Severely compromised soil structure with high erosion risk or instability, requiring comprehensive reclamation to ensure safety and usability.

5. EXAMPLES OF MAPPING DEGRADED LAND IN POST-MINING AREAS

5.1. Areas of concern in Upper Silesian Coal Basin, PL

SOŚNICA Coal Mine, Gliwice Poland

The area of active coal mine Sośnica is the first case study, where degradation and severe mining impacts were defined. Area of degraded land is an active waste heap with natural succession, and brownfield which is the area where mining facilities (shafts, buildings and mining plant) are currently under operation.

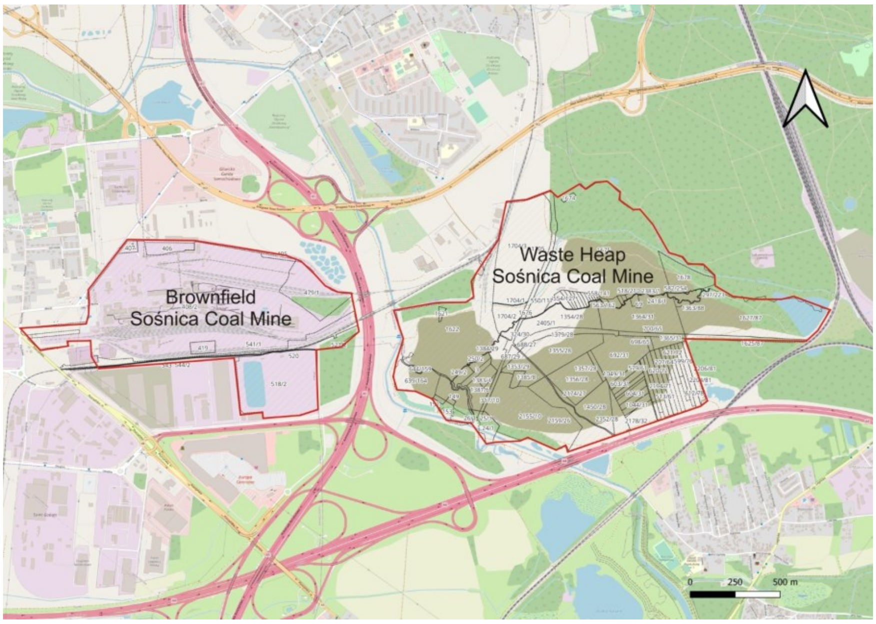

Fig. 9. Location of brownfield and waste heap, Sośnica Coal Mine

BOLESŁAW ŚMIAŁY Coal Mine, Łaziska Poland

The area of active coal mine Bolesław Śmiały is the case study, where degradation and severe mining impacts were defined. Area of degraded land is a waste heap already with cultivated surface, and brownfield which is the area where mining facilities (shafts, buildings and mining plant) - currently under operation.

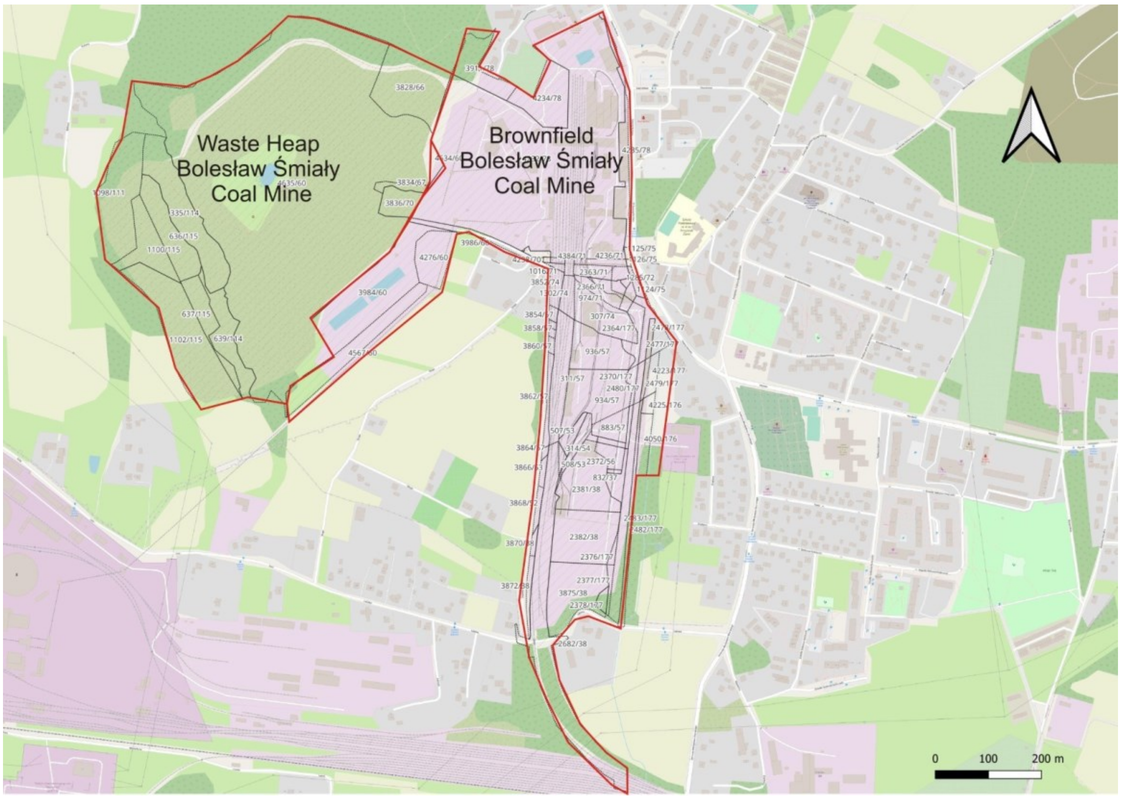

Fig. 10. Location of brownfield and waste heap, Bolesław Śmiały Coal Mine

WUJEK Coal Mine, Katowice Poland

The area of active coal mine Wujek is the case study, where up to now closure process has started. Area of degraded land is a brownfield which is the area where mining facilities (shafts, buildings and mining plant) - currently under operation and mine water pond (tailing) which already is not used for sedimentation process.

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Fig. 11. Location of brownfield and mine water pond, Wujek Coal Mine

5.1.1. Type of post-mining area: PRE-MINING BROWNFIELD

Considering the degradation factors and specific features of areas of concern, assessment of degradation as well as chosen indicators of possible degradation it is important to note that mining areas are not monitored frequently in that scope. Parameters of degradation such as contamination of soils, LSA, NDVI, NDMI are quite simple to assess using available tools such as satellite imaginary or maps of land development. Therefore for each areas of concern relevant indicators were calculated and a defined degree of land degradation was set out, based on thresholds proposed in Annex II table. Below there is description of related factors with necessary calculations and assessment.

- **Land degradation:** stability loss
- **Description:** slope stability is key indicator of safety, maintenance costs and potential for reuse of the site (risk of loss safety in static and erosion potential of the slopes)
- **Indicator:** Angle of slope
- **Methods**: Slope determined using DTM (digital terrain model)
- **Source of data:** https://mapy.geoportal.gov.pl/
- **Results:** The analysed areas of coal mines that will soon be extinguished (pre-mining brownfield) are characterised by a predominance of flat terrain. The highest proportion of sloping terrain that may restrict economic use and cause erosion problems was identified within Bolesław Śmiały Coal Mine. The results of the percentage of areas with each land degradation class are summarized in the table below. An exemplary visualization of the degradation of the site in terms of gradients is shown on the figure below.
- **Indicator evaluation:** Angle of slope (AS) is one of the key determinants (predisposing factor) for the occurrence of slope instability. The calculation method using DTM, makes it possible to calculate the index for extensive areas with relatively little effort. In order to comprehensively determine the stability of high slope terrains, it is necessary to analyse in detail other factors influencing slope stability such as the type of material stored, degree of compaction, vegetation cover, etc.

Tab. 8. Participation of degree of land degradation in terms of potential stability loss on analysed pre-mining brownfield

Degree of land degradation	Threshold value	Participation [%]		
		Bolesław Śmiały Coal Mine	Sośnica Coal Mine	Wujek Coal Mine
Class 4 (Necessary Fundamental Modification)	AS > 34° (67,45%)	10,2	4,7	6,5
Class 3 (Recommended Reclamation Intervention)	AS >26° (48,8%)	8,2	4,0	3,3
Class 2 (Degradation without Need for Reclamation)	AS> 15° (26,79%)	19,0	12,1	9,1
Class 1 (No Degradation or Achievement of Reclamation Goal)	AS < 5° (5.23%)	62,6	79,2	81,1

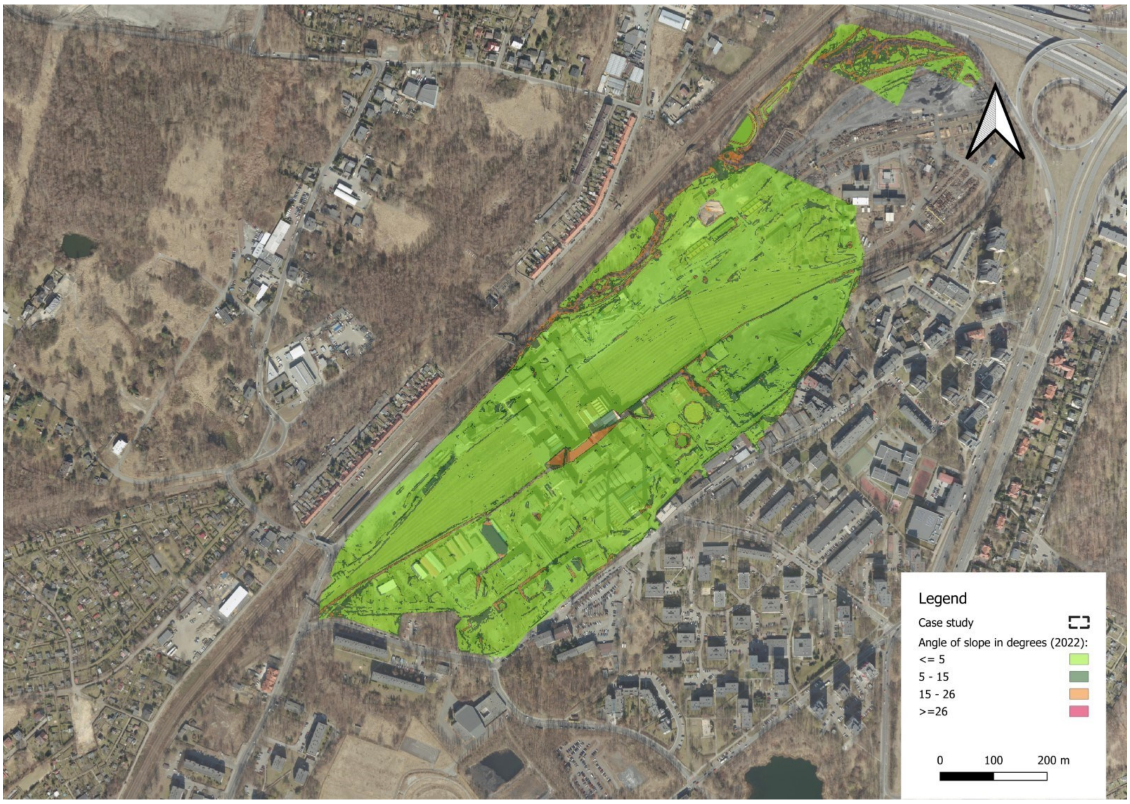

Fig. 12. Participation of degree of land degradation in terms of potential stability loss on Wujek Coal Mine

- **Soil degradation:** Contamination of soil
- **Description:** Current and past land use, including in particular the location of plants and installations where harmful substances are used or stored, determines the risk of soil contamination. Information on accidents which have or could have caused soil contamination, and field investigations of soil quality confirming the presence of such contamination have to be also collected (if available). Soil contamination has significant impact on safety, reclamation and remediation costs and the potential for redevelopment of such post-mine sites
- **Indicator: Risk of soil contamination**
- **Methods**: delineation of areas with confirmed or potential contamination on the basis of available data (orthophotomap, mine plan, list of accidents, historical data)
- **Sorce of data:** orthophotomap,

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- **Results:** Sośnica Waste Heap characterised by a relatively low of around 50m and a significant proportion of low-slope areas (50,1%). Slopes of more than 26 degrees is below 25% of the heap's area. The relative height of the spoil heap is about 90 and the relief is characterised by a predominance of slopes of more than 74 % one percent. Flat terrain constitutes only the analysed area (11.7).
- **Indicator evaluation:** Current and past land use only identifies the risk of land contamination. Information confirming soil contamination is mostly unavailable. Field survey of soil contamination is necessary to confirm or exclude soil contamination post mining pre-brownfields.

Tab. 9. Participation of degree of land degradation in terms of risk of soil contamination on analysed pre-mining brownfield

Degree of land degradation	Threshold value	Participation [%]		
		Bolesław Śmiały Coal Mine	Sośnica Coal Mine	Wujek Coal Mine
Class 4 (Necessary Fundamental Modification)	Confirmed land contamination limiting redevelopment of the site (remediation required)	0,0	0,0	0,0
Class 3 (Recommended Reclamation Intervention)	Probability of site contamination limiting re-use of the site (higher environmental risk installations)	15,9	3,1	8,0
Class 2 (Degradation without Need for Reclamation)	Probability of increased concentrations of pollutants due to the industrial nature of the site	84,1	96,9	92,0
Class 1 (No Degradation or Achievement of Reclamation Goal)	Concentration of pollutants at environmental background level	0,0	0,0	0,0

Fig. 13. Participation of degree of land degradation in terms of potential contamination (Sośnica mine)

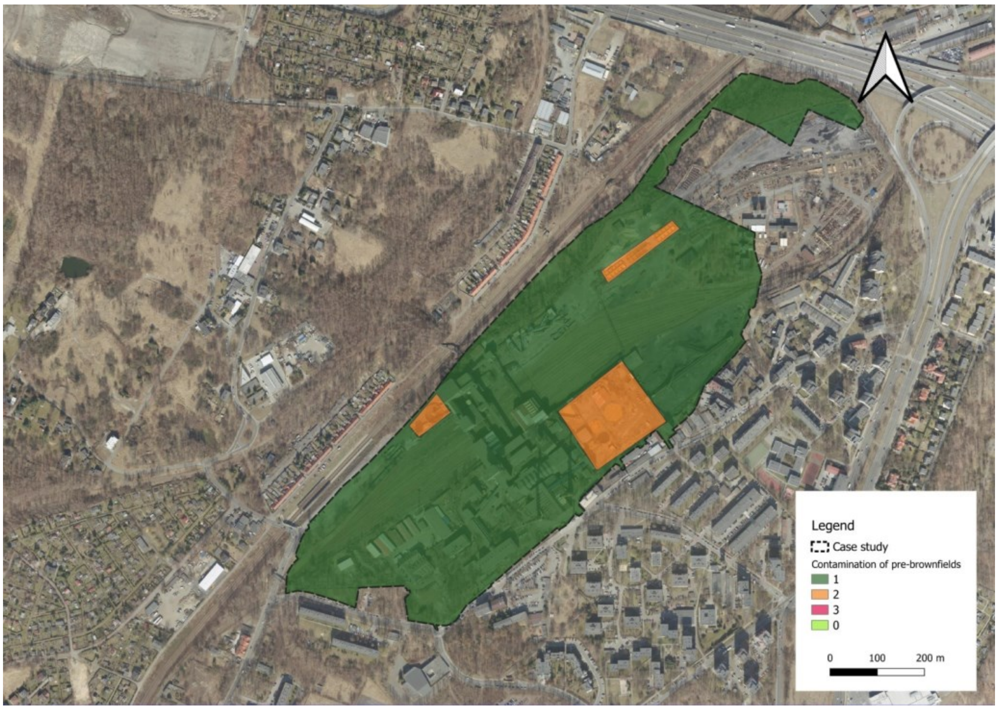

Fig. 14. Participation of degree of land degradation in terms of potential contamination (Wujek mine)

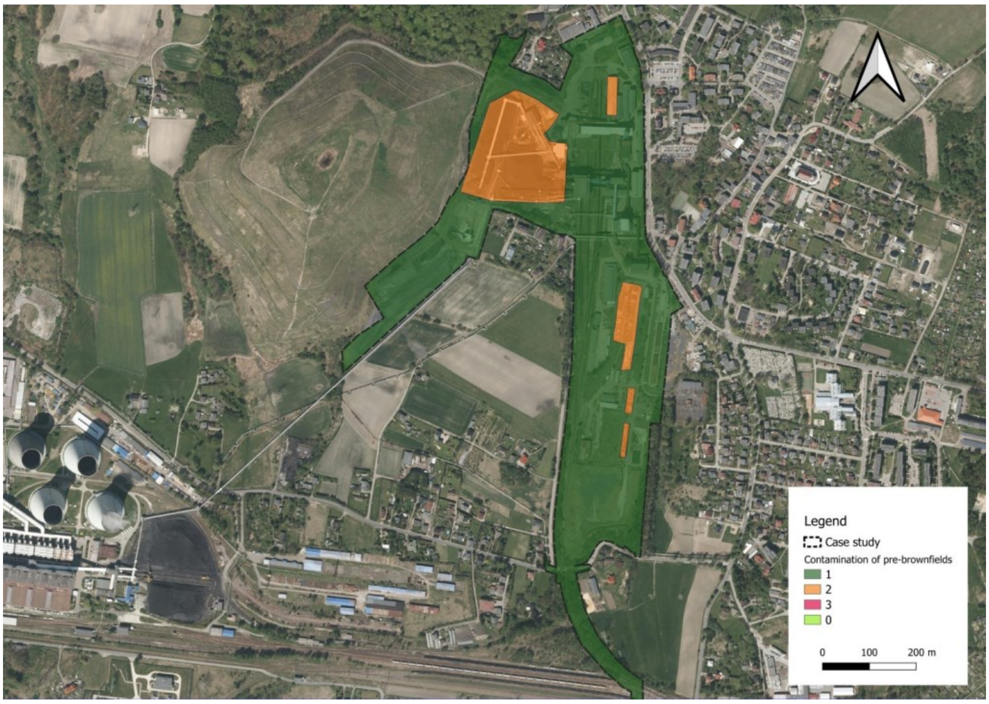

Fig. 15. Participation of degree of land degradation in terms of potential contamination (Bolesław Śmiały mine)

5.1.2. Type of post-mining area: WASTE HEAP

The area one active (Sośnica) and one reclamated waste heap (Skalny) located near the mines that will soon be extinguished (Sośnica Coal Mine and Bolesław Śmiały Coal mine) were analysed. A spoil tip (also called a boney pile, culm bank, gob pile, waste tip or bing) is a pile built of accumulated spoil – waste material removed during mining.

- **Land degradation: Thermal processes**

- **Description:** fires in the area of coal dumps (thermal processes) have a significant impact on environmental pollution, safety, maintenance costs, and the potential for reuse of such mine sites
- **Indicator:** Area of thermal processes
- **Methods**: Land Surface Temperature Differences determined using Landsat 8 satellite data
- **Source of data:** https://apps.sentinel-hub.com/eo-browser
- **Results:** Based on satellite data on 3 October 2023, areas with temperatures 4 Celsius degrees higher than the surrounding areas, were identified on both heaps analysed. Higher surface temperatures were found on the south-eastern steeply sloping slopes of the Skalny Dumps (T above 20 degrees). Places with temperatures as high as 16 were identified within non-vegetated parts of the Sośnica heap. Location of areas with elevated temperatures indicate that the identified differences in temperatures are most probably a result of solar heating of the dumps. The results obtained do not indicate the existence of thermal phenomena within the analysed objects. The results of the percentage of areas with each land degradation class are summarized in the table below. The visualization of the land surface temperature degradation of the site in terms of gradients is shown in the figure below.
- **Indicator evaluation:** The satellite's flight takes place around noon, and cloudless weather conditions are required to take a good quality picture. This makes satellite data not the most reliable source of information for identifying thermal processes. In order to confirm these risks, it is necessary to carry out measurements with thermal cameras directly in the field (manual measurement, measurement from a drone). The spatial resolution of the satellite images used (pixel size 10mx10m) allows the potential identification of only extensive and intensive thermal phenomena within the post mining hard coal heaps.

Tab. 10. Participation of degree of land degradation in terms of thermal processes on analysed pre-mining brownfield

Degree of land degradation	Threshold value	Participation [%]	
		Sośnica Waste Heap	Skalny Waste Heap
Class 4 (Necessary Fundamental Modification)	Area of thermal processes > 10 m^2	0	0
Class 3 (Recommended Reclamation Intervention)	Area of thermal processes > 10 -100 m^2	0	0
Class 2 (Degradation without Need for Reclamation)	Area of thermal processes > 10 m^2	0	
Class 1 (No Degradation or Achievement of Reclamation Goal)	Area of thermal processes = 0 m^2	100	100

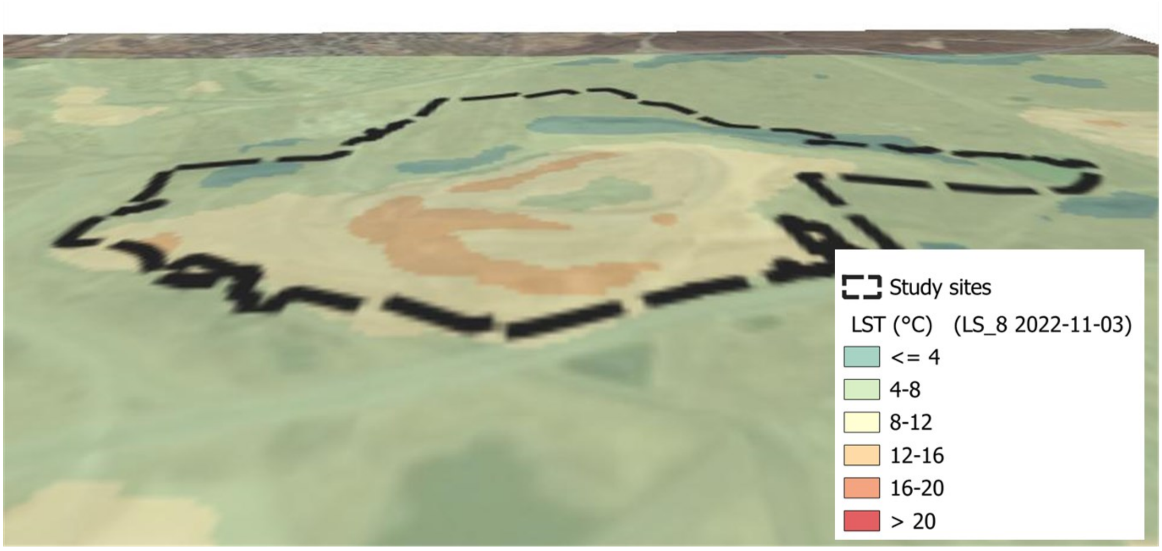

Fig. 16. The land surface temperature of Sośnica Waste Heap determined using Landsat 8 satellite data

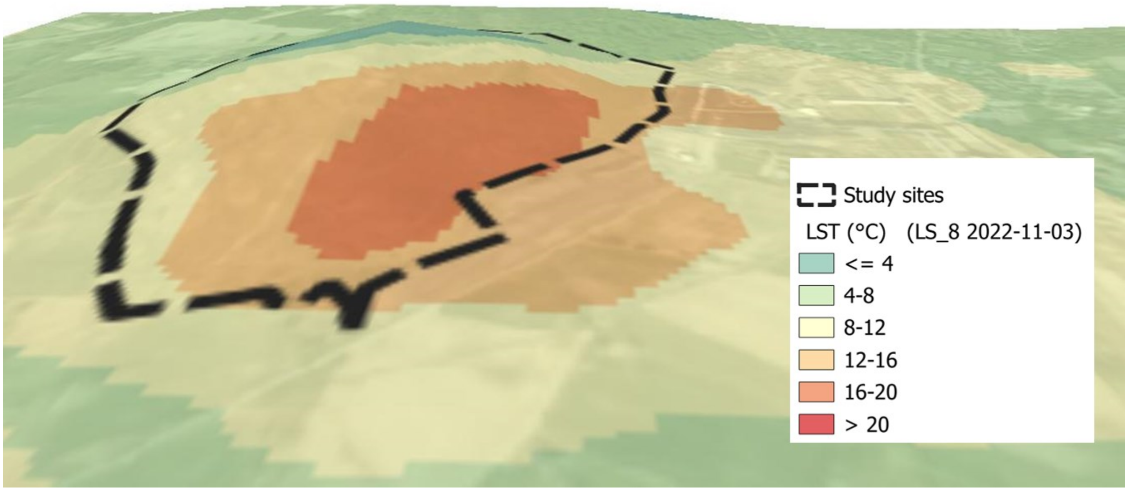

Fig. 17. The land surface temperature of Sośnica Waste Heap determined using Landsat 8 satellite data

- **Land degradation:** stability loss
- **Description:** slope stability is key indicator of safety, maintenance costs and potential for reuse of the site (risk of loss safety in static and erosion potential of the slopes)
- **Indicator:** Angle of slope
- **Methods**: Slope determined using DTM (digital terrain model)
- **Source of data:** https://mapy.geoportal.gov.pl/
- **Results:** Sośnica Waste Heap characterised by a relative height of around 50m and a significant proportion of low-slope areas (50,1%). Slopes of more than 26 degrees are below 25% of the heap's area. The relative height of the spoil heap is about 90 and the relief is characterised by a predominance of slopes of more than 74 % one percent. Flat terrain constitutes only the analysed area (11.7). The results of the percentage of areas with each land degradation class are summarized in the table below. An exemplary visualization of the degradation of the site in terms of gradients is shown in the figure below.
- **Indicator evaluation:** Angle of slope is one of the key determinants of the risk of slope instability. The calculation method used, using DTM, makes it possible to calculate the index for extensive areas with relatively little effort. In order to comprehensively determine the stability of high slope terrains, it is necessary to analyse in detail other factors influencing slope stability such as the type of material stored, degree of compaction, vegetation cover, etc.

Tab. 11. Participation of degree of land degradation in terms of potential stability loss on analysed pre-mining brownfield

Degree of land degradation	Threshold value	Participation [%]	
		Sośnica Waste Heap	Skalny Waste Heap
Class 4 (Necessary Fundamental Modification)	Angle of slope > 34° (67,45%)	5,4	22,7
Class 3 (Recommended Reclamation Intervention)	Angle of slope >26° (48,8%)	18,4	51,3
Class 2 (Degradation without Need for Reclamation)	Angle of slope > 15° (26,79%)	26,1	14,3
Class 1 (No Degradation or Achievement of Reclamation Goal)	Angle of slope < 5° (5.23%)	50,1	11,7

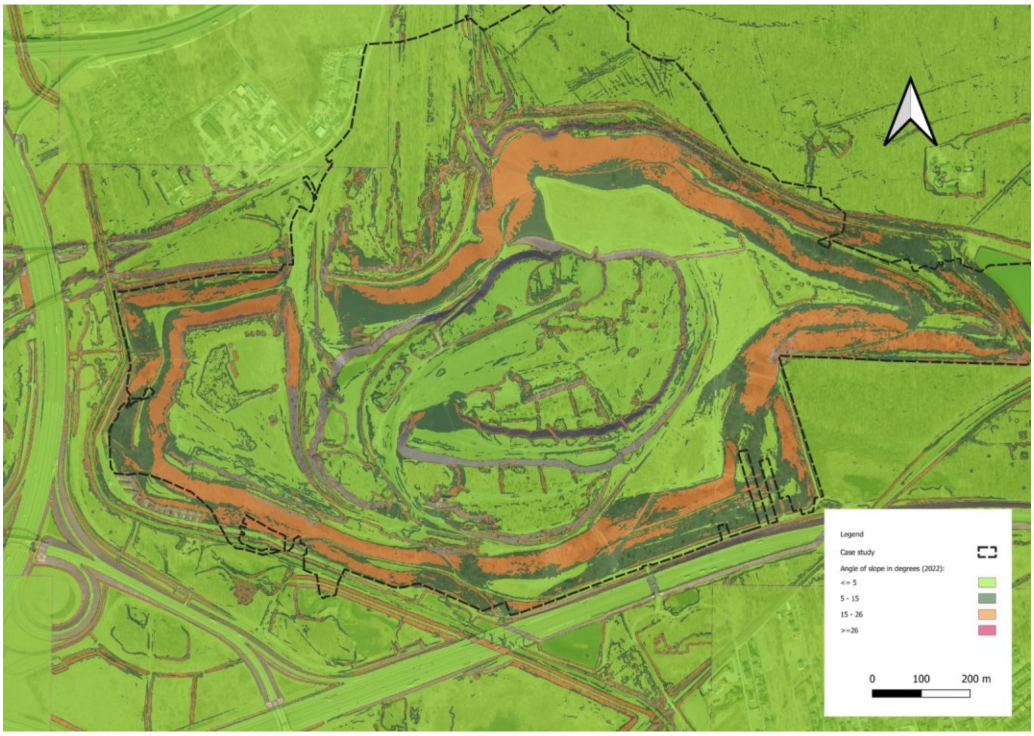

Fig. 18. Participation of degree of land degradation in terms of potential stability loss on Sośnica Waste Heap

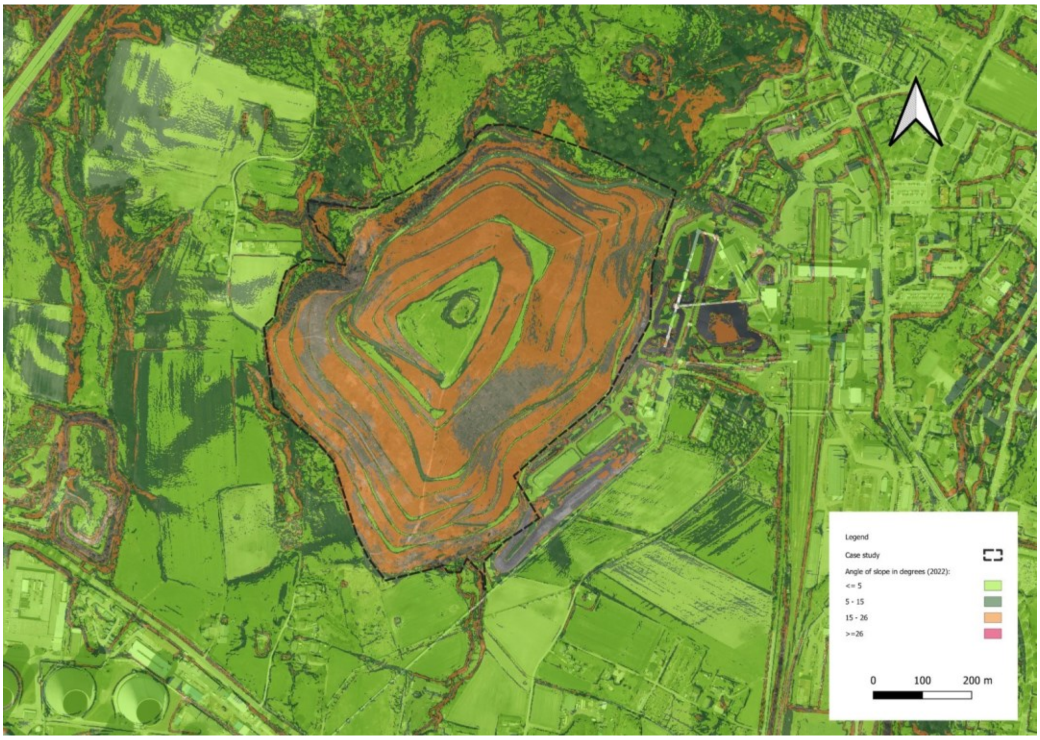

Fig. 19. Participation of degree of land degradation in terms of potential stability loss on Skalny Waste Heap

- **Land degradation**: Inappropriate condition for plant growth
- **Description:** Land Surface Albedo (LSA) quantifies the fraction of the sunlight reflected by the surface of the Earth. Surface albedo plays a controlling role in the surface energy budget, and albedo-induced radiative forcing has a significant impact on climate and environmental change. LSA plays an essential role in surface energy balance and carbon and water cycling. Surface albedo generally varies by land cover type for natural (e.g., wildwood) and artificial surfaces (e.g., buildings) and is also sensitive to various factors besides atmospheric and cloud conditions, such as soil–vegetation.

- **Indicator:** Land Surface Albedo (LSA)
- **Methods**: Calculation based on satellite images
- **Source of data:** Landsat 7 image, 27.07.2023
- **Results:** The LSA indicator shows great diversity in the areas analyzed. It reaches the lowest values for areas without vegetation and for areas where the vegetation cover is discontinuous. In the case of the Sośnica waste heap, low values are also identified in the part covered by surface water. The largest areas were classified as medium degradation. Only in the case of the Sośnica waste heap, 3.7% of the area reaches the reference status for this indicator. The results of the percentage of areas with each land degradation class are summarized in the table below Tab. An exemplary visualization of the degradation of the site in terms of gradients is shown in the figure below.
- **Indicator evaluation:** The LSA indicator is very useful for waste heaps. It enables to identifying areas without sufficient plant cover. What's more, the lack of buildings in these areas means that there is no distortion of the LSA value. Moreover, the area covered by surface water is a good reference point to verify the correctness of the LSA analysis performed.

Tab. 12. Participation of degree of land degradation in terms of inappropriate condition for plant growth on analysed waste heaps as a result of LSA indicator analysis

Degree of land degradation	Threshold value	% of area in category	
		Bolesław Śmiały Coal Mine	Waste Heap Sośnica Coal Mine
Class 4 (Necessary Fundamental Modification)	<0.07	17.4%	23.5%
Class 3 (Recommended Reclamation Intervention)	<0.11	59.0%	38.0%
Class 2 (Degradation without Need for Reclamation)	<0.15	21.2%	34.8%
Class 1 (No Degradation or Achievement of Reclamation Goal)	>0.15	0.0%	3.7%
average value for area:		0.09	0.10

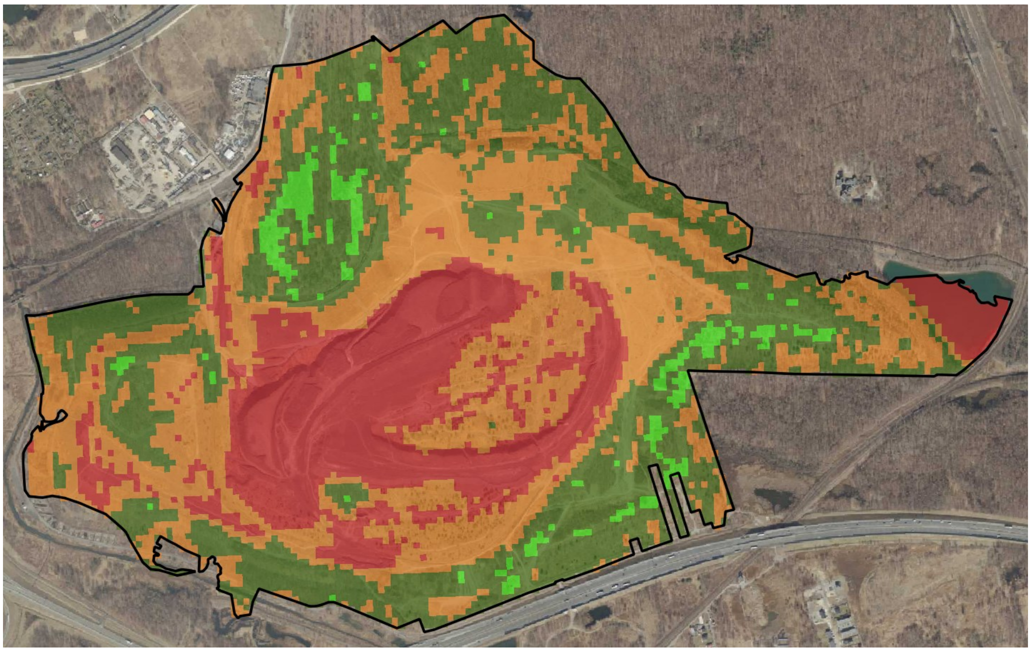

Fig. 20. LSA Indicator, Waste Heap Sośnica Coal Mine, 27.07.2023

- **Land degradation**: Inappropriate condition for plant growth
- **Description:** Normalized Difference Vegetation Index (NDVI) quantifies vegetation by measuring the difference between near-infrared (which vegetation strongly reflects) and red light (which vegetation absorbs). Healthy vegetation (chlorophyll) reflects more near-infrared (NIR) and green light compared to other wavelengths. But it absorbs more red and blue light. NDVI is widely used in agriculture, forestry, and ecology to monitor the growth and health of vegetation and to identify areas of stress or damage. NDVI values can also be used to map and classify vegetation types, and to detect changes in vegetation cover over time.
- **Indicator:** Normalized Difference Vegetation Index (NDVI)
- **Methods**: Calculation based on satellite images
- **Source of data:** Landsat 7 image, 27.07.2023
- **Results:** In the case of the Waste Heap Sośnica, there are clearly visible areas with no vegetation and areas with only residual vegetation cover. Areas classified as high and medium degraded occupy over 40% of its area. The Skalny Waste Heap (Bolesław Śmiały Coal Mine) is dominated by an area of low degradation, and over 15% of the area is above the reference status, which indicates a high level of biomass and good condition of vegetation. There are only small areas where the NDVI index is lower than 0.4, which indicates a poor condition of the plant cover. The results of the percentage of areas with each land degradation class are summarized in the table below. An exemplary visualization of the degradation of the site in terms of gradients is shown in the figure below.
- **Indicator evaluation:** The NDVI indicator for the analyzed areas shows a very good correlation with vegetation cover. In the case of heaps, it can be used to monitor the condition of vegetation and the extent of its occurrence. An important factor in such monitoring will be the period for which the results will be compared - it is important to compare satellite images for the same phase of plants vegetation.

Tab. 13. Participation of degree of land degradation in terms of inappropriate condition for plant growth on analysed waste heaps as a result of NDVI indicator analysis

Degree of land degradation	Threshold value	% of area in category	
		Bolesław Śmiały Coal Mine	Waste Heap Sośnica Coal Mine
Class 4 (Necessary Fundamental Modification)	<0.05	0.0%	11.4%
Class 3 (Recommended Reclamation Intervention)	<0.4	4.1%	30.6%
Class 2 (Degradation without Need for Reclamation)	<0.6	80.4%	56.8%
Class 1 (No Degradation or Achievement of Reclamation Goal)	>0.6	15.5%	1.2%
	average value for area:	0.51	0.36

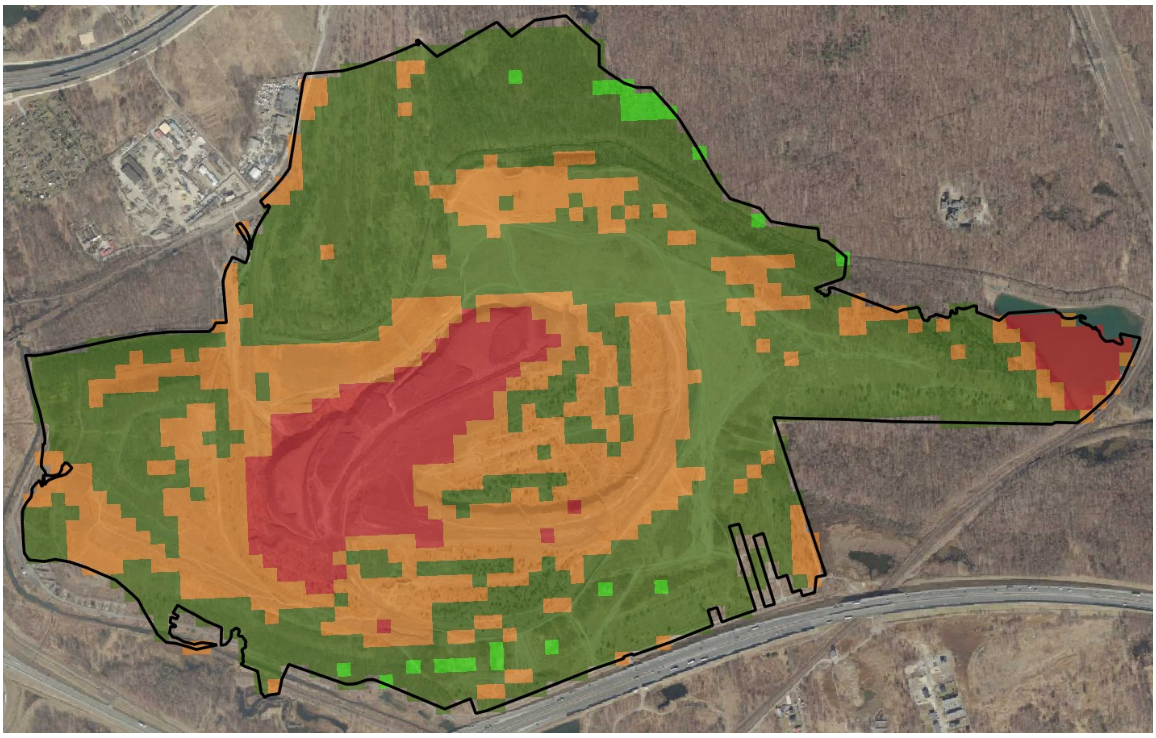

Fig. 21. NDVI Indicator, Waste Heap Sośnica Coal Mine, 27.07.2023

- **Land degradation**: Inappropriate condition for plant growth
- **Description:** Normalized Difference Moisture Index (NDMI) detects moisture levels in vegetation using a combination of near-infrared (NIR) and short-wave infrared (SWIR) spectral bands. It is a reliable indicator of water stress in crops. The SWIR band reflects changes in both the vegetation water content and the spongy mesophyll structure in vegetation canopies, while the NIR reflectance is affected by leaf internal structure and leaf dry matter content but not by water content. The combination of the NIR with the SWIR removes variations induced by leaf internal structure and leaf dry matter content, improving the accuracy in retrieving the vegetation water content.
- **Indicator:** Normalized Difference Moisture Index (NDMI)
- **Methods**: Calculation based on satellite images
- **Source of data:** Landsat 7 image, 27.07.2023
- **Results:** The NDMI values for both heaps correspond to areas of high degradation, which indicates low water content in the plant cover. This indicates large water deficits in the vegetation cover in the analyzed areas. In order to determine the humidity of the habitat and the availability of water for plants, it is necessary to monitor the value of this indicator for different periods in relation to the precipitation, as a significant variability in the value of this indicator is expected over time. The results of the percentage of areas with each land degradation class are summarized in the table below. An exemplary visualization of the degradation of the site in terms of gradients is shown in the figure below.
- **Indicator evaluation:** The NDMI indicator can be used to monitor the humidity of the plant cover on heaps, indicating areas exposed to rapid drying, which creates weak conditions for vegetation growth. This indicator should always be interpreted in relation to the value of the NDVI indicator determining the state of plant cover. The usefulness of the indicator should be confirmed by analyzing satellite data from other periods.

Tab. 14. Participation of degree of land degradation in terms of inappropriate condition for plant growth on analysed waste heaps as a result of NDMI indicator analysis

Degree of land degradation	Threshold value	% of area in category	
		Bolesław Śmiały Coal Mine	Waste Heap Sośnica Coal Mine
Class 4 (Necessary Fundamental Modification)	<0.3	85.7%	59.5%
Class 3 (Recommended Reclamation Intervention)	<0.35	8.2%	13.1%
Class 2 (Degradation without Need for Reclamation)	<0.7	6.1%	27.4%
Class 1 (No Degradation or Achievement of Reclamation Goal)	>0.7	0.0%	0.0%
average value for area:		0.15	0.23

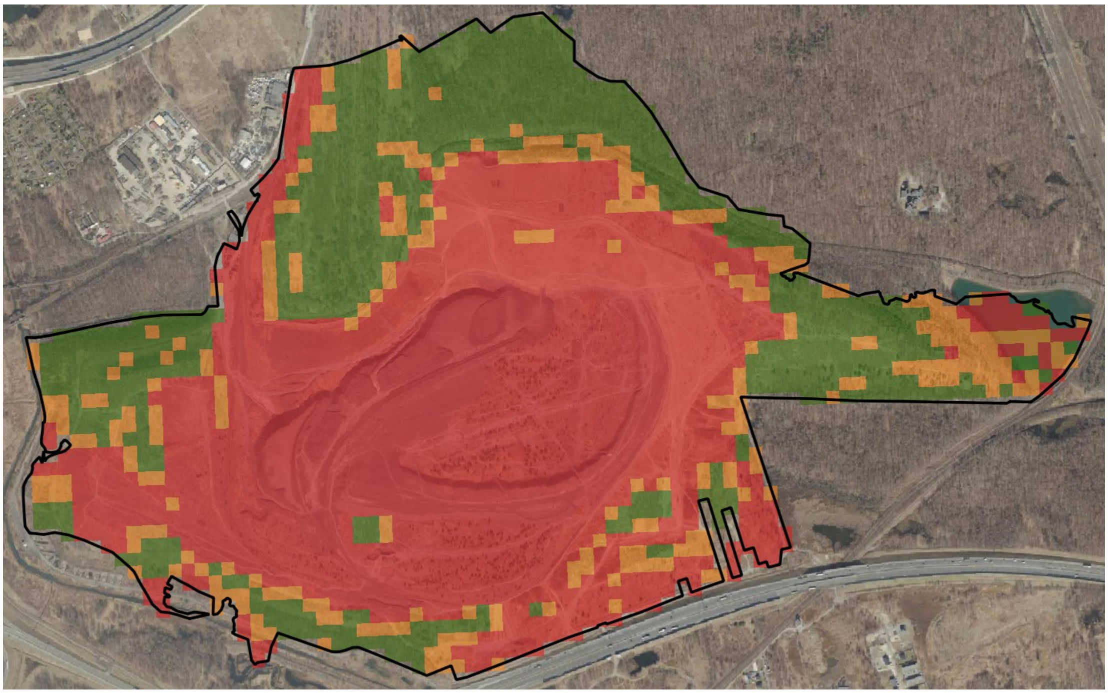

Fig. 22. NDMI Indicator, Waste Heap Sośnica Coal Mine, 27.07.2023

5.1.3. Type of post-mining area: Tailing

As part of the indicator tasting, the non-operational tailings located near the Wujek Coal Mine were analysed. The area is partially reclaimed (after the removal of accumulated sediment. Tailings are the left-over materials from the processing of mined ore. They consist of ground rock, unrecoverable and uneconomic metals, chemicals, organic matter and effluent from the process used to extract the desired products from the resources (coal, ore etc.). Accumulated in constructed tailing dams inevitably disturb landscapes and surrounding areas.

- **Land degradation:** stability loss
- **Description:** slope stability is key indicator of safety, maintenance costs and potential for reuse of the site (risk of loss safety in static and erosion potential of the slopes)
- **Indicator:** Angle of slope
- **Methods**: Slope determined using DTM (digital terrain model)

- **Source of data:** https://mapy.geoportal.gov.pl/
- **Results:** Wujek tailing characterised by a relative deep area (2m) with a significant proportion of low-slope areas (71,2%). Slopes of more than 26 degrees are below 23% of the tailing area. The results of the percentage of areas with each land degradation class are summarized in the table below. A visualization of the degradation of the site in terms of gradients is shown in the figure below.
- **Indicator evaluation:** Angle of slope is one of the key determinants of the risk of slope instability. The calculation method used, using DTM, makes it possible to calculate the index for extensive areas with relatively little effort. In order to comprehensively determine the stability of high slope terrains, it is necessary to analyse in detail other factors influencing slope stability such as the type of material stored, degree of compaction, vegetation cover, etc.

Tab. 15. Participation of degree of land degradation in terms of potential stability loss post-mining Wujek tailings

Degree of land degradation	Threshold value	% of area in category
Class 4 (Necessary Fundamental Modification)	AS > 34° (67,45%)	5,1
Class 3 (Recommended Reclamation Intervention)	AS >26° (48,8%)	17,7
Class 2 (Degradation without Need for Reclamation)	AS> 15° (26,79%)	20,6
Class 1 (No Degradation or Achievement of Reclamation Goal)	AS < 5° (5.23%)	56,6

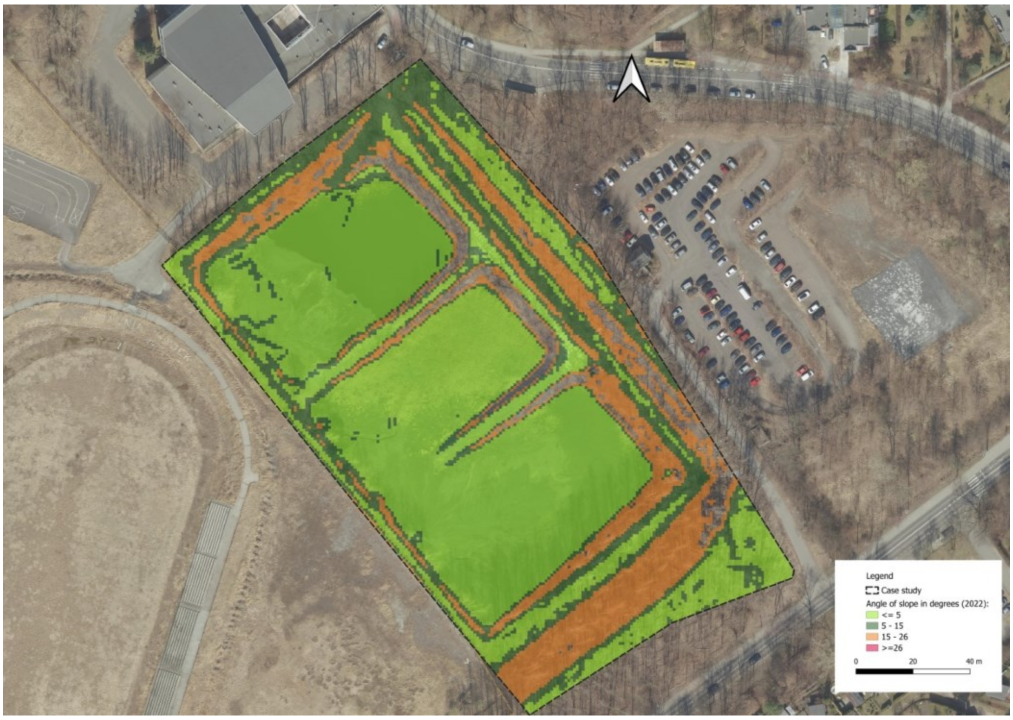

Fig. 23. Participation of degree of land degradation in terms of potential stability loss on post-mining

- **Land degradation**: Inappropriate condition for plant growth
- **Indicator:** Land Surface Albedo (LSA)
- **Methods**: Calculation based on satellite images
- **Source of data:** Landsat 7 image, 11.10.2023

- **Results:** The LSA indicator shows great diversity in the analyzed area. It reaches the lowest values for areas without vegetation and for areas where the vegetation cover is discontinuous. In the case of the Wujek tailing, the largest areas were classified as high degradation. Only in northern part of the area small terrain has light degradation status. The results of the percentage of areas with each land degradation class are summarized in the table below Tab. An exemplary visualization of the degradation of the site in terms of gradients is shown in the figure below.
- **Indicator evaluation:** The LSA indicator could be useful for waste heaps. It allows to identify areas without sufficient plant cover. Similar as on waste heaps, the lack of buildings means that there is no distortion of the LSA value. Further data should be analyzed to confirm the usefulness of LSA indicator at tailing areas.

Tab. 16. Participation of degree of land degradation in terms of inappropriate condition for plant growth on Wujek tailing as a result of LSA indicator analysis

Degree of land degradation	Threshold value	% of area in category
Class 4 (Necessary Fundamental Modification)	<0.07	61.5%
Class 3 (Recommended Reclamation Intervention)	<0.11	34.9%
Class 2 (Degradation without Need for Reclamation)	<0.15	3.7%
Class 1 (No Degradation or Achievement of Reclamation Goal)	>0.15	0.0%
average value for area:	0.064	

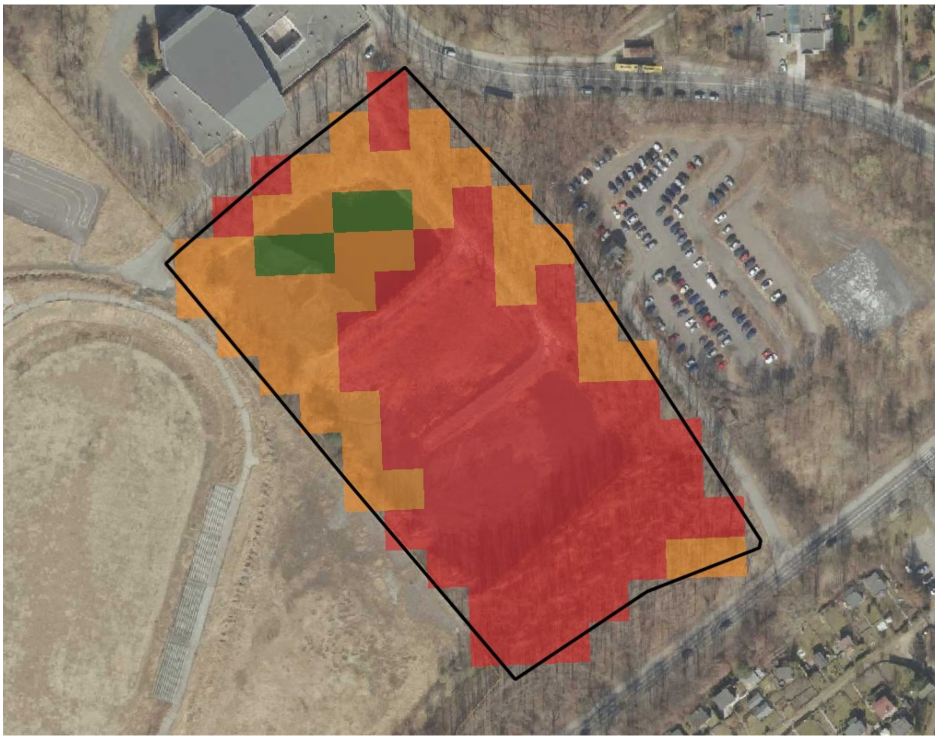

Fig. 24. LSA Indicator, Wujek tailing, 11.10.2023

- **Land degradation**: Inappropriate condition for plant growth
- **Indicator:** Land Surface Albedo (LSA)
- **Methods**: Calculation based on satellite images

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- **Source of data:** Landsat 7 image, 11.10.2023
- **Results:** In the case of the Wujek tailing most of the area has only residual vegetation cover. Areas classified as high and medium degraded occupy 70% of its area. Near the borders of the area, the indicator values are higher, which is related to the presence of trees. The results of the percentage of areas with each land degradation class are summarized in the table below Tab. An exemplary visualization of the degradation of the site in terms of gradients is shown in the figure below.
- **Indicator evaluation:** As the analyzed area has been significantly transformed the NDVI indicator should be verified with existing state of plant cover. In order to establish the correctness of the correlation between the indicator values and field observations are needed. An important factor in such monitoring will be the period for which the results will be compared - it is important to compare satellite images for the same phase of plants vegetation.

Tab. 17. Participation of degree of land degradation in terms of inappropriate condition for plant growth on Wujek tailing as a result of NDVI indicator analysis

Degree of land degradation	Threshold value	% of area in category
Class 4 (Necessary Fundamental Modification)	<0.05	2.8%
Class 3 (Recommended Reclamation Intervention)	<0.4	72.2%
Class 2 (Degradation without Need for Reclamation)	<0.6	25.0%
Class 1 (No Degradation or Achievement of Reclamation Goal)	>0.6	0.0%
average value for area:	0.31	

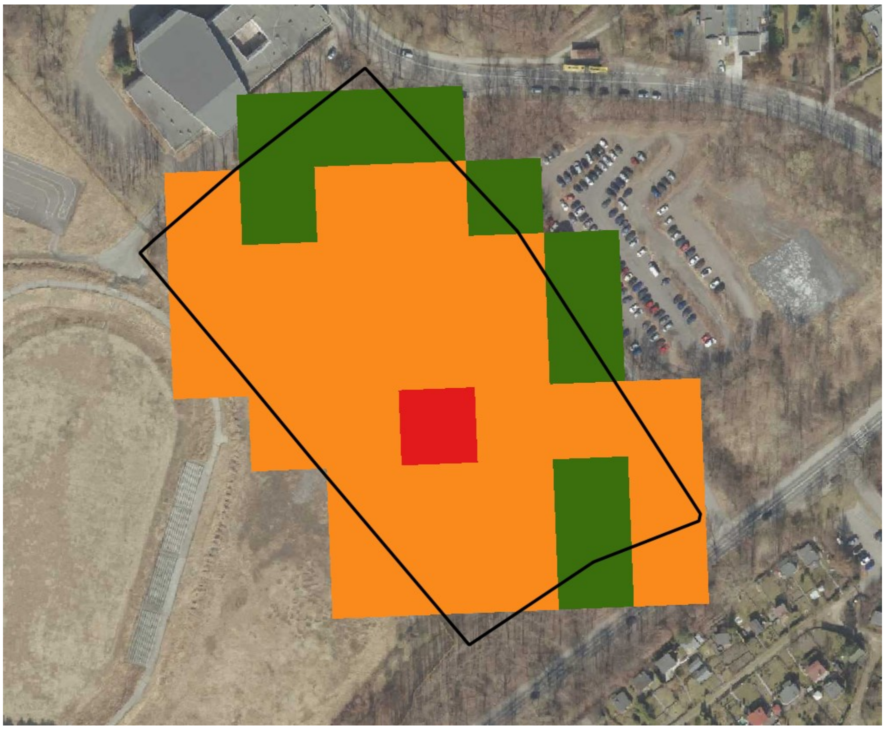

Fig. 25. NDVI Indicator, Wujek tailing, 11.10.2023

- **Land degradation**: Inappropriate condition for plant growth
- **Indicator:** Normalized Difference Moisture Index (NDMI)

- **Methods**: Calculation based on satellite images
- **Sorce of data:** Landsat 7 image, 11.10.2023
- **Results:** The NDMI values for analyzed area indicates large water deficits in the vegetation cover. In order to determine the humidity of the habitat and the availability of water for plants, it is necessary to monitor the value of this indicator for different periods in relation to the precipitation. The results of the percentage of areas with each land degradation class are summarized in the table below Tab. An exemplary visualization of the degradation of the site in terms of gradients is shown in the figure below.
- **Indicator evaluation:** The NDMI indicator can be used to monitor the humidity of the plant cover, indicating areas exposed to rapid drying. This indicator should always be interpreted in relation to the value of the NDVI indicator and should be verified with the existing state of plant cover. In order to establish the correctness of the correlation between the NDMI, NDVI land field observations are needed. The usefulness of the indicator should be confirmed by analyzing satellite data from other periods.

Tab. 18. Participation of degree of land degradation in terms of inappropriate condition for plant growth on Wujek tailing as a result of NDMI indicator analysis

Degree of land degradation	Threshold value	% of area in category
Class 4 (Necessary Fundamental Modification)	<0.3	100.0%
Class 3 (Recommended Reclamation Intervention)	<0.35	0.0%
Class 2 (Degradation without Need for Reclamation)	<0.7	0.0%
Class 1 (No Degradation or Achievement of Reclamation Goal)	>0.7	0.0%
average value for area:	0.14	

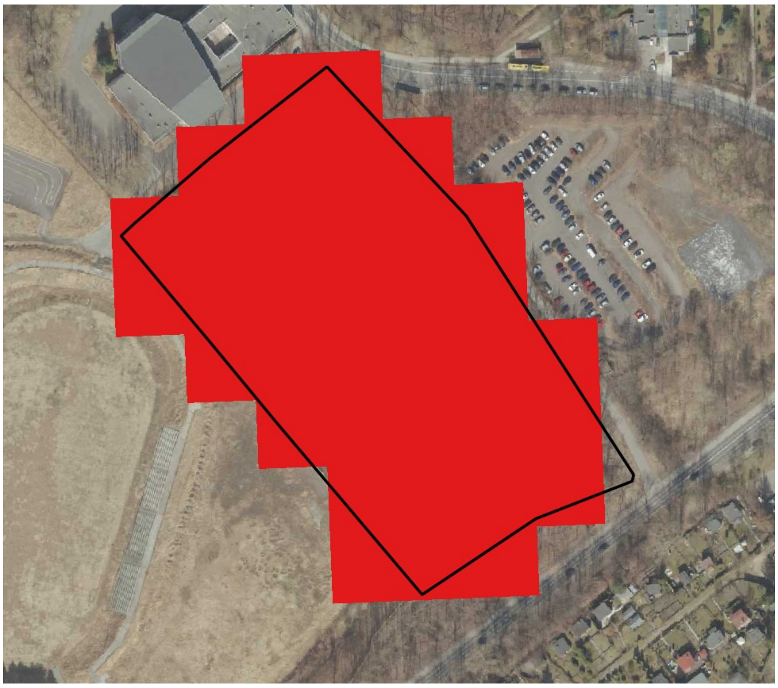

Fig. 26. NDMI Indicator, Wujek tailing, 11.10.2023

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Summary of satellite-source indicators

Tab. 19. Summary of satellite-source indicators

Area of concern	Land Surface Albedo (LSA)	Normalized Difference Vegetation Index (NDVI)	Normalized Difference Moisture Index (NDMI)
Waste Heap Bolesław Śmiały Coal Mine	Class 3	Class 1	Class 4
Waste Heap Sośnica Coal Mine	Class 3	Class 3	Class 4

5.2. Area of concern in Konin Lignite Basin, PL

5.2.1. Type of post-mining area – Dump

The internal heap within the Jóźwin mine at the current stage is an excellent test site for indicators to determine the degree of degradation in terms of vegetation cover and its condition. To measure this, a remote sensing indicator widely used in this type of research, the NDVI, was used. Below is a spatial visualization of this indicator in the area of interest, as well as numerical data showing the distribution of NDVI values for each range. The calculations were performed on multispectral satellite data from the Sentinel-2 mission

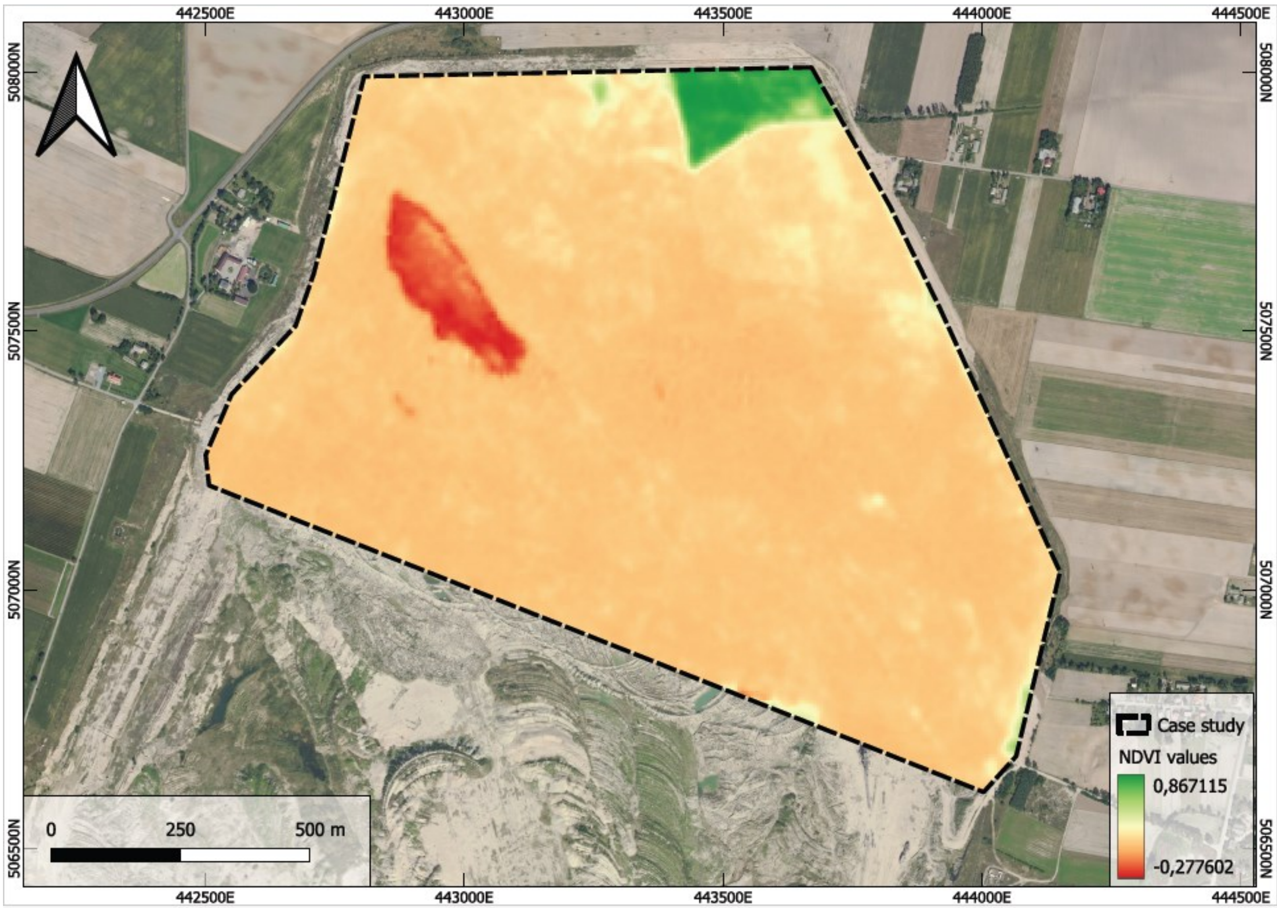

Fig. 27. Spatial visualization NDVI values on case study. Coordinate system – EPSG:2180

Tab. 20. Numerical values of NDVI on case study

NDVI value	pixels	m2	%
0>	1 207	4 4991.66	3.06
0	5	186.38	0.01
0 - 0.1	17 237	642 519.61	43.74
0.1 - 0.2	18 140	676 179.48	46.03
0.2 - 0.3	1 438	53 602.32	3.65
0.3 - 0.4	244	9 095.25	0.62
0,4<	1 141	42 531.47	2.90
sum	**39 412**	**1 469 106.15**	**100.00**

The depiction shows a place with a extremely low value - it is a water reservoir. In addition, the opposition site with high values is visible, where plantings have already been carried out.

The numerical values clearly confirm the need to classify the site as 'Necessary Fundamental Modification', as seen in the visualization. This is because almost 90% of the entire area is depicted as devoid of vegetation, or with residual vegetation (values below 0.2)

5.2.1. Pątnów Mining Site – Angle of slope

In this study, a comprehensive examination of the "angle of slopes" indicator was conducted at various locations within the Pątnów Mining Site. This site, along with its surrounding areas, offers a unique perspective on the environmental impacts associated with mining activities, particularly through the analysis of land stability and erosion potential influenced by slope gradients. The focus of the investigation includes the main operational areas of the Pątnów Mining Site, excluding the broader Pątnów Mining Area. Additionally, the buffer zone surrounding the Pątnów Mining Site serves as a reference point, allowing for comparative analysis against areas directly affected by mining operations.

In the interpretation of land suitability in terms of slope and potential usability, it is proposed to apply the suggestions from the study by Paulo (2008, p. 14) and the references by Chodak (2013, p. 37). According to the guidelines of these authors, the following classification of land usability based on slope inclination can be used:

- < 5° - suitability for agricultural use (arable land);
- < 15° - suitability for agricultural use (pastures);
- < 35° - suitability for forestry use;
- ≤ 60° - conditional suitability for forestry use (due to increased soil cover erosion);
- 60° - the necessity of slope mitigation and soil reclamation before utilization.

The analyses were conducted using the most current series of DEM sheets in the EVRF2007 European vertical reference frame and the highest available resolution. The analyzed area included the entire mining area, encompassing all activities directly related to the extraction and processing of minerals, as well as the mining site, where the impact of mining activities on local terrain morphology was anticipated. Additionally, a buffer zone around the mining area, equivalent in size to the mining area, was analyzed as a comparative area with a terrain morphology unaffected by mining activities (Fig. 28).

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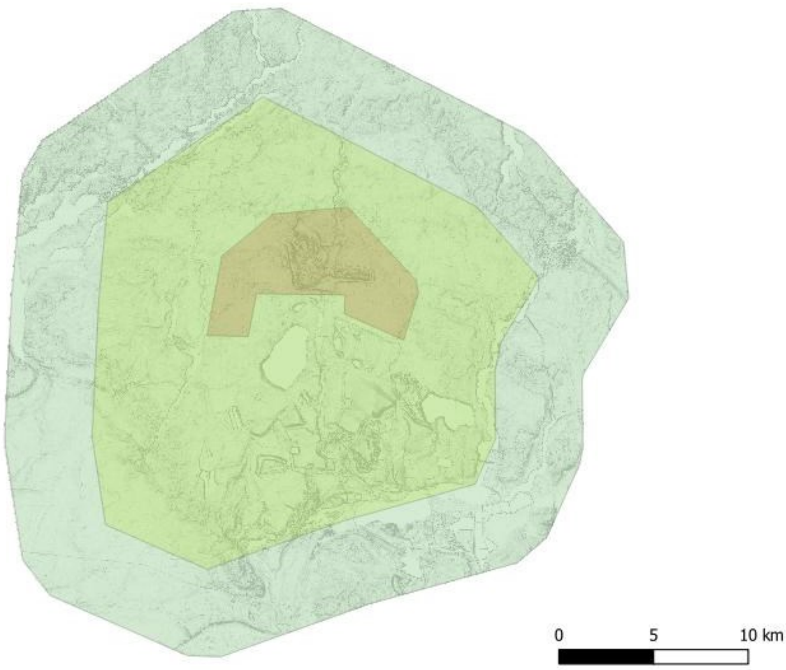

Fig. 28. Terrain morphology analysis area for the Pątnów Region (shaded relief map based on DEM). The area marked in red represents the Pątnów mining area, in green - the Pątnów mining site, in blue - the buffer zone of the mining site

Comparisons of slope inclination were made using built-in analytical tools for raster layers in GIS software. As a result, a pixel distribution with a color range representing the defined slope inclination values in degrees or percentages and a resolution similar to the original DEM raster was created (Fig. 29). Due to the large number of generated pixels, their analysis was generalized and subjected to statistical analysis, using, for example, histograms with separated classes corresponding to the above-mentioned suitability classes.

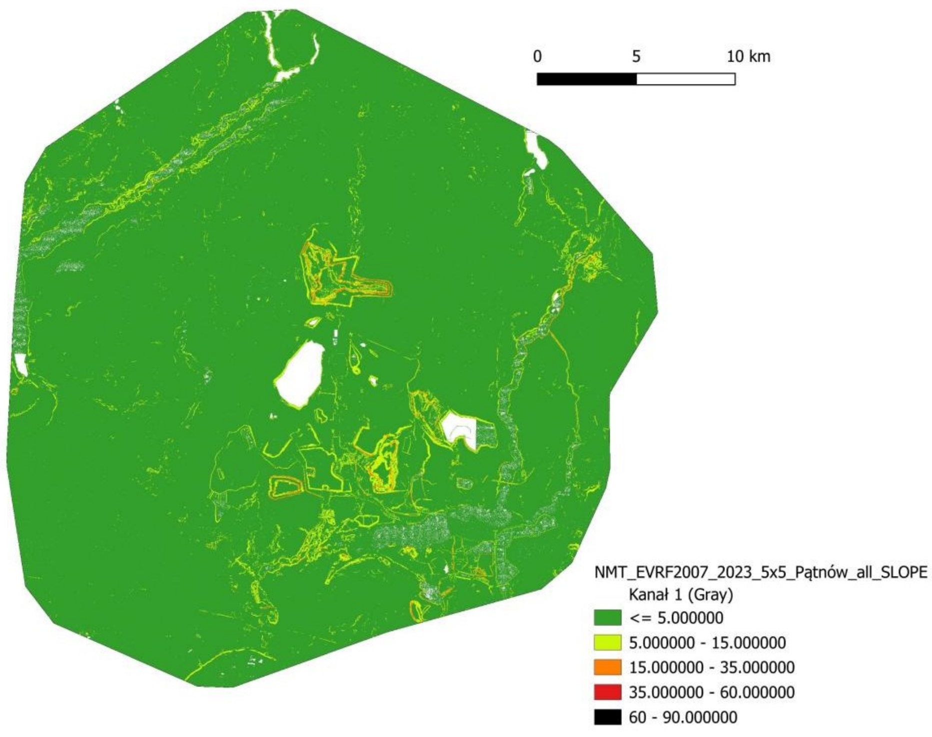

Fig. 29. Slope value map for the Pątnów Region. Class intervals according to the classification by Paulo (2008). Values expressed in degrees. The extent of the presented area is analogous to that in Fig. 28.

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Based on DEM data, the slope distribution was compared with a vector map that illustrates trends in slope directions and local changes in terrain elevation (gradients). This type of analysis forms the basis for predicting surface water behavior and the degree of soil erosion risk, particularly during short-term and intense downpours (Fig. 30).

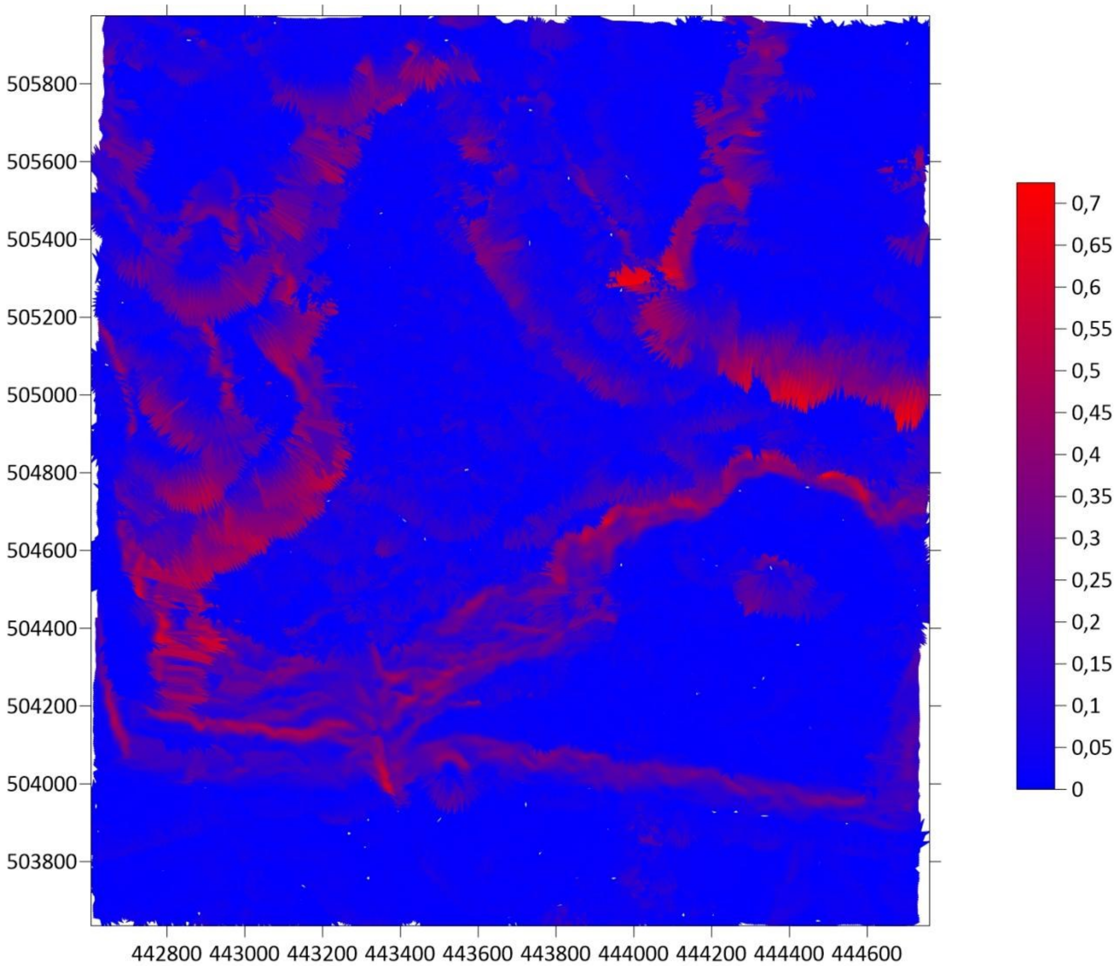

Fig. 30. Vector map of terrain slope for a section of the Pątnów Mining Area (area size: 2155 x 2340 m), Grid 5x5 m, dimensionless gradient. Polish, metric, rectangular coordinate system „1992"

Table 21. and figures 31-33 provide delineates the distribution of land according to the slope classes across different sections of the Pątnów Mining Site, including the mining area itself, the adjacent mining site excluding the main area, and the buffer zone. It categorizes the slopes into various classes, reflecting the potential for post-mining land use based on the degree of incline.

Tab. 21. Distribution of slope angles across different areas of the Pątnów Mining Site

Slope angle	Pątnów Mining Area		Pątnów Mining Site (excluding Pątnów Mining Area)		buffer zone of the Pątnów Mining Site (reference point)	
	m2	%	m2	%	m2	%
< 5°	42 745 300	90%	344 874 725	95%	401 629 675	96%
5° - 15°	3 034 250	6%	15 990 850	4%	12 422 875	3%
15° - 35°	1 125 225	2%	1 582 525	0%	971 675	0%
35° - 60°	3 350	0%	7 850	0%	1 475	0%
> 60°	408 150	1%	1 381 050	0%	2 312 375	1%
total	47 316 275	100%	363 837 000	100%	417 338 075	100%

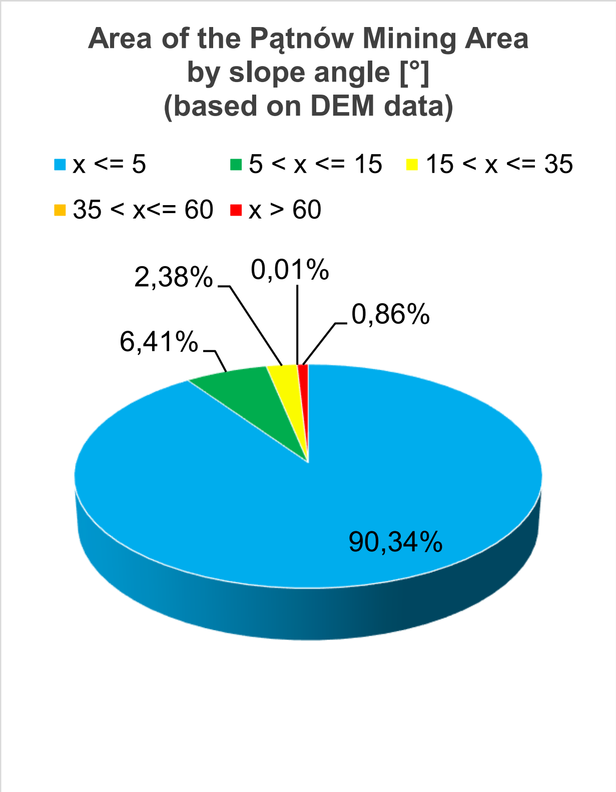

Fig. 31. Area of the Pątnów Mining Area by slope angle [°] (based on DEM data)

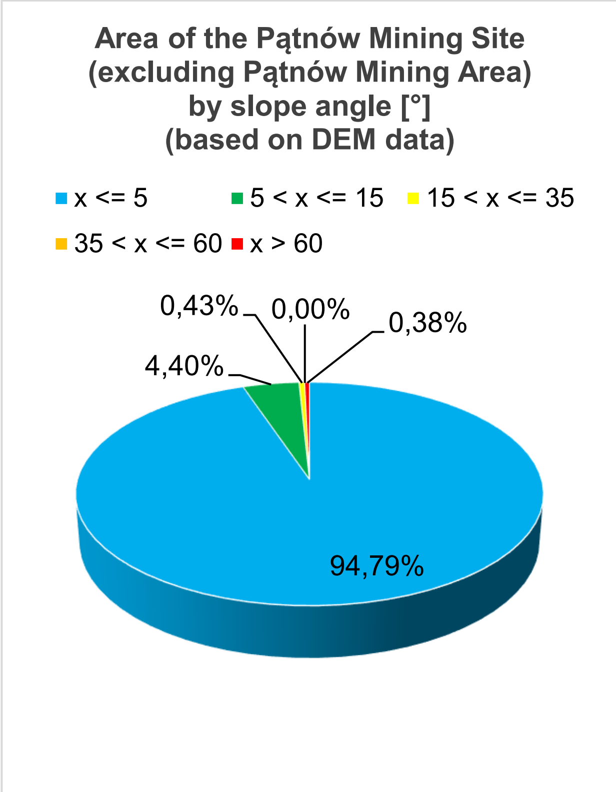

Fig. 32. Area of the Pątnów Mining Site (excluding Pątnów Mining Area) by slope angle [°]

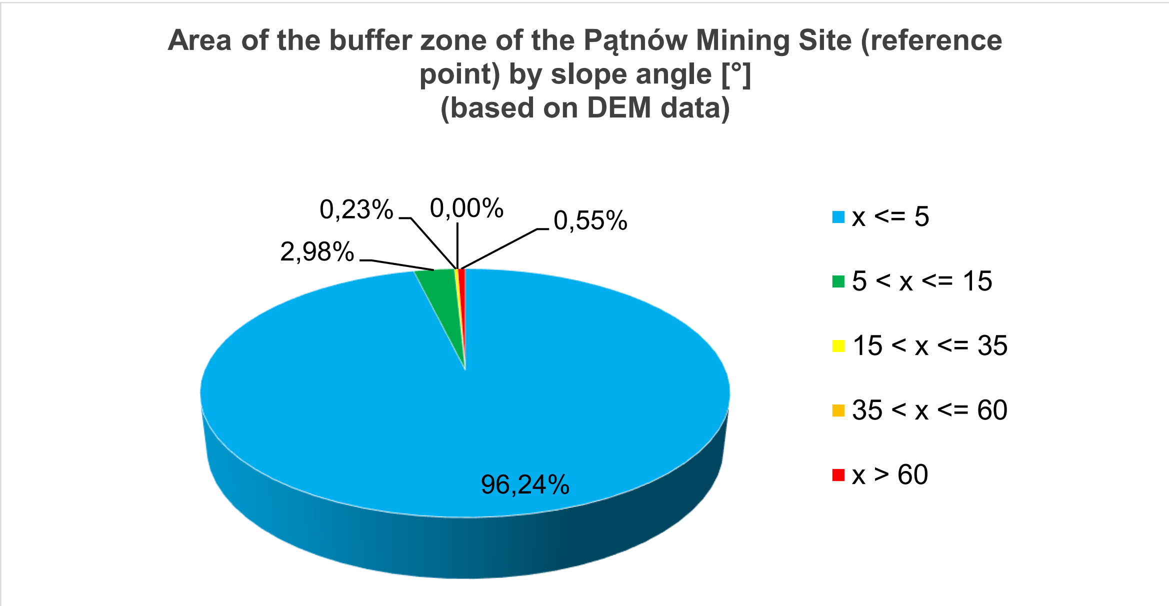

Fig. 33. Area of the buffer zone of the Pątnów Mining Site (reference point) by slope angle [°]

The steepest terrains, particularly those with slopes greater than 60 degrees, correspond primarily to inactive mining pits. These areas are not suitable for agricultural use due to their extreme inclinations and represent lands that remain inactive and unreclaimed. In contrast, the majority of the other terrains have been subjected to technical reclamation, making them suitable for agricultural or forestry activities. This transformation has been successful in mitigating land degradation, with most areas now fitting into the **first class of degradation**, which indicates no significant degradation or that the reclamation goals have been achieved.

Future analysis could explore terrain slope changes resulting from mining activities by comparing contemporary slope distributions with those from archival maps created before mining began. These archival maps could be georeferenced and integrated into the current geographic coordinate system. Contour lines from these georeferenced raster backgrounds could then be digitized and transformed into a regular grid of interpolated values using various interpolation methods, such as different kriging variants, inverse distance weighting, and linear triangulation. Ensuring that compared grids possess identical geometry and range would be crucial, particularly for methods that do not allow data extrapolation outside the range of data points.

Additionally, the analysis of the area's historical slope before mining could be conducted using similar methods to those used for modern DEM data. By examining changes in slope inclination over decades, one could employ classifications such as:

- no significant changes - slope change within the same class;
- slight change - slope change by 1 class;
- significant change - slope change by 2 classes;
- considerable change - slope change by 3 classes;
- critical change - slope change by 4 classes.

This approach would allow for a comprehensive understanding of how mining activities have altered the landscape over time and could serve as a foundation for predicting future changes and planning effective land reclamation and management strategies.

5.3. Areas of concern in Most Basin, CZ

The survey of the terrain is carried out using test pits, which are located in Most basin (Fig. 34.) to a depth of 0.6 m in the soil profile of each investigated site. Determining the number of sampling points per 1 ha depends on the heterogeneity of the soil, usually one test pit is made per square 50 x 50 m.

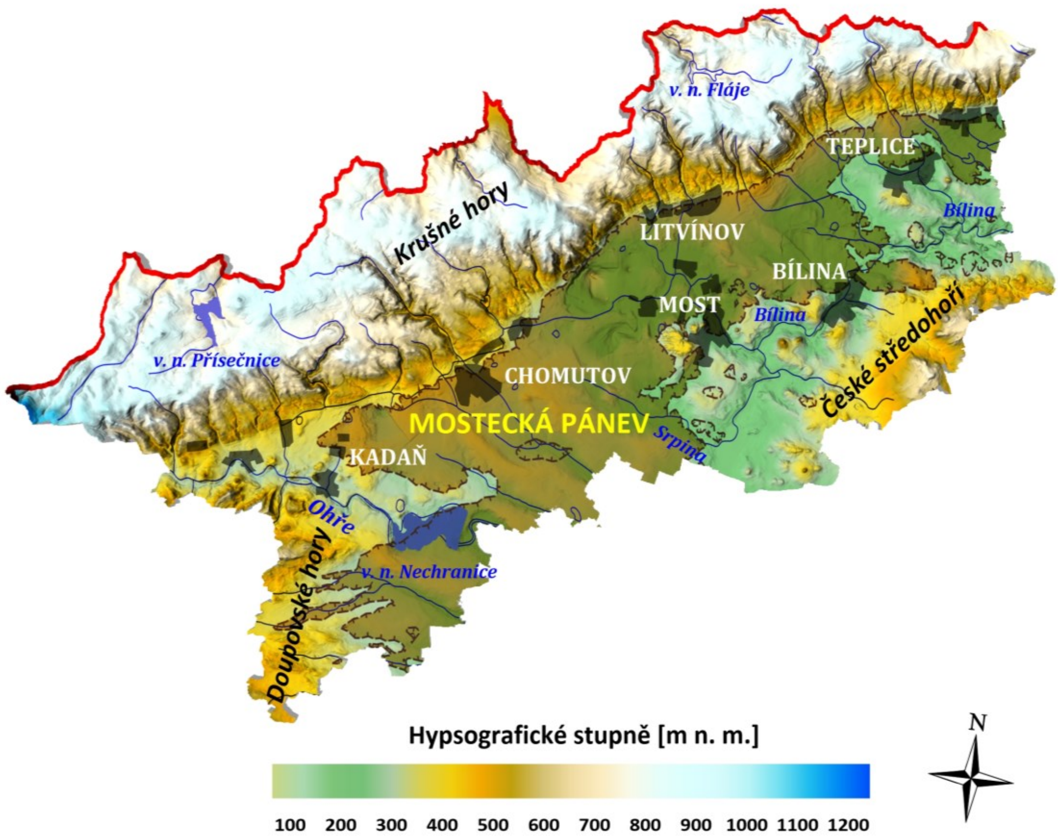

Fig. 34. Most Basin situation (Řehoř M., Schmidt P., 2021)

Soil samples are taken from the exposed wall of the test pit and only from horizons that are macroscopically different (granularity, colour). The amount of soil taken for one sample is 1 - 1.5 kg, in the case of gravel representation in the soil above 20%, it increases to 3 - 5 kg. The sampling points are recorded in the working map. Photo documentation is always carried out during sampling.

The selection of laboratory tests and analyses of their results was determined in the range of proven methodologies used in the Most Basin for a long time in reclamation activities (Vráblíková J., et al. 2018). For each sample, granularity determination, evaluation of mineralogical composition on Siemens X-ray diffractometer, determination of soil reaction, determination of CaCO3 content were carried out, determination of the content and quality of Cox carbon and humus, determination of nitrogen content, determination of sorption capacity and determination of the content of acceptable nutrients according to Melich III.

All performed laboratory analyses were carried out by testing laboratories VÚHU and VÚMOP accredited by ČIA according to ČSN EN ISO/IEC 17025 on the basis of internal methodological procedures based on the relevant standards (Zkušební laboratoř č. 1078).

The limit contents of risky trace elements are based on Decree No. 153/2016 (Tab. 22.), on the determination of the details of the protection of the quality of agricultural land and on the amendment of the Decree No. 13/1994 Coll., which regulates some details of the protection of the agricultural soil fund, where the so-called preventive values of the contents are given of risk elements in agricultural soil determined by the extraction of the acidum chloronitrosum (mg.kg-1 dry matter) and are also in full correlation with Decree No. 257/2009 Coll., on the use of sediments on agricultural land (Vráblíková J., et al. 2018).

Tab. 22. Limit contents of risky trace elements, PCB, Pau

Element	Content ($mg.kg^{-1}$) Lightly soil	Content ($mg.kg^{-1}$) Common soils
As	15	20
Be	1,5	2
Cd	0,4	0,5
Co	20	30
Cr	55	90
Cu	45	60
Hg	0,3	0,3
Ni	45	50
Pb	55	60
V	120	130
Zn	105	120
PCB	0,02	0,02
PAU	1,0	1,0

Limit values according to Decree No. 153/2016 Coll. (Czech Republic)

They are therefore valid for agricultural land in the soil fund of the Czech Republic, when it is necessary to consider the land as degraded if the limit is exceeded. In the case of forestry reclamation, these are only indicative limits, where any natural geological background can also be taken into account.

The implementation of this complex set of analyses is very demanding both financially and in time. Therefore, it is recommended to carry out as a priority, a granularity analysis, determining the soil reaction, sulphur content and coal mass content. These analyses are sufficient for indicative determination of soil degradation.

5.3.1. Areas of soils contaminated with coal seam rock

These areas are contaminated with coal mass, sulphur and iron sulphides. They are now relatively rare, most of them have already been reclaimed. They form smaller areas on old spoil heaps. Probably the most significant today is the non - reclaimed part of the Střimice spoil heap

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The non - reclaimed area of the Střimice spoil heap

It is about 10 ha large, peripheral part of the spoil heap. Part of it is the two-hectare experimental area Střimice I., with an area of 2 ha. The estimated age of the area is 45 years (Řehoř M., et al., 2018). The situation of the area is shown in figures 35 and 36.

The predominant soil type here is a heterogeneous mixture of overburden soils from the coal seam strata of the Bílina open pit mine. Sandy loams and sands with a significant admixture of coal and siderite predominate. These are extremely acidic, phytotoxic soils. A unique development of erosion grooves with a depth of up to several meters can be observed on the surface. Considering the extremely acidic character of the area, minimal plant representation was found here, but rare acid-loving species may occur. For many years now, the relatively rare acid-loving mushrooms (Pisolithus arrhizus) have been found here. Uniquely developed erosion phenomena deserve long-term protection.

The chemical-pedological parameters of two samples of selected soil types are shown in the following table 23.

Tab. 23. Chemical-pedological properties of the soils of the Střimice area

No. of sample	N_c (%)	Cox (%)	$CaCO_3$ (%)	pH KCl	acceptable nutrients ($mg.kg^{-1}$)			sorption capacity		
					P	K	Mg	S	T	V
								mmol/100 g		(%)
2023										
sample 1	-	3,7	0,3	5,0	2	58	185	9	9	100
sample 2	-	5,0	0,2	3,9	1	35	95	0	24	0

sample1 – test pit profile consists of sandy clay (sampling interval 0 - 0,5m),
sample2 – test pit profile consists of coaly clay (sampling interval 0 - 0,5m)

Fig. 35. Situation of the contaminated areas of the Střimice landfill

Fig. 36. Part of the contaminated area of Střimice (degradation level 3)

5.3.2. Areas of soils contaminated with risky trace elements

According to the results of the research works, the main contaminant is arsenic. It occurs to a limited extent on areas contaminated with coal seam soils, where it is bound to the iron sulphides pyrite and marcasite. Increased concentrations of other trace elements (especially cobalt, chromium, copper, vanadium and nickel) were found on areas reclaimed using bentonite, which is their source. However, the most significant degraded area is the arsenic-contaminated strip of Quaternary soils at the foot of the Krušné Hory Mountains.

Flushes from metamorphites of the Ore Mountains

It is a discontinuous strip of clayey gravel, clay soils and topsoils under the Krušné Hory Mountains roughly between Klášterec nad Ohří and Litvínov. In this case, the source of degradation is runoff from the metamorphites of the Krušné Hory Mountains. In certain areas (e.g. the sediments of former Lake Komořany) the content of arsenic, is very difficult to explain in any other way.

This area of degraded soils must be taken into account during reclamation works in the area of the Nástup Tušimice Mines and the ČSA open pit mine, where it is advisable not to establish agricultural reclamation under the Krušné Hory Mountains (arsenic contamination was also detected in samples of topsoil). Arsenic-contaminated gravel from the internal dump of the ČSA open pit mine is shown in the following Fig. 37.

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Fig. 37. Arsenic-contaminated clay gravel

The following table No. 24 shows the results of analyses of the content of risky trace elements in three samples of clayey gravel.

Tab. 24. Content of risky trace elements in gravel samples

No of sample	Risky trace element content (mg . kg^{-1})										
	As	Be	Cd	Co	Cr	Cu	Ni	Pb	V	Zn	Hg
sample 1	41,5	1,76	0,76	25,4	56,8	95,8	41,7	58,8	82,8	105,5	0,112
sample 2	83,6	1,11	1,75	47,6	56,9	108,3	43,5	67,9	101,6	125,9	0,225
sample 3	53,8	1,23	0,98	37,1	61,2	98,4	46,5	75,5	88,9	115,4	0,211

5.4. Areas of soils contaminated by coal combustion products

Degraded soils contaminated by coal products are relatively frequent in the Most Basin. It is storages of ashes, fly ash, slag, stabilizer and energy gypsum. From the point of view of soil degradation, energy gypsum and stabilizers are the most problematic (a very alkaline soil reaction causes soil degradation of the 3rd degree).

Important locations include the Třískolupy, Letiště, Severní lom and Stodola storages and surrounding areas. In rare cases, even reclaimed areas are contaminated. An example can be forestry reclamation on the area of Prunéřov VI.

Reclamation of the area of Prunéřov VI contaminated with energy gypsum

The survey was carried out at three sites of the Prunéřov VI area. The sites were located along the road Libouš – Prunéřov. The ranking of sites was marked as 1 – 3 to the right of the road in the direction from Prunéřov to Libouš. At stations 1 and 2, the gradual death of larch trees was observed right next to the road. At station 3, there is already an extensive clearing by the road, and the larch forest approx. 100 m from the road behind the clearing is affected.

Samples were taken from test pits with a depth of 0.4 m. At sites 1 and 2, 1 sample was taken at the roots of a larch, at site 3, 1 sample was taken from a clearing and one sample was taken at the roots of a larch. Sampling of contaminated soil is shown in Figure 39.

A macroscopic description was made for each sample, then laboratory analyses were carried. Significant results achieved are shown in the following tables No. 25 – 27 (test pit 1 was chosen as a typical example).

Tab. 25. Geological description and mineralogical composition of the collected samples

No. of sample	Sampling interval (m)	Area	Geological description	Mineralogical composition
sample 1	0–0,4m	Pruněřov VI	grey-white to white sandy soil with admixture of humus	gypsum, trace admixture of clay minerals and calcite

Tab. 26. Determination of Nc, Cox, CaCO3 content and soil reaction

No. of sample	$CaCO_3$ content (%)	pH/H_2O	Cox (%)	N_c (%)
sample 1	3,1	8,6	1,2	-

Tab. 27. Acceptable nutrients content and sorption capacity

No. of sample	Acceptable nutrients ($mg.kg^{-1}$)			Sorption capacity ($mmol\ .100g^{-1}$) (%)		
	P	K	Mg	S	T	V
sample 1	8	20	111	3	3	100

Considering the determined properties of the soils shown in tables no. 25-27 (especially the extremely alkaline soil reaction), it was possible to state that it is a clearly phytotoxic area with soil degradation level 3. The cause of the poor soil properties and the subsequent significant death of trees was contamination with energy gypsum from the area its nearby storage.

The successful solution to the problem was the removal of the contaminated soil layer to a depth of 0.7 m in the range recommended in the expert report of VÚHU and its replacement with a reclamation additive.

The following pictures No. 38 - 40 show the situation of the contaminated area, the soil probe containing energy gypsum and the area of interest after the removal of the upper horizon.

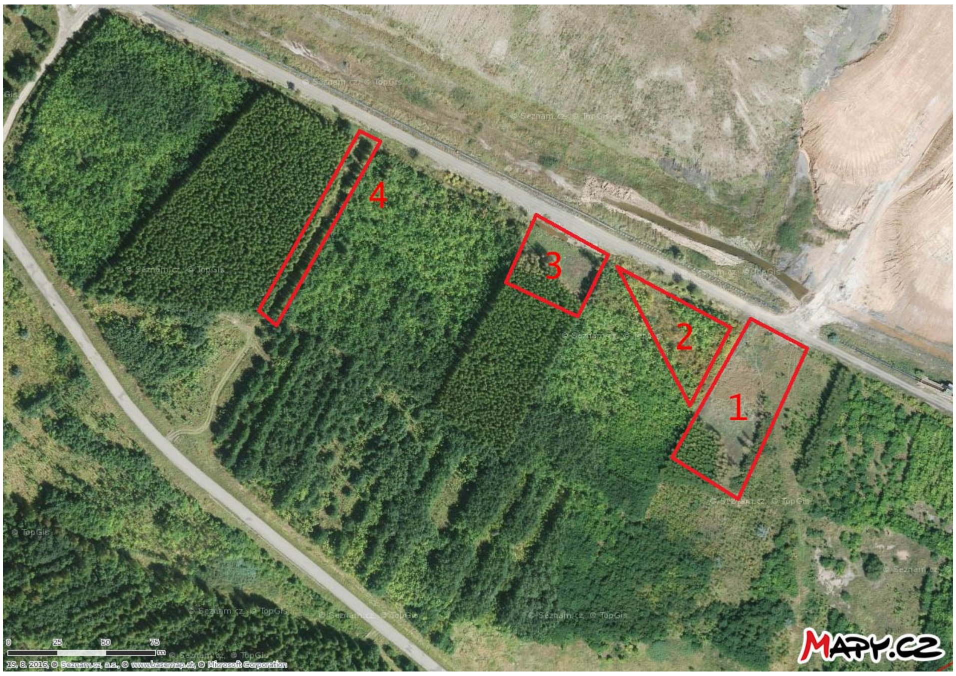

Fig. 38. The situation of the area of Pruněřov VI contaminated with energy gypsum

Fig. 39. Soil probe with energy gypsum content

Fig. 40. Area of interest of Prunéřov VI after removal of the upper horizon (upper part of the photo)

5.5. Areas of soils degraded by an increased content of the sandy component and the threat of erosion

Overall, it can be stated that soils with a higher content of the sandy component and susceptibility to erosion are currently found mainly in the area of the internal dump of the Bílina open pit mine and, to a lesser extent, also in the area of the internal dump of the Vršany open pit mine. Their source is frequent sand strata of the delta-sand assemblage of both quarries. These soils are usually affected by the second degree of degradation. The Radovesice spil heap was a similar site in the past, but technical reclamation with the application of a reclamation additive had already been carried out here.

A specific case is the area of the coal seam outcrop under the Krušné Hory Mts. In this case, the danger of erosion results rather from steep slopes. Here, gravels, sandy and clayey soils alternate. Another cause of soil degradation here is contamination with arsenic and, locally, coal matter. For these reasons, soils are mostly affected by the third degree of degradation.

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Reclamation of the area of the Bílina internal dump contaminated with a high content of sand

The internal dump of the Bílina open pit mine is characterized by an increased occurrence of sand. It is not the entire area of the spoil heap, but there are individual areas made up of practically sterile sands. In terms of physical and chemical properties, they can be quite heterogeneous, often containing a significant proportion of clay admixtures. In the case of the content of a significant proportion of dust particles, these are floating sands, which have extremely unfavourable hydro - physical soil properties. The mineral composition is dominated by quartz. They have a very low content of acceptable nutrients, a very low sorption capacity of the soil, are carbonate-free and in most cases do not contain toxic additives. The soil reaction can be neutral to strongly acidic (in the case of coal mass admixture content). They show very poor erosion stability and slide susceptibility. From the point of view of recultivation, they are not phytotoxic, but their properties are similar to sterile soils.

The results of the survey of one of the sandy areas, where 3 test pits were realised, are given in the following tables.

Tab. 28. Geological description of the collected samples

No. of sample	Sampling interval (m)	Area	Geological description
sample 1	0 – 0,40	internal dump II	gray-yellow sand, slightly clayey, rarely with plant roots
sample 2	0 – 0,40	internal dump II	gray-yellow sand, slightly clayey, rarely with plant roots
sample 3	0 – 0,40	internal dump II	gray-yellow sand, slightly clayey, rarely with plant roots

Tab. 29. Determination of Nc, Cox, CaCO3 content and soil reaction

No. of sample	$CaCO_3$ content (%)	pH/H_2O	C_{ox} (%)	N_c (%)
sample 1	0,3	6,1	0,4	0,03
sample 2	0,1	5,8	0,1	0
sample 3	0,3	6,2	0,3	0,01

Tab. 30. Acceptable nutrients content and sorption capacity

No. of sample	Acceptable nutrients ($mg.kg^{-1}$)			Sorption capacity (mmol/100 g)		Sorption capacity (%)
	P	K	Mg	S	T	V
sample 1	1	85	198	9	9	100
sample 2	0	74	155	9	9	100
sample 3	1	94	121	8	8	100

Tab. 31. Results of granularity evaluation of clayey sand

No. of sample	Grain category I	Grain category II	Grain category III	Grain category IV	Gravel category
	%	%	%	%	%
sample 1	21	12	6	41	12
sample 2	18	11	4	46	9
sample 3	23	14	5	39	10

- Grain category I - fraction < 0,01 mm
- Grain category II - fraction 0,01-0,05 mm
- Grain category III – fraction 0,05-0,1 mm
- Grain category IV – fraction 0,1-2 mm
- Gravel category - fraction > 2 mm

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A successful solution for the technical reclamation of the degraded area was the application of 0.2 m of brown clay and used as a reclamation additive. The following picture No. 41 shows the general situation of the internal dump of the Bílina open pit mine.

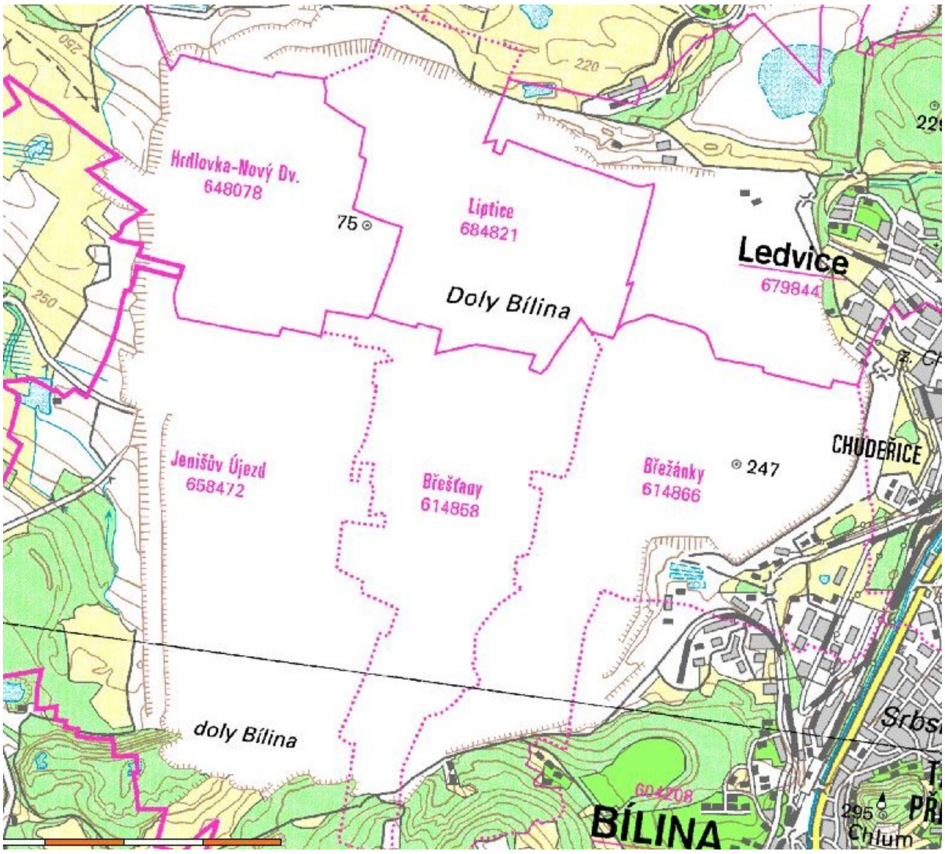

Fig. 41. The overall situation of the Bílina quarry's internal dump

5.6. Areas of soils degraded by increased content of the clay component

Overall, it can be stated that soils with a higher content of the clay component are found locally in the area of the Nástup Tušimice Mines dumps and rarely in the area of the internal Vršany dump. Fortunately, these soils are rare from the point of view of in terms of the entire Most Basin

The cause of soil degradation is the occurrence of yellow clays, which geologically form upper horizon of Tertiary sediments. Their mineralogical and pedological properties are suitable, but their extremely fine granular composition, physical and hydro - physical properties are completely unsuitable. This can only be changed with the help of very economically demanding melioration measures, during which the treated soil is perfectly mixed (homogenized) with the melioration sorbent (sand) using special technique. Due to the technical and financial demands of this procedure and the relative rarity of yellow clays, it is advisable to realise simple grassing of the area without forest reclamation. The level of soil degradation varies between the second and third depending on the content of the clay fraction.

Reclamation of area 3 of Libouš internal dump contaminated with a high content of clay

A significant death of trees was detected on the he surveyed area. Therefore, a survey was carried out aimed at finding out the cause of the death and at proposing the next procedure for the reclamation of the area. The samples were taken from three test pits with a depth of 0.4 m. The test pits were located in the area with the maximum death of trees (see pictures no. 42 and 43).

A geological description was made for each sample, then laboratory analyses were carried out. Significant results achieved are shown in the following tables no. 32-35 (test pit 1 was chosen as a typical example, the results of the other sample analyses were practically identical).

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Tab. 32. Geological profile of test pit 1

No. of sample	Sampling interval (m)	Geological description of collected samples
sample 1	0 - 0,09	brown clay with rare plant roots
sample 2	0,09 - 0,30	clay yellow, plastic, extremely fine-grained

Tab. 33. Results of granularity evaluation of samples

No. of sample	Grain category				Gravel category
	I	II	III	IV	
	%				
sample 1	56	23	3	17	1
sample 2	74	20	2	4	0

- Grain category I - fraction < 0,01 mm
- Grain category II - fraction 0,01-0,05 mm
- Grain category III – fraction 0,05-0,1 mm
- Grain category IV – fraction 0,1-2 mm
- Gravel category - fraction > 2 mm

Tab. 34. Determination of Nc, Cox, CaCO3 content and soil reaction

No. of sample	$CaCO_3$ content (%)	pH/H_2O	Cox (%)	N_c (%)
sample 1	1,2	7,0	1,5	0,06
sample 2	1,3	7,3	1,1	0,01

Tab. 35. Acceptable nutrients content and sorption capacity

No. of sample	Acceptable nutrients ($mg.kg^{-1}$)			Sorption capacity		
				($mmol .100g^{-1}$)		(%)
	P	K	Mg	S	T	V
sample 1	10	288	825	16	16	100
sample 2	11	310	893	15	15	100

Fig. 42. Area of interest with the death of tree plantings

Fig. 43. A sample of yellow clay

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The area of interest consists of a horizon of recultivable clay with a thickness of up to 0.1 m, under which there is plastic clay. Due to the difficulty of the technical recultivation solution of this situation, it was recommended to leave the area grassed with a scattered planting of shallow woody plants.

5.7. Areas of soils degraded by salinization

The problem of soils degraded by salinity was detected only in some areas of the spoil heaps of the Doly Nástup Tušimice Mines area, fortunately it does not occur in other areas of the Most Basin.

In the years 2016 - 2023, the cause of the excessive death of trees was observed on a number of areas. The brown clays of the locality are pedologically quite homogeneous and their soil characteristics (with the exception of too fine grain composition) are very favourable. Practically the only explanation for the death of woody plants was an extremely alkaline soil reaction.

The alkaline soil reaction of the soil (pH above 7.5) actually has major negative consequences for most tree species. Blockage of acceptable nutrient (especially Mg) and disruption of the photosynthesis process is particularly significant. In general, woody plants tolerate slightly acidic soils rather than alkaline ones.

The presence of hydrogenated gypsum was documented in the evaluated samples. The presence of salts in the upper soil horizon makes the situation even worse and is clearly negative. Bonding to water (gypsum) dries the surface. The level of soil degradation varies between the second and third depending on the pH value given by the gypsum content.

Reclamation of the area Libouš I degraded by salinization

An example of an area degraded by salinity (gypsum contamination) can be the area of Libouš I. A significant death of trees was found in the evaluated area. Therefore, a survey was carried out aimed at finding out the cause of the death and at proposing the next procedure for the reclamation of the area. The samples were taken from six test pits with a depth of 0.4 m. The test pits were located in the area with the maximum death of woody plants.

A geological description was made for each sample, then laboratory analyses were carried. Significant results achieved are shown in the following tables no. 36 – 39 (test pits 1 and 2 were selected as a typical example, the results of other sample analyse were practically identical).

Tab. 36. Geological description of collected samples

No. of sample	Sampling interval (m)	Area	Geological description of samples
sample 1	0–0,30	Libouš I	brown clay with a proportion of plastic yellow-brown clay and numerous plant roots.
sample 2	0–0,30	Libouš I	brown clay with a proportion of plastic yellow-brown clay and numerous plant roots

Tab. 37. Results of granularity evaluation of samples

No. of sample	Grain category				Gravel category
	I	II	III	IV	
	%				
sample 1	60	26	3	9	2
sample 2	60	27	4	5	4

- Grain category I - fraction < 0,01 mm
- Grain category II - fraction 0,01-0,05 mm
- Grain category III – fraction 0,05-0,1 mm
- Grain category IV – fraction 0,1-2 mm
- Gravel category - fraction > 2 mm

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Tab. 38. Determination of Nc, Cox, CaCO3 content and soil reaction

No. of sample	$CaCO_3$ content (%)	pH/H_2O	Cox (%)	N_c (%)
sample 1	1,1	7,8	1,6	0,04
sample 2	0,7	8,0	2,1	0,05

Tab. 39. Acceptable nutrients content and sorption capacity

No. of sample	Acceptable nutrients ($mg.kg^{-1}$)			Sorption capacity ($mmol .100g^{-1}$)		(%)
	P	K	Mg	S	T	V
sample 1	5	255	911	15	15	100
sample 2	3	267	891	16	16	100

The cause of the death of the trees was clearly soil salinization (gypsum content) causing an extremely alkaline soil reaction (see picture no. 44). As a partial solution to the problem, the application of ammonium sulphate in appropriate dosage can be recommended (however, the application must be repeated regularly at an interval of approx. 2-3 years. Another option is to leave the area as grassed.

Fig. 44. Gypsum crystals on a clay sample taken

5.8. Conclusions from Mapping Degradation in the Most Basin

The partial research report summarizes the current results of VÚHU in solving WP3 (Task 3.1). The first stage of the research devoted to the characteristics of degraded soils in the Most Basin area is evaluated here.

The report describes the methodology of the work, which includes the definition of the concept of soil degradation for the purposes of the project solution, a proposal for the classification of soil degradation in the Most Basin, the methodology of the necessary pedological research and the selection of pedological parameters, including limit values for individual levels of degradation.

The report contains a brief description and localization of areas of degraded soils in the Most Basin. In individual chapters, areas affected by different types of degradation are briefly described, one locality is always described in more detail as a case study area.

The main results of the research so far are, primarily, the first proposal for the classification of the level of soil degradation, determination of limit values of soil parameters for individual levels of degradation, and a brief characterization and localization of areas with different types of soil degradation. Part of the work is a map of degraded soils in the Most Basin.

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Tab. 40. Situation of areas of the Most Basin with degraded soils

Area	cause of degradation	critical parameter	level of degradation
Unreclaimed area of spoil heap Střimice	Contamination by coal mass and FeS_2	pH, S	4
The area of Quaternary soils at the foot of the Krušné Hory Mountains	Contamination by As	As	3
	Contamination by coal mass and FeS_2 (locally)	pH, S	4
	Threat of erosion (locally)	Slope, gravelly soil	3
Třískolupy , Letiště, Severní Lom and Stodola storages and nearby surrounding areas	Storage of coal combustion products	Contamination with stabilizer, energy gypsum	3-4
Individual local areas of the internal dumps of the Bílina and Vršany open pit mines	High sand content	Coarse grain compo-sition, erosion effects	3
Individual local areas of Libouš and Vršany open pit mines spoil heaps	High clay content	Extremely fine granular composition	3-4
Individual local areas of Libouš open pit mine spoil heaps	Salinization, high content of Gypsum	pH	3-4

The situation of the areas of degraded soils in the Most Basin is shown in Figure No. 32. Only areas of the 3rd and 4th class of degradation are defined here (the 2nd level of degradation does not require reclamation measures, it corresponds to all the spoil heap areas shown).

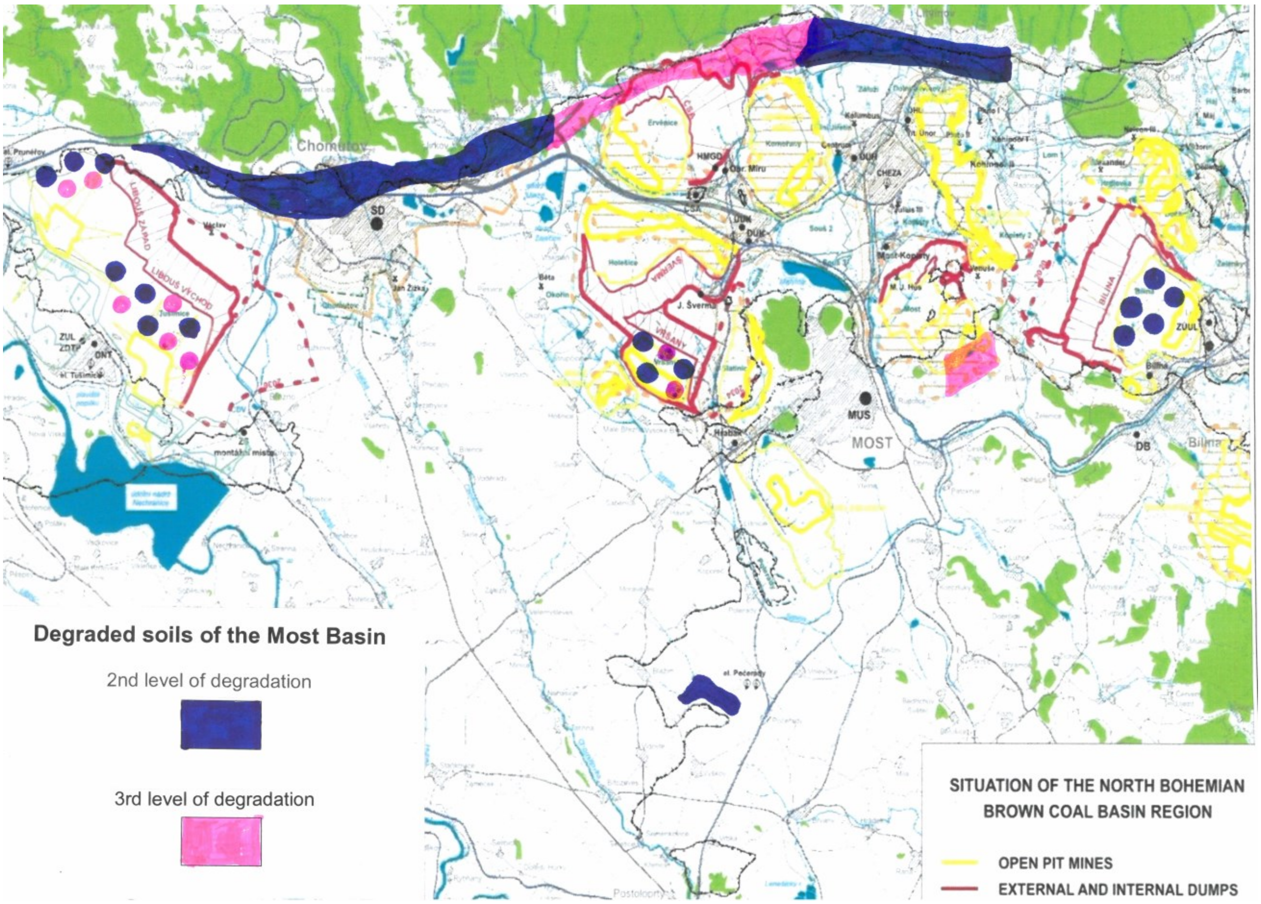

Fig. 45. Degraded soil areas in the Most Basin (North Bohemian Brown Coal Basin)

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6. CONCLUSIONS AND RECOMMENDATIONS

This comprehensive study has conducted an extensive review of various indicators crucial for describing ecosystem degradation on post-mining lands, focusing particularly on landscape and soil which are key for ecological rehabilitation. The investigation into these indicators has enriched the understanding of their application and effectiveness in classification of the post-mining land's degradation as well as in monitoring ecological recovery and guiding reclamation efforts. The study introduced a four-class system to categorize lands based on their ecological condition and reclamation needs. Class 1 includes areas that show no signs of degradation and maintain their original ecological functions, demonstrating full functionality and capability to support existing and planned land uses without any need for intervention. This class indicates ecosystems that have either naturally preserved their vitality or have been successfully reclaimed to meet or exceed original environmental standards. In contrast, Class 4 encompasses areas that suffer from severe degradation and require substantial reclamation efforts to restore usability.

Additionally, thresholds for selected indicators have been established to determine whether the land retains required characteristics or if the soil is in a healthy state. These thresholds are vital for guiding reclamation practices and ensuring that restored lands meet ecological and usability standards. The advent of the EU Soil Directive proposal presents a promising development that this classification system can align with, enhancing collaboration among EU countries in ecosystem monitoring and management. This alignment can streamline efforts across member states, fostering a unified approach to soil health and land reclamation.

Furthermore, the findings from this study are imperative for policymakers and mining/reclamation companies to implement evidence-based decisions and policies that not only comply with the upcoming EU regulations but also promote sustainable mining practices. This can lead to a proactive management of mining sites, aiming to minimize environmental impacts and facilitate quicker ecological recovery. The effective application of these insights and classifications may serve as a framework for ecological assessments and reclamation practices, providing a reference point for similar efforts across Europe.

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APPENDIX I Indicators for Assessing Ecosystem Degradation in Post-Mining Landscapes

Tab. 41. Indicators for Assessing Ecosystem Degradation in Post-Mining Landscapes

ECOSYSTEM ELEMENT	FEATURES	INDICATOR NAME	SYMBOL	UNIT	FORMULA	FORMULA EXPLANATION	CHARACTERISTICS	DATA SOURCE
LANDSCAPE	Elevation	Standard Deviation of Elevation	SDE	m	$\sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(h_i - \bar{h}\right)^2}$	hi - the elevation of point i, h^- average elevation of all points within the analyzed area/window, n - number of the points in the area/window	The anomaly of the elevation of the ground in relation to the whole area. To apply this method practically, choose an appropriate window size for the analysis that can capture local elevation differences. This might be a 3x3, 5x5, or larger window, depending on the resolution of elevation data and terrain specifics.	DEM data from aerial surveys (drone, satellites, UAV) / external databases
		Topographic Wetness Index	TWI	(-)	$TWI = \ln\left(\frac{SCA}{\tan\beta}\right)$	SCA (Specific Catchment Area) is the specific catchment area, expressed as catchment area per unit contour width [m²/m], β is the slope angle expressed in radians.	The Topographic Wetness Index quantifies the influence of topography on hydrological processes, indicating potential soil moisture and water accumulation based on slope and upstream contributing area.	DEM data from aerial surveys (drone, satellites, UAV) / external databases
	Vegetation	Normalized Difference Vegetation Index	NDVI	(-)	$\frac{NIR - RED}{NIR + RED}$	NIR - near-infrared reflectance, RED - red light reflectance	index used to assess the condition and density of vegetation based on remotely sensed spectral data.	spectral data from aerial surveys (drone, satellites, UAV)
	Water occurance	Normalized Difference Water Index	NDWI	(-)	NDWI=(GREEN - NIR)/(GREEN+ NIR)	NIR - near-infrared reflectanc, GREEN - green bands of the electromagnetic spectrum	NDWI is designed to enhance the visibility and detection of surface water bodies in remotely sensed images. NDWI is particularly sensitive to the moisture content in vegetation, making it useful for assessing water content in soil and plants as well as distinguishing water bodies in various landscapes.	spectral data from aerial surveys (drone, satellites, UAV)
	Water occurance concerning vegetation	Modified Normalized Difference Water Index	MNDWI	(-)	MNDWI=(GREEN - MIR)/(GREEN+ MIR)	MIR - Mid-Infrared reflectan, GREEN - green bands of the electromagnetic spectrum	MNDWI enhances the visualization of water bodies by using the green and mid-infrared (MIR) wavelengths to suppress built-up land and vegetation features, thus making it more effective than NDWI for mapping water features in urban and vegetated areas.	spectral data from aerial surveys (drone, satellites, UAV)

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		Slopes	Angle of slope	AS	°	$\cot\left(\frac{lenght\ of\ slope}{height\ of\ slope}\right)$	trigonometric function of bottom and upper slope elevation difference, data from DTM	The assessment of land degradation hinges on the reclamation objectives, where the slope inclination requirements vary with the intended use of the land.	DEM data from aerial surveys (drone, satellites, UAV) / external databases
		Thermal processes	Area of thermal processes	ATP	m2	total m² of thermally altered terrain	Measures the total area in square meters that has been affected by thermal processes, commonly observed in regions impacted by underground activities such as coal mining.	This indicator identifies changes in land surface temperature, providing insight into the extent and severity of thermal alterations in the terrain. Analysis of these temperature variations is conducted using Land Surface Temperature Differences data.	spectral data from aerial surveys (drone, satellites, UAV)
		Albedo	Land Surface Albedo	LSA	-	$LSA = \frac{(R_\lambda - R_p) \cdot \pi \cdot d^2}{ESUN_\lambda \cdot \cos(\theta_s)}$	R λ and Rp - spectral radiances at different wavelengths, d2 - square of the distance between the Earth and the sun, ESUN λ - extraterrestrial solar irradiance at wavelength λ, θs - solar zenith angle	Land Surface Albedo measures the proportion of sunlight that is reflected by the earth's surface, compared to the total sunlight it receives.	spectral data from aerial surveys (drone, satellites, UAV)
SOIL	GEOCHEMICAL FEATURES	Heavy metals contamination	Amount of pollutant contamination in soil	As Ba Cr Sn Zn Cd Co Cu Mo Ni Pb Hg	mg/kg	$\frac{mass\ of\ elements,\ chemical}{mass\ of\ soil}$	calculates the concentration of heavy metals or chemical pollutants in the soil by dividing the mass of the pollutant elements by the total mass of the soil sample	This indicator measures the concentration of heavy metals contaminants within a soil sample. It is crucial for assessing soil pollution levels, identifying potential risks to human health and the environment, and guiding remediation efforts. The assessment of heavy metal concentrations is essential for determining compliance with environmental quality standards and for monitoring the effectiveness of pollution control measures.	Samples taken in situ, data processed in laboratory
		Organic carbon content	Soil Organic Carbon	SOC	%	$\frac{mass\ of\ carbon}{mass\ of\ soil}$	proportion of organic carbon present in a soil sample. It is expressed as a ratio of the mass of organic carbon to the total mass of the soil, indicating the concentration of organic carbon	Soil Organic Carbon (SOC) is a critical indicator of soil health and fertility, reflecting the soil's ability to support plant growth and store carbon, thereby contributing to the global carbon cycle. It plays a key role in nutrient cycling and retention, water retention capacity, and soil structure.	Samples taken in situ, data processed in laboratory
			SOC/clay ratio	SOC/clay	(-)	$\frac{Soil\ Organic\ Carbon\ content}{Clay\ content}$	The SOC/clay ratio quantifies the relationship between the organic carbon content of the soil and its clay content.	This ratio helps in assessing soil health, as it reflects the balance of organic matter that can be stabilized by fine mineral particles in the soil.	

		Salinization			Electrical Conductivity	SS	mS/m	-	-	Electrical conductivity is a measure used to indicate the salinity level of soil or water. High conductivity values imply high salinity, which can be detrimental to plant growth and soil health. It is a crucial parameter for assessing soil salinization risks and managing agricultural inputs in saline-prone areas.	Samples taken in situ, data processed in laboratory
		Acidity			Soil Acidity	SA	pH	-	-	Soil acidity, measured by pH levels, affects nutrient availability, microbial activity, and plant growth. Low pH values (acidic soil) can lead to nutrient deficiencies or toxicities, impacting crop yields and soil health. Adjusting soil pH is fundamental for improving crop production and restoring soil fertility in degraded lands.	Samples taken in situ, data processed in laboratory
	GEOTECHNIC FEATURES	soil structure	porosity		Soil Porosity	Φ	%	$\frac{volume\ of\ void\ spaces}{volume\ of\ solid\ material}$	Proportion of the volume of voids over the total volume of the soil, including both the voids and the solid materials. It represents the fraction of total volume that is not occupied by solid soil particles, which is crucial for determining soil water retention, drainage capabilities, and the overall soil health.	Porosity is an essential soil physical property that influences water and air movement in the soil, root penetration, and microbial activity. High porosity generally suggests good aeration and drainage, favorable for root growth and microbial activities, which are vital for sustainable agricultural and environmental management.	Samples taken in situ, data processed in laboratory
			density		Soil Density	ρ	(-)	$\frac{mass\ of\ soil}{volume\ of\ soil}$	Calculated by dividing the mass of the soil by its total volume. It reflects the compactness of the soil and is a critical indicator of soil structure.	Soil density affects the movement of air and water through the soil profile. Denser soils may restrict root growth and decrease soil fertility due to reduced porosity. Managing soil density is crucial for improving plant health and yield, especially in agricultural and rehabilitated soils.	Samples taken in situ, data processed in laboratory
		soil erosion	RUSLE	RUSLE	Revised Universal Soil Loss Equation	A	(-)	$A = R \times K \times LS \times C \times P$	explanation below	RUSLE is a widely used empirical model that estimates the average annual rate of erosion on field slopes based on rainfall pattern, soil type, topography, crop system, and management practices. It quantifies potential long-term average annual soil loss in tonnes per hectare per year.	other indices
				R-factor	Rainfall Erosivity Factor	R	(-)	$\sum_{i=1}^{12} 1{,}735 \times 10^{\left(1{,}5 \log \frac{p_i^2}{p} - 0{,}8188\right)}$	Where: pi - total monthly precipitation (mm), p - mean annual precipitation	R-factor is a function of the rainfall amount and intensity	external databases

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				K-factor	Soil Erodibility Index	K		$\frac{2{,}1 \times 10^{-4}(12-OM)M^{1{,}14}+3{,}25(S-2)+2{,}5}{7{,}59} \times 100$	Where: OM - soil organic matter content, M - product of the primary particle size fractions (%silt + %very fine sand 0.063 - 0.1) * (100 - %clay), S - soil structure code (1- very fine granular, 2 - fine granular, 3 - mod or coarse granular, 4 - blocky, ploty or massive, P - permeability class. 1-6 (rapid - very low)	rate of soil loss per erosion index unit, determine by percentage of fraction types	Samples taken in situ, data processed in laboratory
				LS-factor	Slope Lenght and Slope Stepness Factor	LS	(-)	$\left(\frac{\lambda}{22{,}13}\right)^m (65{,}41 sin^2\beta + 4{,}56 sin\beta + 0{,}065)$	Where λ is the horizontal projection of the slope length (m), m is the constant dependent on the value of slope, and β is the downhill slope angle (°), 0.5 if the slope angle is greater than 2.86°, 0.4 on slopes of 1.72° to 2.86°, 0.3 on slopes of 0.57° to 1.72°, and 0.2 on slopes less than 0.57°.	Slope length (L) and slope steepness (S) are the most important topographic attributes influencing soil susceptibility to erosion	DEM data from aerial surveys (drone, satellites, UAV) / external databases
				C-factor	Cover and Management Factor	C	(-)	$\frac{NDVI - NDVI_{min}}{NDVI_{max} - NDVI_{min}}$	Where f represents vegetation cover, NDVImax is best vegetation cover, and NDVImin is worst vegetation cover in the study area (soil).	the ratio of soil loss under specific cropping conditions to soil loss occurring in bare soil	spectral data from aerial surveys (drone, satellites, UAV)
				P-factor	Support Practice Factor	P	(-)	$0{,}2 + 0{,}03 \times S$	S - slope stepness (%)	indicates the impact of management through the control of runoff, with specific reference on how the management practices (e.g. contour tillage, strip cropping, and terraces) reduces and alters the pattern, direction and speed of that runoff	DEM data from aerial surveys (drone, satellites, UAV) / external databases

APPENDIX II Example Threshold Values for Ecosystem Degradation Classification in Post-Mining Landscapes

Tab. 42. Example Threshold Values for Ecosystem Degradation Classification in Post-Mining Landscapes

ECOSYSTEM ELEMENT	FEATURES	SYMBOL	UNIT	INDICATORS THRESHOLDS DESCRIPTION	LITERATURE
LANDSCAPE	Elevation	SDE	m	**Low values** of local standard deviation indicate **smoother** and more homogeneous terrain surfaces. **High values** of local standard deviation indicate **rougher** and more heterogeneous terrain surfaces.	C. H. Grohmann, M. J. Smith and C. Riccomini, "Multiscale Analysis of Topographic Surface Roughness in the Midland Valley, Scotland," in IEEE Transactions on Geoscience and Remote Sensing, vol. 49, no. 4, pp. 1200-1213, April 2011, doi: 10.1109/TGRS.2010.2053546
		TWI	-	**Low TWI values** indicate **drier** areas with lower soil moisture content and reduced water accumulation. **High TWI values** signify **wetter** areas with higher soil moisture content and greater water accumulation.	Sørensen, R., Zinko, U., and Seibert, J.: On the calculation of the topographic wetness index: evaluation of different methods based on field observations, Hydrol. Earth Syst. Sci., 10, 101–112, https://doi.org/10.5194/hess-10-101-2006, 2006.
	Vegetation	NDVI	-	The NDVI index, depending on the range of values, allows identification of vegetation types. Therefore, the most authoritative, in terms of vegetation condition, are measurements within a class. Low vegetation (meadows, shrubs) - **about 0.2 - 0.4** High vegetation (forests) - **above 0.4**	Rizvi, R. H., Yadav, R. S., Singh, R., Datt, K., Khan, I. A., & Dhyani, S. K. (2009, September). Spectral analysis of remote sensing image for assessment of agroforestry areas in Yamunanagar district of Haryana. In National Symposium on "Advances in Geo-spatial Technologies with Special Emphasis on Sustainable Rainfed Agriculture", RRSSC, Nagpur (Vol. 7).
	Angle of slope	AS	°	**Agricultural Direction**: For lands targeted for agricultural use, the ideal angle of slope should be less than 15 degrees. This gradient allows for effective farming practices, minimizing soil erosion risks and facilitating the use of farming machinery, thereby ensuring that the land can be efficiently cultivated. **Forestry Direction:** In cases where the rehabilitation goal is to develop forest areas, the angle of slope can be accommodated up to 35 degrees. This higher threshold reflects the greater tolerance of forest ecosystems to steeper slopes, which can support tree growth without necessitating the intensive soil management required in agricultural settings.	1) Paulo A., 2008, Przyrodnicze ograniczenia wyboru kierunku zagospodarowania terenów pogórniczych, „Gospodarka surowcami mineralnymi", t. 24, z. 2/3. 2) Chodak, M. 2013. Metody rekultywacji i zagospodarowania obszarów poeksploatacyjnych w górnictwie skalnym. Kraków – Wrocław: Wyd. Poltegor-Instytut Instytut Górnictwa Odkrywkowego,
	Area of thermal processes	ATP	m^2	The degradation level classification based on ATP is directly linked to the affected area: **light degradation** occurs when the area is up to 10m², indicating minimal thermal disturbance. **Moderate degradation** is noted when the area spans from 10m² to 100m², suggesting a significant but manageable impact. **High degradation** is assigned to areas exceeding 100m², where the thermal processes have extensively altered the landscape. **The aim of rehabilitation efforts** is to reduce the ATP to 0m², restoring the area to its reference status and mitigating the impacts of mining activities.	-
	Land Surface Albedo	LSA	-	**Light Degradation**: An LSA value less than 20% indicates light degradation. This level suggests minimal disruption, where the surface still retains much of its original reflectivity, indicating fewer disturbances or changes in land cover. **Moderate Degradation**: When LSA values range from 20% to less than 25%, it signifies moderate degradation. This range implies more significant alteration of the surface properties, potentially due to partial loss of vegetation cover or changes in soil composition that reduce its reflectivity. **High Degradation**: LSA values from 25% to less than 30% are indicative of high degradation. At this level, the surface shows substantial alterations, often due to extensive mining operations or severe land use changes that greatly impact its reflective properties. **Reference Status (Aim of Rehabilitation):** The goal for rehabilitation is to achieve an LSA value of less than 19%, restoring the land close to its original state or to an optimal condition for future ecological resilience and sustainability. This target is essential for minimizing heat absorption and enhancing ecosystem recovery.	Kuśmirek - Tomaszewska R., Żarski J., Dudek S., 2015, Impact of type of surface coverage in spatial diversity of heat stress, Infrastructure and Ecology of Rural Areas vol. IV/1/2015, PAN

ECOSYSTEM ELEMENT	FEATURES	SYMBOL	UNIT	INDICATORS THRESHOLDS DESCRIPTION			LITERATURE
geochemistry	Heavy metals contamination			Each country has its own regulations regarding the maximum permissible levels of heavy metals in soils. Therefore, it is essential to consult the specific regulations applicable in the respective jurisdiction. The data provided below pertain to the situation in Poland, specifically concerning agricultural requirements, and serve to illustrate the potential structuring of such regulations. This information should be understood as a guide to familiarize with the regulatory landscape, rather than as a universal standard.			Rozporządzenie Ministra Środowiska z dnia 1 września 2016 r. w sprawie sposobu prowadzenia oceny zanieczyszczenia powierzchni ziemi, Dz.U. 2016 poz. 1395
				subgroup I	subgroup II	subgroup III	
		As	mg/kg	10	20	50	
		Ba	mg/kg	200	400	600	
		Cr	mg/kg	150	300	500	
		Sn	mg/kg	10	20	40	
		Zn	mg/kg	300	500	1000	
		Cd	mg/kg	2	3	5	
		Co	mg/kg	20	30	50	
		Cu	mg/kg	100	150	300	
		Mo	mg/kg	10	25	50	
		Ni	mg/kg	100	150	300	
		Pb	mg/kg	100	250	500	
		Hg	mg/kg	2	4	5	
	SOC/clay ratio	SOC/clay	-	**Degraded Condition:** A SOC/clay ratio of less than 1:13 indicates a degraded soil structure. At this level, the proportion of organic carbon is insufficient relative to clay, which can lead to compaction, reduced porosity, and poor water retention, adversely affecting crop growth and soil health. **Moderate to Good Condition:** A SOC/clay ratio between 1:13 and 1:8 suggests a moderate to good soil structure. This range indicates a more balanced relationship between organic carbon and clay, supporting adequate soil aggregation, moisture retention, and nutrient availability. **Very Good Condition:** A ratio greater than 1:8 represents a very good soil structural condition. High levels of organic carbon relative to clay contribute to excellent soil structure, promoting enhanced aeration, drainage, and microbial activity, all of which are crucial for optimal plant growth and soil fertility.			Proposal for a DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on Soil Monitoring and Resilience (Soil Monitoring Law) COM(2023) 416 final

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ECOSYSTEM ELEMENT	FEATURES	SYMBOL	UNIT	INDICATORS THRESHOLDS DESCRIPTION	LITERATURE
	Extractable phosphorus	Olsen-P	(mg Olsen-P kg− 1 soil	Extractable Phosphorus, measured using the P-Olsen method, reflects the bioavailable phosphorus content crucial for assessing soil fertility. This index defines five fertility classes based on phosphorus levels in the soil: **Very Low (< 5 ppm):** Indicative of severe phosphorus deficiency, requiring substantial phosphorus supplementation to prevent yield limitations. **Low (6-9 ppm):** Suggests inadequate phosphorus for optimal growth, needing moderate fertilization to improve crop productivity. **Medium (Optimum) (10-13 ppm):** Represents ideal phosphorus levels that support optimal crop yield without excessive leaching risks. **High (14-18 ppm):** Higher than necessary for most crops, which may lead to decreased efficiency of phosphorus usage and potential environmental risks due to runoff. **Very High (> 18 ppm):** Excessively high levels that might not enhance crop yield further and could pose serious environmental concerns, such as phosphorus leaching, necessitating management to reduce P levels to prevent ecological impacts. Additionally, the new EU Directive on Soil Monitoring and Resilience specifies that Member States must establish a "maximum value" for extractable phosphorus within the range of **30-50 mg/kg**, aiming to standardize soil health assessments across the EU and ensure sustainable agricultural practices.	1) Steinfurth, Kristin & Börjesson, Gunnar & Denoroy, Pascal & Eichler-Lobermann, Bettina & Gans, Wolfgang & Heyn, Johannes & Hirte, Juliane & Huyghebaert, Bruno & Jouany, Claire & Koch, Dierk & Merbach, Ines & Mokry, Markus & Mollier, Alain & Morel, Christian & Panten, Kerstin & Peiter, Edgar & Poulton, Paul & Reitz, Thomas & Rubaek, Gitte & Buczko, Uwe. (2022). Thresholds of target phosphorus fertility classes in European fertilizer recommendations in relation to critical soil test phosphorus values derived from the analysis of 55 European long-term field experiments. Agriculture, Ecosystems & Environment. 332. 107926. 10.1016/j.agee.2022.107926. 2) https://www.eea.europa.eu/publications/soil-monitoring-in/file 3) Proposal for a DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on Soil Monitoring and Resilience (Soil Monitoring Law) COM(2023) 416 final
	Salinization	SS	dS/m	**Less than 4 dS/m at 25°C** when measured using the saturated soil paste extract method (eEC). This level is recognized as the upper limit for non-saline conditions conducive to most agricultural activities. Areas typically excluded from productive land use include naturally saline regions and those affected by sea level rise, both characterized by high salt levels that hinder conventional agriculture and increase vulnerability to degradation.	Proposal for a DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on Soil Monitoring and Resilience (Soil Monitoring Law) COM(2023) 416 final
	Acidity	SA		**Very Acid (pH < 4.9 H_2O, pH < 4.5 KCl)**: Represents extreme soil acidity that can significantly limit the growth of most plants and microbial activity, leading to severe degradation of the ecosystem. Such acidity may necessitate substantial liming and other soil amendments to mitigate toxicity and restore ecological balance. **Acid (pH 5.0 – 5.9 H_2O, pH 4.6 - 5.5 KCl):** Indicates moderately acidic conditions that might restrict the diversity of plant species and microbial functions. While not immediately toxic, this level of acidity may hinder certain agricultural uses and require moderate soil conditioning. **Lightly Acid (pH 6.0 – 6.9 H_2O, pH 5.6 - 6.5 KCl):** Slightly acidic soil conditions that generally support a broader range of plant life but may still pose mild restrictions on certain sensitive species or crops. Minor adjustments such as light liming might be beneficial. **Neutral (pH 7.0 H_2O, pH 6.6 - 7.2 KCl):** Ideal for most agricultural and natural ecosystem functions, indicating no degradation related to acidity. This range is typically targeted in reclamation efforts to ensure the maximum functionality of the soil. **Lightly Alkaline (pH 7.1 – 8.0 H_2O, >7.2 KCl):** These conditions are generally favorable for many types of plant life and microbial populations but may begin to restrict the availability of certain nutrients such as iron, manganese, and phosphorus. **Alkaline to Very Alkaline (pH 8.1 – 9.4 H_2O and >9.4 H_2O):** High alkalinity can lead to significant challenges in nutrient uptake for plants, potentially leading to degradation if not managed properly. Reclamation may involve soil acidification processes to reduce pH to more suitable levels.	

ECOSYSTEM ELEMENT	FEATURES		SYMBOL	UNIT	INDICATORS THRESHOLDS DESCRIPTION	LITERATURE
geotechnics	soil structure	porosity	Φ	%	Soil should have about **50%** porous space that is filled with air or water. Ideal conditions for plant growth occur when the soil has the right balance of water-filled and air-filled pores	Stirzaker, R.J., Passioura, J.B. & Wilms, Y. Soil structure and plant growth: Impact of bulk density and biopores. Plant Soil 185, 151–162 (1996). https://doi.org/10.1007/BF02257571
		Bulk density	ρ	g/m^3	**Healthy soil condition:** **Sand, Loamy Sand, Sandy Loam, Loam (<1.80 g/cm³):** These textures are ideal for maintaining good porosity and aeration, facilitating root penetration and efficient water management. **Sandy Clay Loam, Loam, Clay Loam, Silt, Silt Loam (<1.75 g/cm³):** These soils balance moisture retention and structural stability, requiring careful management to maintain their health. **Silt Loam, Silty Clay Loam (<1.65 g/cm³):** The increased silt and clay content in these soils necessitates careful monitoring to prevent excessive compaction and promote good drainage and root development. **Sandy Clay, Silty Clay, Clay Loam with 35-45% clay (<1.58 g/cm³):** High clay content makes these soils more susceptible to compaction, emphasizing the need for practices that enhance structure and fertility. **Clay (<1.47 g/cm³):** Given their tendency towards high compaction, maintaining low bulk density is crucial for ensuring sufficient porosity and aeration in these highly clay-rich soils.	Proposal for a DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on Soil Monitoring and Resilience (Soil Monitoring Law) COM(2023) 416 final
	soil erosion	RUSLE	A	t/ha/y	The upper limit of tolerable soil erosion, which is equal to the rate of soil formation, is about **1.4 t/ha/year**. This is the value that maintains the balance between soil loss and formation, which is essential for maintaining soil ecosystem services. The lower limit of tolerable soil erosion is about **0.3 t/ha/year**. This value is considered the minimum at which the soil is able to continue to perform its functions without significant degradation. It is recommended that the precautionary principle be applied in environmental policy, meaning that soil loss should be kept below **1 t/ha/year** to ensure long-term sustainability. Exceeding this value can lead to the gradual disappearance of soils with particularly low formation rates. In some regions of Europe, tolerated erosion values can be higher due to specific soil and climatic conditions. In Switzerland, for example, the tolerated value is 1 t/ha/year, and is increased to 2 t/ha/year for certain soil types.	F.G.A. Verheijen, R.J.A. Jones, R.J. Rickson, C.J. Smith, Tolerable versus actual soil erosion rates in Europe, Earth-Science Reviews, Volume 94, Issues 1–4, 2009, Pages 23-38, ISSN 0012-8252, https://doi.org/10.1016/j.earscirev.2009.02.003.

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