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Report on crucial factors influencing dumps and potential indicators of dump deformation and best practices and failures for re-utilization

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SUMMARY

Outer and inner dumps created during coal and lignite mining are among the biggest and most intricate geotechnical structures. Their behavior is governed by extreme spatial heterogeneity and time-dependent evolution which differentiate them fundamentally from natural soils. Recent European projects such as SLOPES and SUMAD and new datasets from Poland, Czechia and Greece confirm that spoil geomaterial properties (index, stiffness, strength, compressibility, permeability) vary more than in typical in-situ formations due to excavation, haulage and dumping methods, source lithology, and construction sequencing. This variability, together with hydrological conditions, features both shallow and deep-seated instabilities as well as long-term settlements that affect reutilization.

This report consolidates deformation indicators that are practical and sensitive to triggering mechanisms leading to instabilities. These deformation indicators refer to surface and in-depth displacements (rate/acceleration), pore-water pressure, soil moisture, rainfall intensity/duration, longitudinal and transversal seismic waves velocities and groundwater level. It also includes vegetation/spectral change as a representation for moisture and erosion. Moreover, the report frames re-utilization pathways (e.g., renewable energy installations, recreation/forestry, agriculture) and common failure modes in redevelopment. Best practices for the sustainable re-utilization of mine waste dumps are presented, drawing from a comprehensive review of existing literature and successful case studies. Conversely, common failures and their underlying causes are also analyzed to provide valuable lessons for future reclamation projects.

The report underscores the necessity of a holistic approach that integrates thorough site characterization, robust monitoring, and sound engineering design to ensure long-term stability and beneficial reuse of mines dumps. The findings and recommendations presented herein are intended to contribute to the development of a comprehensive risk assessment framework within the MiDSafe project, ultimately promoting safer and more sustainable post-mining landscapes.

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1. Introduction

The extraction of coal and lignite, particularly through surface mining methods, generates vast quantities of overburden material that are typically deposited in large, engineered structures known as mine dumps or spoil heaps. These mine waste dumps (external and in-pit) are constructed not only from excavated overburden but also sometimes from processing residues such as coal fly ash. Unlike natural stratified soil formations, mine waste dumps are randomly mixed by excavation, transport, and deposition, spanning particle sizes from clay to boulders and often showing coarse-to-fine segregation at faces and lift interfaces. Their internal structure reflects dumping method (end-dumping, push-dumping, layer placement, stacker spoiling), construction sequencing, and source geology, yielding steep heterogeneity in density, suction, stiffness, and strength—hence obviously non-uniform drainage and deformation responses.

A Europe-wide state-of-the-art review shows spoil properties vary more than typical natural soils, with time-dependent changes (e.g., suction loss with wetting, ongoing consolidation) and both shallow translational and deep-seated mechanisms reported (Masoudian, et al., 2019). This variability challenges classical limit-equilibrium assumptions and favors combined deterministic–probabilistic, hydro-mechanically coupled analyses calibrated by monitoring.

These issues are of pressing concern and have great historical and societal implications. For instance, the 1966 Aberfan disaster, which occurred due to the rapid failure of a colliery tip situated over springs triggered by heavy rainfall, serves as an affecting warning story. It underscores the critical importance of saturation, drainage, and effective stewardship in the context of geological disasters (British Geological Survey). Moreover, the advent of modern regulatory frameworks, exemplified by Directive 2006/21/EC, has codified risk management practices for extractive waste, including waste rock dumps (EUR-Lex).

Consequently, these dumps, often covering extensive areas and reaching significant heights, represent a considerable challenge to environmental management and long-term land use planning. The stability of these structures is of paramount importance, as failures

can have catastrophic consequences, including loss of life, environmental damage, and significant economic losses. Furthermore, the large area of land occupied by mine dumps necessitates their effective reclamation and re-utilization to restore ecosystems and create beneficial post-mining landscapes.

This report of MiDSafe (Advancing Post-Mining Waste Dump Safety and Sustainability) research project, refers to Tasks 2.3 (development of potential indicators of dump deformation) and 2.4 (analysis of re-utilisation options) for large spoil dumps associated with coal and lignite surface mining. It aims to identify crucial factors influencing dump stability, potential indicators of deformation, and best practices for their safe and sustainable re-utilization. This is particularly important for the large dumps created from coal and lignite mining, which are often characterized by heterogeneous and geotechnically complex materials. More specifically, the objectives of this report are to:

- Identify and analyze potential indicators of dump deformation. This involves a thorough review of monitoring techniques and early warning signs of instability, which are essential for proactive risk management.
- Investigate the geotechnical factors and soil properties that critically influence the re-utilization of mine dumps. Understanding the complex relationship of these factors is fundamental to designing stable and sustainable reclamation schemes.
- To describe best practices for the re-utilization of mine dumps and common failures. By learning from both successful and unsuccessful case studies, this report will provide practical guidance for future projects.

Based on the above the next parts of the report are:

In Section 2 the key factors affecting mine dump stability, the most common indicators (warning signs) for dump deformation and the best practices in monitoring the crucial factors affecting the stability of mine dumps are presented. Section 3 reviews the main geotechnical factors and soils properties affecting dumps re-utilization. Best practices for dumps re-utilization and common failures are described in Section 4, and finally in Section 5 the conclusions are given.

2. Mine waste dump stability, deformation indicators and monitoring practices

2.1 Crucial factors affecting mine waste dump stability

A variety of geotechnical, hydrological, environmental, and anthropogenic factors act in combination to control the stability of a mine dump. Table 2.1 summarizes the critical factors in each category and their typical influence on dump stability. These factors determine the dump's factor-of-safety against slope failure and must be considered in dump design and management. Geotechnical factors largely determine the dump's inherent shear strength and gravity stresses, whereas hydrological factors (water content and pressures) often provide the trigger that reduces strength and induces movement while environmental conditions can impair both. Particularly, foundation conditions are often the weakest link since poor foundation support (soft or wet ground under the dump) is a frequent cause of slope instability. Stable bedrock or compacted soil foundations offer high strength, but soft clay or wet soil foundations may settle or fail when overloaded. In practice, many failures occur due to a combination of factors – for instance, an end-dumped spoil pile with loosely placed fine material might stand for years when dry, but after heavy rains it could build pore pressure in an underlying weak layer, leading to a sudden rotational slip (Hawley & Cunning 2017).

From a risk management perspective, it is helpful to distinguish static predisposing factors (like geometry and material properties) from dynamic triggering factors (like intense rain, rapid loading, or seismic events) (Wei et al., 2018; Jiang et al., 2022). Static factors set the stage – they determine how close to the brink of instability a dump is – while triggers push the dump towards failure. Human factors include operational decisions in dump construction which affect the static stability, and human activities which can also introduce triggers (for example, allowing uncontrolled water accumulation, or blasting too near a steep dump). MiDSafe project aim to analyze and mitigate these multi-faceted risks, by building extensive geotechnical databases and developing risk assessment methodologies for European coal and lignite waste dumps.

Table 2.1. Key factors influencing mine dump stability.

Factor Category	Specific Factors	Influence on Stability
Geometric (Design)	<p>Dump configuration: Height, overall slope angle, volume, overall shape.</p> <p>Foundation geometry: Slope of base ground, confinement (valley vs. flat).</p>	<p>Taller dumps and steeper slopes induce greater driving forces and larger potential slide volumes. Large dump volume can extend failure runout. A high, over-steepened dump is more prone to collapse. A concave (decreasing) foundation slope and valley confinement improve stability by providing lateral support. In contrast, dumping on a sloping or unconfined foundation can exacerbate instability (Hawley & Cuning, 2017).</p>
Geotechnical (Material)	<p>Dump material properties: Grain size distribution, fraction of fines/clay, particle shape and durability, shear strength (cohesion, friction angle).</p> <p>Layering and heterogeneity: Placement of weak layers or soft soil within stronger rock, presence of weak planes.</p> <p>Degree of compaction: Density achieved during dumping, presence of loose zones.</p>	<p>Strong, coarse, durable rock fragments with little fines form the most stable dumps, similar to rockfill. Abundant fine-grained or weatherable materials (e.g. mudstone, shale) lower shear strength over time (fines can absorb water and reduce friction). Weathering (wet-dry or freeze-thaw cycles) can degrade rock to smaller particles, further reducing stability. If soft or weak materials are dumped beneath harder rock, they can act as glide planes for failure. Poor compaction or loose tipping results in low density and lower shear strength, making the dump more susceptible to settlement and shear failure (Hawley & Cuning, 2017).</p>
Hydrological	<p>Water content & pore pressure: Rainfall infiltration, snowmelt, groundwater level within dump and foundation (Wei et al., 2018).</p>	<p>Water is often the critical trigger in dump failures. Infiltration from heavy rain or snowmelt raises pore water pressure, which reduces effective stress and material shear strength, potentially leading to slope failure or flow slides (Jiang et al., 2022). Well-drained, coarse dumps can remain effectively dry and stable, but if</p>

Factor Category	Specific Factors	Influence on Stability
Environmental	Drainage conditions: Surface runoff control, presence (or absence) of internal drains, perched water tables.	fines accumulate and “blind” the base drainage, water can build up internally. Poor dump drainage or a high water table in the foundation (especially if the dump sits on clay or an aquifer) greatly increases failure risk. Proper design (e.g. diversion ditches, drainage blankets) is needed to prevent water accumulation.
	<p>Climate and weather: Intense rainfall (as above), prolonged wet periods, freeze-thaw cycles, temperature variations.</p> <p>Chemical reactions: Oxidation of sulfides (acid generation) or spontaneous combustion in coal-rich dumps (SUMAD project, 2022).</p>	<p>Extreme weather can destabilize dumps. Intense or long-duration rain is a primary cause of dump failures (e.g. triggering landslides or debris flows). Freeze-thaw and thermal cycles cause material breakdown and loosening, reducing strength over time. In certain coal or pyrite-rich waste piles, exothermic oxidation or slow burning can occur internally, creating voids or weakening the structure (as seen in Libiąż, Poland, where an endogenous fire affected a spoil heap) (SUMAD project, 2022). Such processes undermine dump integrity and complicate reuse efforts.</p>
Seismic & Dynamic	Seismic vibrations: Earthquakes or mining-induced tremors/blasting vibrations.	Vibrations can induce instability by rapidly generating shear stresses and pore pressures. The greatest seismic concern is liquefaction when saturated fine-grained dump materials or weak foundation soils may lose strength during an earthquake. Even if full liquefaction doesn't occur, dynamic loads can weaken dump structure or trigger incremental deformations. Mine blasts or heavy traffic vibrations similarly can aggravate marginally stable slopes. Dumps in seismically active regions require dynamic stability analysis and possibly lower slope angles.
	Dynamic loading: Vibrations from heavy equipment or nearby explosions.	
Anthropogenic	Construction method: Dumping technique (end-dump vs. layer placement), dumping rate, use of compaction.	The way a dump is built strongly affects stability. End-dumping from height tends to segregate coarse and fine material. It can create a free-draining toe (coarse base), it also can form loose, layered slopes prone to slip along interfaces. Rapid, mass dumping of loose material can generate high pore pressures (from loading

Factor Category	Specific Factors	Influence on Stability
	<p>Operational alterations: Excavation at dump toe, adding loads (infrastructure) atop dump, or poor maintenance of drainage controls.</p>	<p>faster than water can drain) and cause rotational failures. Dumping fine wet material at the crest can over-steepen the face (temporary apparent cohesion) until it collapses, with slope angles observed $>43^\circ$ in such cases (Hawley & Cuning 2017). Dumping rate is crucial since without pauses for consolidation, a dump may build up excess pore pressure. Additionally, human activities like cutting into the toe of a dump (for extracting material or by erosion) or adding structures on top without proper foundation treatment can disturb the equilibrium and trigger failure. Lack of maintenance (e.g. clogged ditches, unchecked seepage) also falls in this category, as it allows minor issues to compound into major instability.</p>

2.2. Indicators of mine dump deformation

Early identification of dump instability is vital to prevent catastrophic failure. There are often progressive signs of movement or distress in a dump that, if recognized, can prompt intervention. These indicators may be observed visually in the field, measured instrumentally, or detected via remote sensing. They typically reflect the dump mass deforming, cracking, or its drainage conditions changing as the slope's stability degrades. Table 2.2 below lists common deformation indicators and what they potentially signify.

In practice, no single indicator should be considered in isolation since engineers look for a combination of signs. For example, gradual displacement data (from GPS or InSAR) verified by the appearance of cracks and tilting trees presents a convincing case of developing instability. By systematically monitoring these signs, mine operators can move from reactive to proactive management – identifying creep long before a collapse. In summary, early deformation indicators range from the qualitative (visual changes in slope condition or vegetation) to the quantitative (instrument-recorded movements, micro-seismic signals, moisture levels). Recognizing and tracking these indicators is fundamental to dump safety, forming the basis for the monitoring practices presented below in section 2.3.

Table 2.2. Observable indicators of mine dump deformation and their implications.

Indicator of Instability	Potential cause or significance
<i>Indicators based on motion or geometry change</i>	
<p>Measured ground displacement – for example, via survey benchmarks, GNSS/GPS stations, or InSAR remote sensing.</p>	<p>The most direct indicator of instability is the ground actually moving. Prisms or survey targets on the dump, when monitored by total station or GPS, may show slow downslope movements (e.g. a few mm or cm per day). Space-borne InSAR can detect broad deformation across the dump surface in the order of millimeters. An increasing rate of measured displacement is a critical warning sign of an impending slope failure. Modern satellite radar or ground-based radar can map these deformations over the whole dump in near-real time (Wei et al., 2018).</p>
<p>Surface cracks or fissures (especially near the dump crest or on slopes) – e.g. tension cracks opening on top benches or scarps forming on slope faces.</p>	<p>Cracking indicates that the dump mass is stretching or bending under movement. Tension cracks at the crest suggest the upper part of the dump is pulling away (precursor to a slide or slump). Cracks may allow water infiltration, accelerating failure. Monitoring crack width/depth over time (with gauges) helps assess if movement is active (Hawley & Cuning, 2017).</p>
<p>Bulging or “cattle track” patterns on slope faces – wavy, hummocky outward bulges of material on the dump surface.</p>	<p>A bulge midway down a slope is a classic sign of creep or slow outward movement in the dump. As the toe pushes out, the slope material above can deform into ridges (hence the term cattle tracks). This usually precedes a rotational slip. Any new bulging of dump toes or slope mid-sections indicates internal stress redistribution and potential failure developing (Girard, 2001).</p>
<p>Tilting or curving of trees, poles, fences, or other upright objects on or near the dump.</p>	<p>Progressive slope movement can tilt objects. On unstable slopes, live trees may grow with a pronounced curvature (as they continually adjust to tilt), and dead trees or poles tend to lean downhill in the direction of movement. Such vegetative indicators are useful where direct measurement equipment is absent. If poles or trees that were previously vertical on a dump are no longer upright, this indicates that the ground beneath them has shifted. (Girard, 2001).</p>

Indicator of Instability**Potential cause or significance**

Sudden appearance of fresh rubble at the toe of the dump or small rockfalls/slides from dump faces.

New debris accumulations at the base signal that material is breaking off from higher up – a likely sign that portions of the slope are failing. Small falls often precede larger collapses. If there is an increase in minor slides, sloughs, or falling rocks from a dump slope (especially in periods of rain or thaw), it suggests the slope's stability is worsening (Girard, 2001).

Indicators based on moisture and vegetation change

Wet spots, seeps, or springs emerging where none existed before (or water flowing out of the dump face).

Changes in the dump's hydrology can indicate internal stress changes. New wet areas or seepage on the slope might mean water is finding a path through a developing shear zone or that the phreatic surface (water table) inside the dump has risen. Such seepage can further weaken the material by lubricating slip surfaces (Hawley & Cunning, 2017).

Rising pore water pressure and upward migration of the phreatic surface.

Rising pore water pressure and upward migration of the phreatic surface reduce effective stress and shear strength. In layered, segregated dumps, perched water tables can form where fines accumulate and blind drains. Initial high permeability from end-dumping can be lost as fines migrate and foundation interface blinding develops, creating perched zones and local softening even where coarse rockfill predominates. These indicators can be measured by using:

- Piezometers (standpipe and vibrating-wire/MEMS arrays) across benches and foundations to map pore water pressure fields and perched horizons.
- Skempton - B-bar (response of pore water pressure to total stress change) during dumping phases as a compact stability indicator in spoil dumps.

Indicator of Instability

Potential cause or significance

Rainfall intensity - duration

Many large waste-dump instabilities are triggered by rainfall, with both storm intensity and prior ground moisture conditions playing a critical role. Global reviews and threshold models (intensity–duration, intensity–duration–antecedent precipitation) provide a framework for site-specific thresholds relating forecast rain to expected pore water pressure suction responses (Jiang et al., 2022). Ways of determining the above include on-site rain gauges, soil moisture and pore water pressure to calibrate thresholds and link storm thresholds to operational controls (e.g activate drainage, restrict access).

Abnormal vegetation changes on the dump surface (besides tilting): e.g. patches of vegetation dying off or sudden lush growth of hydrophilic flora.

Vegetation stress or growth patterns can reflect subsurface conditions. For instance, if part of a slope gets waterlogged due to a rising water table, trees might die from root rot (too much water) or certain reeds might invade, indicating excessive moisture – a red flag for stability, as high moisture correlates with lower strength. Conversely, if an area of a coal-rich dump heats up (internal fire), vegetation will wither. So, unusual plant health changes could indirectly indicate deformation or internal chemical reactions. Multispectral indices (NDVI, NDRE, thermal) can detect stressed vegetation from moisture anomalies, shallow settlement or erosion.

Others

Micro-seismic activity or unusual sounds (e.g. muffled rumbling, cracking noises) coming from the dump.

Earthquakes or vibrations from mining operations (blasting, heavy trucks movement) can induce additional stresses within the dump, potentially triggering failures, especially in already weakened structures (Poulsen et al., 2014).

2.3. Monitoring and ensuring long-term stability

Continuous monitoring is essential to manage mine dump stability over the long term. Best practices involve deploying a suite of monitoring techniques to track dump behavior in real time (or near-real time) and to ensure any emerging instability is detected early. Modern mine dump monitoring is a multi-disciplinary effort, combining geotechnical instrumentation, remote sensing, and advanced modeling. In the completed RFCS project SLOPES emphasized integrating modern monitoring techniques into automated systems that provide real-time risk assessments, with a particular focus on UAV (drone) surveys to reduce the need for humans in hazardous areas. Below is given an overview of the key monitoring practices and stability management strategies:

- **Regular geotechnical surveys:** Classical methods include installing survey markers or prisms on the dump and periodically measuring their positions with GPS or automated total stations. A network of such points can reveal millimeter-to-centimeter scale movements over time. For example, prism reflectors can be read automatically by a robotic total station on a daily or hourly basis, establishing movement trends. Additionally, precise leveling can detect any settlement of the dump surface. These geodetic measurements provide quantitative displacement data to validate visual observations.
- **Instruments in Boreholes:** Slope inclinometers (in boreholes drilled into the dump or its foundation) are a standard technique for detecting internal movement. An inclinometer casing allows periodic probing to measure any lateral deflection at various depths, thus identifying the depth of a slipping layer if one forms. Similarly, vibrating wire or piezometric pore pressure gauges can be installed to monitor groundwater levels inside the dump and foundation. A rising piezometric level is a red flag (since elevated pore pressure reduces stability). Many monitoring plans include standpipe piezometers or TDR (time-domain reflectometry) cables to sense shear deformations subsurface. These instruments directly address the critical parameters identified earlier, the rock mass displacement, and ground water conditions (Girard, 2001).

- **Surface inspection and crack monitoring:** Mine personnel should routinely inspect dump slopes for any new cracks, slumps, or drainage issues. Simple tools like crack gauges can track the progression of surface fractures. Photographic records or ground lidar scans also help compare changes over time. Importantly, rainfall data is collected on-site (rain gauges) because precipitation is often the trigger for movements – correlating rainfall intensity with any observed deformation helps in stability analysis (Dong et al., 2025). Operators also watch for any signs like those in Section 2 (bulging, leaning objects, etc.). Regular inspections following heavy rain or spring thaw are necessary.
- **Remote sensing technologies:** Satellite-based interferometric synthetic aperture radar (InSAR) has become a powerful tool to monitor dump movements over large areas. InSAR can detect ground deformations (on the order of millimeters) by comparing phase changes between radar images over time. It has been successfully used in waste dump monitoring to map spatial deformation patterns and identify active zones (Wei et al., 2018). In addition to satellites, ground-based InSAR (a radar unit on a tripod or trailer scanning the slope) can provide near-real-time deformation imaging of a dump, even in a dusty environment or darkness. European mines can obtain InSAR data every few days from the Sentinel-1 satellites to watch for any accelerating trends.
- **Drone (UAV) photogrammetry:** Drone photogrammetry is another state-of-the-art approach where drones can fly over a dump to capture high-resolution images used to construct a 3D digital surface model. By repeating flights (e.g. weekly or after major rain events) and differencing the 3D models, morphological changes, new scarps, or volumetric changes in the dump can be detected. UAV-based monitoring has proven capable of handling large structures and provides a safe way to survey inaccessible dump slopes (Mankar & Koner, 2023). For accuracy, these photogrammetric models use ground control points to tie into known coordinates. Some studies combine UAV surveys with numerical modeling – e.g. capturing the current geometry in a 3D

model and then running stability analyses on that model (Chand & Koner, 2025). Overall, remote sensing offers broad coverage and frequent data without requiring physical access to the dump.

- **LiDAR (Light Detection and Ranging):** LiDAR is a complementary remote sensing technique that provides highly accurate three-dimensional representations of mine waste dumps by emitting laser pulses and measuring their return time from the surface. Airborne LiDAR, deployed via aircraft or UAV platforms, can generate dense point clouds that allow precise characterization of dump geometry, slope angles, crest positions and surface roughness, even in areas with sparse vegetation where photogrammetry may struggle. Repeated LiDAR surveys enable change-detection analyses, making it possible to quantify small-scale deformations, erosion features, or progressive slope movements with centimetric to decimetric accuracy (Jaboyedoff et al., 2012; Glenn et al., 2016). For mine waste dumps, LiDAR has proven particularly valuable in long-term stability monitoring, where subtle precursory deformations can precede larger failures. Several studies highlight the robustness of LiDAR-based monitoring under varying illumination and surface texture conditions, making it well suited for integration with geotechnical analyses and numerical slope-stability models (Oppikofer et al., 2009; Abellán et al., 2014). When combined with UAV photogrammetry, LiDAR enhances the reliability of surface deformation assessments and supports early-warning strategies for mine waste dump instability.
- **Sensor networks and IoT:** Recent innovations include wireless sensor networks placed on or in dumps to provide continuous monitoring. MiDSafe project is aiming to develop a low-power IoT network of sensors across a dump, each node capable of measuring tri-axial vibrations (accelerations), small deformations, and environmental parameters like moisture and temperature. These nodes communicate wirelessly (Zigbee/WiFi mesh) to send data to a central system in real time. A dense array of accelerometers can detect micro-seismic activity or subtle movements that might precede a larger failure. Some

sensor systems also include tiltmeters (measuring tilt of the ground or structures) and strain gauges. Micro-seismic monitoring (using geophones or acoustic emission sensors) can effectively “listen” for sounds of cracking or movement inside the dump that are too slight to feel otherwise. By analyzing such data with advanced algorithms (e.g. fuzzy inference systems, as foreseen in MiDSafe), continuous stability assessments can be made.

- **Hydrological and environmental controls:** Best practices include robust drainage control (keeping water off and out of the dump as much as possible), slope erosion protection like re-vegetation or rock armoring of drainage channels and sometimes covers or liners to prevent water infiltration (Hawley & Cuning, 2017). Many European regulations require closed dumps to have a rehabilitation plan that addresses these issues. Monitoring of water is critical: this includes not just piezometers as noted but also checking that diversion ditches aren’t clogged and that no new springs have appeared. Some dumps prone to combustion are fitted with temperature probes to monitor internal heat. In essence, long-term stability management often means transforming an “active” dump into a fully rehabilitated landform – graded to gentler slopes, properly drained, and vegetated – and then monitoring it for years or decades. For example, installing permanent inclinometers and piezometers that are read periodically even after closure can ensure any post-closure movements are caught early (Girard, 2001).
- **3D stability modeling and risk assessment:** Monitoring data should feed into ongoing stability analysis. The best practice is the use of 3D numerical models (finite element or limit equilibrium models) that simulate the dump and can be updated as material properties become better known or if deformation trends indicate changing conditions. The SLOPES project applied advanced numerical modeling and probabilistic analyses to interpret monitoring results and predict future stability. By comparing model predictions with observed behavior (from instruments), the model (observational method) can be refined and the accuracy of stability calculations can be improved. Probabilistic methods (reliability

analysis) are particularly useful since they account for uncertainties in material properties and loading and provide a probability of failure rather than a single factor of safety. This helps decision-makers understand the risk level in quantifiable terms. Some projects are creating software to integrate geotechnical data, monitoring inputs, and reliability calculations to guide dump reuse decisions (Białas & Kozłowski, 2024). In practice, companies often have trigger action response plans that link monitored values to actions for instance, if prism movement exceeds a warning value of mm/day, declare alert level, if exceeds an alarm value of mm/hour, evacuate the area and stop work. Continuous modeling and risk review ensure that such thresholds are appropriate and that the dump remains stable under expected conditions (and even extreme events like a 100-year rain or seismic event).

In summary, best practices for monitoring mine dumps involve a combination of:

- Frequent field inspections and qualitative observations.
- A set of instruments measuring displacements, pore pressures, and environmental factors continuously or at regular intervals.
- Adoption of remote sensing (drones, InSAR, etc.) for broad coverage and detecting slow trends.
- Real-time data analysis tools that assimilate these measurements into assessments of stability (often visualized on dashboards or alarm systems).

Deploying multiple, redundant monitoring methodologies is essential for mitigation, ensuring that the potential failure of one system is covered by alternative observational techniques. Monitoring must extend into the post-operational phase since the primary goal is proactive risk management.

3. Geotechnical factors governing the re-utilisation of coal and lignite waste dumps

The re-utilisation potential of coal and lignite mine waste dumps is controlled predominantly by their geotechnical behaviour. These large anthropogenic landforms differ fundamentally from natural soil deposits due to their mode of construction, material origin, and time-dependent evolution. These dumps are typically formed by rapid placement of heterogeneous overburden materials excavated from multiple lithological units and deposited using methods that promote segregation and variable compaction. Consequently, their internal structure, hydraulic regime, and mechanical properties exhibit pronounced spatial variability and evolve over operational and post-closure timescales (Masoudian et al., 2019; Zevgolis et al., 2021).

Extensive European datasets from Greece, Poland, and the Czech Republic confirm that spoil properties—index parameters, density, stiffness, permeability, and strength—show substantially higher coefficients of variation than those typically reported for natural soils (Zevgolis et al., 2020; Baecher & Christian, 2003). This variability, coupled with strong hydro-mechanical sensitivity, governs both the stability of dumps and their suitability for subsequent land uses. As a result, the feasibility of reuse is more often limited by deformation and usability considerations than by ultimate limit states, particularly for infrastructure exposed to cyclic loading or stringent performance criteria (SUMAD Project, 2022).

3.1 Material variability and basic geotechnical characteristics

Coal and lignite mine dumps materials encompass a wide spectrum of soils, commonly ranging from sandy or gravelly materials to fine-grained silts and clays with moderate to high plasticity. Case studies from European lignite mines demonstrate that fines contents exceeding 40–60 wt% are frequent, leading to predominant classifications of MH, ML, CL, and CH soils (according to the Unified Soil Classification System - USCS), interbedded irregularly with coarser layers

(Zevgolis et al., 2020; Zevgolis et al., 2021). Atterberg limits, natural water content, and unit weight exhibit large scatter, even within individual benches, reflecting both geological heterogeneity and dumping procedures.

This material variability has direct implications for reuse design since fine-grained, plastic spoils tend to exhibit reduced shear strength, higher compressibility, and lower permeability, whereas coarse zones may behave in a rockfill-like manner but are prone to segregation-induced anisotropy. Importantly, heterogeneity is not solely lithological but also procedural since end-dumping typically promotes particle-size segregation, while dozed or layered placement modifies density and fabric (Hawley & Cuning, 2017; Piteau Associates et al., 2017). Consequently, geotechnical characterisation for reuse must be statistically robust, reporting distributions and design quantiles rather than relying on single characteristic values, as recommended by reliability-based geotechnical practice (Baecher & Christian, 2003).

3.2 Hydraulic behaviour and hydro-sensitivity

Hydraulic conditions constitute the dominant control on both short-term stability and long-term performance of mine dumps. Permeability within a single dump can vary by several orders of magnitude due to segregation, layering, and progressive fines migration. Although coarse end-dumped zones initially provide effective drainage, weathering and particle breakage may lead to clogging of voids and blinding of interfaces, resulting in perched water tables and localised pore-pressure build-up (Masoudian et al., 2019; SLOPES project, 2019).

In fine-grained spoils, unsaturated conditions often prevail near the surface, with matric suction contributing significantly to shear strength. However, intense or prolonged rainfall can rapidly dissipate suction, leading to marked reductions in effective stress and strength, as demonstrated by coupled hydro-mechanical studies on European lignite dumps (Masoudian et al., 2019). Monitoring experience from the SLOPES project has shown that pore-water pressure

evolution, particularly when interpreted using Skempton's B-bar coefficient, provides a sensitive indicator of impending instability during both operational and re-utilisation phases (SLOPES project, 2019). These findings highlight the necessity of conservative infiltration assumptions and robust surface and internal drainage systems in any reuse scheme, consistent with the objectives of Directive 2006/21/EC on extractive waste management (EUR-Lex, 2006).

3.3 Strength, stiffness, and deformation behaviour

Shear strength parameters of coal and lignite spoils show wide scatter and strong dependence on grading, plasticity, density, and saturation state. Coarse, low-fines materials may be reasonably approximated using friction angles comparable to natural angles of repose, whereas fines-rich spoils commonly exhibit lower effective friction angles and modest apparent cohesion (Zevgolts et al., 2020). Time-dependent processes such as consolidation, weathering, and chemical alteration can further modify strength and stiffness over years or decades (Masoudian et al., 2019).

For reuse applications, useability limit states are generally more critical than ultimate limit states. Spoils are typically highly compressible compared to natural soils of similar plasticity, with settlements arising from immediate particle rearrangement, primary consolidation, and long-term creep (Theocharis et al., 2022). These deformations can govern performance well before bearing capacity is mobilised, particularly for assets sensitive to rotation or differential settlement, such as photovoltaic installations and wind turbine foundations. Consequently, deformation-based criteria in accordance with Eurocode 7 guidance (European Commission, 2013) should form the basis of reuse design.

3.4 Cyclic loading, liquefaction potential, and interface effects

Re-utilisation introduces load conditions that differ noticeably from those experienced during dump construction. Cyclic horizontal and overturning loads from wind turbines, repeated traffic loading, and seasonal moisture variations can induce progressive accumulation of deformation at stress levels well below ultimate capacity. Numerical and experimental investigations within the SUMAD project demonstrated that serviceability, rather than strength, governs the feasibility of such reuses, often necessitating load-transfer systems or ground improvement (SUMAD project, 2022; Bhattacharya, 2019).

Although not abundant, the potential for static softening or liquefaction must be considered where saturated, contractive layers exist, particularly if drainage is impeded by low-permeability caps. Documented flow slide failures in coal waste dumps underline the importance of identifying such conditions through laboratory testing and field monitoring (Dawson et al., 1998). In addition, the interaction between the dump and its foundation plays a critical role since ongoing consolidation of weak subgrades beneath dumps can alter stress paths and stiffness distributions, influencing the response of new foundations placed at the surface (SLOPES project, 2019).

3.5 Ground improvement and engineering adaptation for reuse

Given the typical thickness of mine dumps, reuse strategies focus on improving the near-surface zone or transferring loads through inclusions rather than full-depth treatment. Field experience across Europe indicates that dynamic compaction and rolling dynamic compaction can significantly increase stiffness and reduce settlements in suitable spoils (Woods et al., 2016). Chemical stabilisation using lime, cement, or fluidised-bed combustion ash has also demonstrated substantial gains in bearing capacity and modulus, supporting photovoltaic parks and light structures while aligning with circular-economy principles (SUMAD project, 2022).

For applications with stringent deformation limits, such as wind turbines, piled solutions or rigid inclusions beneath rafts are often required to control rotation and differential settlement (Bhattacharya, 2019; Al Heib et al., 2022). Equally important are hydraulic measures including chimney drains, toe drains, interceptor ditches, and erosion protection which directly address the primary triggering mechanisms associated with water ingress and pore-pressure rise. Successful reuse therefore relies on integrated mechanical and hydraulic adaptation rather than geometry modification alone (Hawley & Cunning, 2017).

3.6 Integrated design approach and asset-specific implications

A robust design methodology for dump re-utilisation integrates desk studies, risk-led site investigation, coupled hydro-mechanical analysis, and serviceability-based foundation design within an observational framework. Zoning of dumps according to placement history, material composition, and drainage characteristics provides the basis for targeted investigation and modelling. Parameters should be treated statistically, and monitoring data, particularly pore-water pressure and displacement, should be used to refine assumptions during construction and operation, consistent with the observational method endorsed in Eurocode 7 (European Commission, 2013).

Different reuse options impose distinct geotechnical performance requirements. Photovoltaic systems are sensitive to differential settlement and seasonal moisture changes, industrial platforms require adequate stiffness for traffic and slabs, and wind turbines demand strict control of rotation under cyclic loading. Matching the reuse option to achievable ground performance, supported where necessary by ground improvement and drainage, is therefore central to achieving safe and sustainable post-mining land use (Al Heib et al., 2022; SUMAD project, 2022).

4. Best practices for dumps reutilization, common failures

Best practices for remediation and subsequent reclamation/reutilization of dumps follow structured framework. This framework provides both a conceptual and operational linkage between long-term strategic planning, technical and engineering measures, ecological restoration processes, and the socio-institutional dimensions of post-mining landscape transformation. This chapter focuses on those aspects that, according to current research and practical experience, are most critical in determining the effectiveness of reclamation interventions. In particular, this includes the physical characteristics of dumps (Section 4.1), namely their geotechnical stability, morphological configuration, and hydrogeological conditions, which substantially influence the selection of appropriate engineering and nature-based restoration measures. Subsequent management of soil cover and vegetation (Section 4.2) represents a prolonged ecological–successional trajectory through which ecosystem structures and functions are progressively re-established. The following Section 4.3 describes best practices in the planning process and in selecting reutilization options. The final part of this section presents selected examples of sites where reclamation of dumps has already been carried out, illustrating different approaches and degrees of success achieved in applying post-mining landscape reclamation strategies.

Furthermore, increasing emphasis is placed on public participation and stakeholder engagement, which have become central components of socially and culturally embedded post-mining landscape transitions. At this stage, the process is introduced in a general form (Section 4.4), as the project includes a detailed case study from the Czech Republic that examines the application of these principles in a specific territorial and institutional context. The results of this case study will be published in an article, and the analytical outputs will also be included

in Deliverable 5.3, thereby providing a more comprehensive methodological and interpretative basis for the practical application of the proposed framework.

4.1 Best practices in stability assessment

A comprehensive assessment of the stability of dumps is a crucial step in ensuring their safe closure, rehabilitation, and integration into the post-mining landscape. Unlike natural slopes, dumps are anthropogenic landforms characterized by high spatial heterogeneity, variable compaction, and heterogeneous material composition. These properties result in complex mechanical behaviour and long-term changes due to settlement and weathering, requiring a systematic, multidisciplinary approach to stability analysis (Hawley & Cunning, 2017; Gupta et al., 2021). The goal is to ensure that dump slopes remain stable and safe in the long term for planned post-mining land use.

Geotechnical characterization and slope stability analysis

Dump materials are primarily composed of overburden rocks and spoil fragmented sediments and rock debris often mixed with clay-rich and weakly consolidated layers. These materials exhibit variable grain-size distributions, differing moisture sensitivities, and varying susceptibility to weathering, leading to significant variability in shear strength parameters within the dump body (Bishwal et al., 2018). Proper geotechnical characterization therefore combines laboratory tests (e.g., direct shear tests, triaxial compression tests, Atterberg limits) with in-situ field measurements (e.g., bulk density, degree of compaction, shear wave velocity).

Slope stability of dumps is typically assessed using limit equilibrium methods (e.g., Bishop, Janbu, Spencer) and increasingly through advanced numerical modeling (finite element or finite difference methods). Numerical models allow simulation of processes such as rock weakening due to water infiltration and the progressive development of failure zones within the slope (Gupta et al., 2021). For long-term static conditions, a Factor of Safety (FoS) of at least 1.3 is generally required, while higher minimum values may be necessary in cases of seismic loading, elevated

pore pressures, or the presence of critical infrastructure on the dump (Hawley & Cuning, 2017). In addition to overall stability, attention must also be paid to specific phenomena:

- localized shear zones formed during dumping operations
- internal stratification reflecting the sequence of deposition
- zones of differential settlement due to uneven compaction and loading in different parts of the dump

These internal features may not be visible at the surface and often require geophysical surveys or borehole investigations for detection and analysis.

Hydrogeological conditions and drainage management

Water is one of the key factors affecting dump stability. Its presence reduces effective stress in the rock mass and can activate deep-seated shear surfaces. A hydrogeological assessment should therefore include:

- determination of rainfall infiltration rates into the dump body and the dump's response to intense precipitation
- potential formation of perched water tables in fine-grained clay layers within the dump
- existence of preferential flow paths or internal drainage channels formed by permeable coarse-grained material
- hydraulic connectivity between the dump and surrounding aquifer systems

Intense rainfall and insufficient drainage can lead to rapid increases in pore water pressure and reduced slope stability. In operational conditions, dump failures triggered by extreme rainfall events have been repeatedly documented when adequate drainage of stormwater was not ensured (Koner & Chakravarty, 2016).

If the dump contains sulfide-bearing rocks prone to oxidation (so-called PAF—Potentially Acid Forming materials), the contact of pyrite, oxygen, and water can generate Acid Mine Drainage (AMD). AMD significantly damages the environment

and accelerates chemical weathering, weakening the internal structure of the dump material (Adibee et al., 2013). To mitigate these processes, engineered cover systems are often proposed, such as surface layers that limit rainfall infiltration into the dump body and oxygen diffusion to reactive minerals. These cover systems may be permeable and store-and-release type in arid regions, or impermeable (e.g., clay barrier types) in humid climates, and are designed to minimize the generation and release of contaminated water from the dump over the long term. Typical dump drainage systems include:

- surface collection and diversion ditches to direct runoff and prevent uncontrolled infiltration into the dump
- rock drains or drainage galleries within the dump body to control internal pore pressures
- berms (horizontal benches) on slopes to divide long slopes into smaller segments, guiding runoff and reducing slope erosion.

Drainage design is often supported by hydrological modelling of water flow and rainfall retention using tools such as HELP, SEEP/W, or MODFLOW. These tools help size drains and surface ditches to ensure that even extreme rainfall events do not lead to water accumulation within the dump and a reduction in its stability.

Slope recontouring and progressive rehabilitation

Long-term operational experience shows that steep and unmanaged dump slopes are highly susceptible to erosion, shallow landslides, and rill formation. Therefore, progressive rehabilitation efforts focus on reshaping slopes to stable angles and geometries during dump construction. Recommended final slope angles typically range from 18–26° (approximately 1:3 to 1:2, height: base ratio), depending on material properties, climate, and vegetation potential for the site (Hawley & Cuning, 2017). Rehabilitation measures typically include:

- terracing of slopes and construction of berms to segment long slopes, these features interrupt continuous slope surfaces, slow surface runoff, and reduce deep erosion

- application of erosion control mats, mulches, or fiber rolls on slopes—these materials temporarily stabilize the soil surface until permanent vegetation is established,
- revegetation involves establishing vegetation cover on the dump using suitable plant species to reduce surface runoff, reinforce the soil through root systems, and increase evapotranspiration.

Plant selection is based on local ecological and hydrological conditions, with preference given to deep-rooted, drought-tolerant pioneer species. Vegetation plays a dual role: it mechanically reinforces the surface soil layers of the slope through root systems (roots act as reinforcement and increase soil shear strength) and helps regulate the water balance by reducing infiltration and increasing evapotranspiration. Studies show that a well-developed vegetation cover can significantly reduce surface erosion and rill formation, thereby limiting further infiltration into the slope (Ranjan et al., 2015). Native species that are suited to their local environment are commonly utilised (see more in chapter 4.2).

4.2 Best practices in soil and vegetation management

Effective soil and vegetation management is fundamental for successful land restoration on post-industrial or post-mining sites. A healthy soil foundation and a well-established plant cover work in tandem to control erosion, rebuild ecosystem functions, and facilitate long-term self-sustainability of the reclaimed landscape (Sheoran et al., 2010; Zine et al., 2024). The most widely accepted practices focus on restoring soil quality (physical structure, fertility, microbial activity) and ensuring robust revegetation with appropriate species. Below are key proven methods, supported by recent scientific studies.

Topsoil conservation and replacement

Salvaging topsoil before disturbance and reapplying it during reclamation is a best practice that retains native seeds, nutrients, and soil microorganisms, thereby jump-starting ecosystem recovery (Mackenzie & Naeth, 2024). Direct placement

of fresh topsoil (avoiding long stockpiling) has been shown to produce richer vegetation and higher biodiversity than using stockpiled soil, which often suffers losses of organic matter and biotic viability. When direct replacement is not possible, stockpiled topsoil should be stored for the shortest time feasible and in low mounds to preserve its quality (Nsiah & Schaaf, 2019).

Alleviating soil compaction

Reducing compaction is critical for root penetration and water infiltration on reclaimed sites. Heavy machinery can leave mine soils dense and impermeable, leading to poor plant growth. Best practice is to deep rip or loosen compacted substrates before planting, creating a friable soil to at least 1–1.5 m depth. Research shows that trees and shrubs establish more successfully on loosely graded or ripped mine soils than on smooth, compacted surfaces, due to better root growth and moisture availability (Groninger et al., 2017; Sheoran et al., 2010). This practice helps prevent the “arrested succession” often observed on unreformed mine soils (wherein only hardy grasses persist and forest development is stalled).

Soil amendments and fertility management

Degraded spoils frequently lack nutrients and organic matter. Incorporating organic amendments (such as compost, manure, sewage sludge, wood chips, or biochar) is a proven method to improve soil structure, increase water-holding capacity, and supply essential nutrients for plants (Sheoran et al., 2010; Buta et al., 2019). Organic matter amendments stimulate microbial activity and nutrient cycling, which in turn supports sustainable fertility. For example, a 40-year study in Romania found that adding farmyard manure and planting nitrogen-fixing legumes significantly improved soil carbon and nitrogen levels on reclaimed mine lands (Buta et al., 2019). Adjusting soil pH is another important step: many dumps are acidic or alkaline to extremes. Applying lime to acidic soils (or sulfur to highly alkaline soils) ensures pH is in a neutral range optimal for plant growth and microbial function (Sheoran et al., 2010).

Erosion control and surface stabilization

Newly reclaimed slopes are prone to erosion until vegetation takes hold. To protect the soil, practitioners deploy mulches, erosion control blankets, and sediment barriers immediately after regrading. Mulching with straw or wood fiber helps retain moisture and shields the soil from rain impact, while biodegradable geotextile mats (jute, coir) support steep slope stabilization. These measures are complementary to rapid revegetation: quick-growing cover crops (grasses or legumes) are often seeded to provide interim groundcover that anchors the soil within the first growing season (Ranjan et al., 2015).

Use of native and suitable plant species

Best practice is to utilize native or locally adapted plant species for seeding and planting, as they are genetically suited to the climate and soil, and they support local biodiversity (Gairola, Bahuguna, & Bhatt, 2023). A diverse mix of species is preferred over monocultures: combining grasses, forbs, shrubs, and trees can mimic natural successional processes and lead to a more resilient ecosystem (Zine et al., 2024). For instance, Zine et al. (2024) report that introducing indigenous tree species alongside herbaceous cover in Moroccan mine lands led to improved soil organic matter and a return of native fauna, compared to exotic grass seeding. Nitrogen-fixing plants (e.g., clovers, lupines, acacias) are often included to naturally enrich soil nitrogen and assist other plants' growth (Ranjan et al., 2015).

Maintenance and adaptive management

In the initial years of reclamation, some maintenance is necessary to secure the success of soil and vegetation efforts. This includes weed control, which prevents invasive or undesirable species from outcompeting the planted natives (Skousen & Zipper, 2014). It is recommended to monitor vegetation cover, species composition, and soil parameters (such as nutrient content or pH) in order to be able to respond flexibly to any problems that may arise, such as nutrient deficiencies, pest infestations, or incipient erosion (Wortley et al., 2017). For example, if monitoring reveals low nitrogen in soil after a few years, managers might interseed additional legumes or apply fertilizer to bolster plant growth.

In summary, best practices in soil and vegetation management for land restoration revolve around rebuilding a fertile, stable soil profile and establishing a self-sustaining plant ecosystem. Core recommendations include conserving and improving topsoil, relieving compaction, enhancing soil organic matter and nutrients, protecting the surface from erosion, and using site-suited native vegetation with a successional strategy. These practices are strongly supported by reclamation research and decades of field experience (Sheoran et al., 2010; Gairola et al., 2023; Zine et al., 2024). Implementing such practices increases the likelihood that a reclaimed site will quickly develop into a stable landscape that functions ecologically and requires minimal long-term maintenance.

4.3 Best practices in planning process and in selection of reutilisation options

Effective reclamation planning and the selection of appropriate post-mining land uses require a systematic approach that accounts for both environmental and socio-economic characteristics of the site. In recent years, multi-criteria assessment methods have gained prominence, enabling a comprehensive evaluation of land potential for various uses, including ecological restoration, agricultural and forestry development, as well as recreational, energy, or industrial functions (Arratia-Solar et al., 2022). A key component of this process is participatory planning, which involves local governments, expert institutions, landowners, and the public. This inclusive approach strengthens the legitimacy of proposed solutions and increases the likelihood of their long-term sustainability (Worden et al., 2024).

The choice of a specific reutilisation option should be based on a detailed assessment of geotechnical and soil conditions, infrastructure availability, ecological value, and spatial relationships to settlement structures. In areas near municipalities, reclamation interventions with aesthetic and recreational functions are generally preferred, while in open landscapes, forestry or agricultural uses are more appropriate (Frantál et al., 2024). Another key criterion is the ability of each

form of reutilization to contribute to the socioeconomic advancement of the region, particularly in areas affected by the decline of the mining industry.

Definitions and terminology (Reclamation, Rehabilitation, Restoration, Reutilization)

There is still uncertainty regarding terminology in the field of post-mining land transformation and planning for its future use. Frantál et al. (2024) point to inconsistent and often confused terms such as recultivation, restoration, remediation, rehabilitation, regeneration, revitalization, and recycling, whose meanings vary depending on the discipline, regional traditions, and intentions of individual actors. This inconsistency complicates interdisciplinary communication, hinders project planning and evaluation, and can lead to misunderstandings about the goals and success of the transformation. In this report, we therefore use the following terms for terminological clarity.



Reclamation

Reclamation represents the broadest and most comprehensive approach to landscape restoration after mining. Its goal is to restore the ecological value, economic functionality, and overall usability of the area, either by returning it to its original state or by creating a new type of landscape use. Reclamation includes both technical modifications (e.g., terrain shaping, ensuring stability) and biological and functional interventions (e.g., grass planting, tree planting, soil preparation for agriculture or other forms of use). It is a basic framework that encompasses other specific approaches such as rehabilitation, restoration, and reutilization.



Rehabilitation

Rehabilitation is primarily focused on ensuring the technical safety and physical stability of the area. It mainly concerns dumps, slopes, or other terrain formations that are at risk of erosion, landslides, or other hazardous phenomena. It is not a return to the original ecosystem, but rather the creation of conditions that will enable safe and stable long-term use of the area. Rehabilitation is often a necessary first step before other types of reclamation measures.



Restoration

Restoration focuses on restoring the natural ecosystem as close as possible to its original state. It aims to restore the original species composition, soil conditions, and ecological functions—in other words, to recreate the natural environment. Restoration is usually more demanding, longer-term, and often implemented in cases where the area has high ecological or conservation value. It often goes hand in hand with the goals of biodiversity, natural restoration, or landscape aesthetics.



Reutilization

Reutilization means new, functional use of post-mining landscapes for purposes other than ecological ones. This may involve converting the area into zones for renewable energy sources (e.g., photovoltaic power plants), recreational areas, agricultural production, housing, or industrial areas. An important aspect is the adaptation of the space to current and future social needs. Reutilization therefore often represents an opportunity for the socioeconomic revitalization of the area, especially in regions affected by the decline of mining.

Reclamation planning process (past and present)

The planning of reclamation activities has evolved significantly over time in response to changing mining practices, societal expectations, and increasing environmental awareness. Understanding the temporal and spatial dynamics of land degradation and subsequent restoration is essential for designing effective and sustainable post-mining land use strategies. Reclamation is increasingly viewed not merely as a technical requirement but as a complex socio-environmental process that must be tailored to the specific conditions of each site. The relationship between mining activities, land degradation, and reclamation evolves throughout the mining lifecycle. As illustrated in Figure 4.1, this cycle spans several decades, with the intensity and nature of reclamation activities varying markedly across different project phases, from exploration and site development through operation, closure, and post-closure. While early stages offer limited opportunities for land restoration, the transition from active extraction to

closure represents a critical turning point, enabling the gradual release of land for reclamation. Figure 4.1 also shows approximately how long this cycle lasts:

- During the period from the opening of the deposit to the full development of mining, extensive land acquisition for the mine and external dumps prevails, while recultivation is only possible to a limited extent in areas not needed for mining.
- In the period after mining has developed until its termination, conditions are created for the gradual release of land from mining for reclamation, to an extent corresponding to further land acquisition. External dumps are gradually abandoned, and soil is returned to the mined areas as internal dumps. The reclaimed area gradually exceeds the mining area.
- After the end of mining, there is no further acquisition of land and virtually the entire area affected by mining is suddenly released for reclamation – including dumps and residual pits. This period can be called the post-closure period, and the level of activity is lower, requiring long-term specific care.

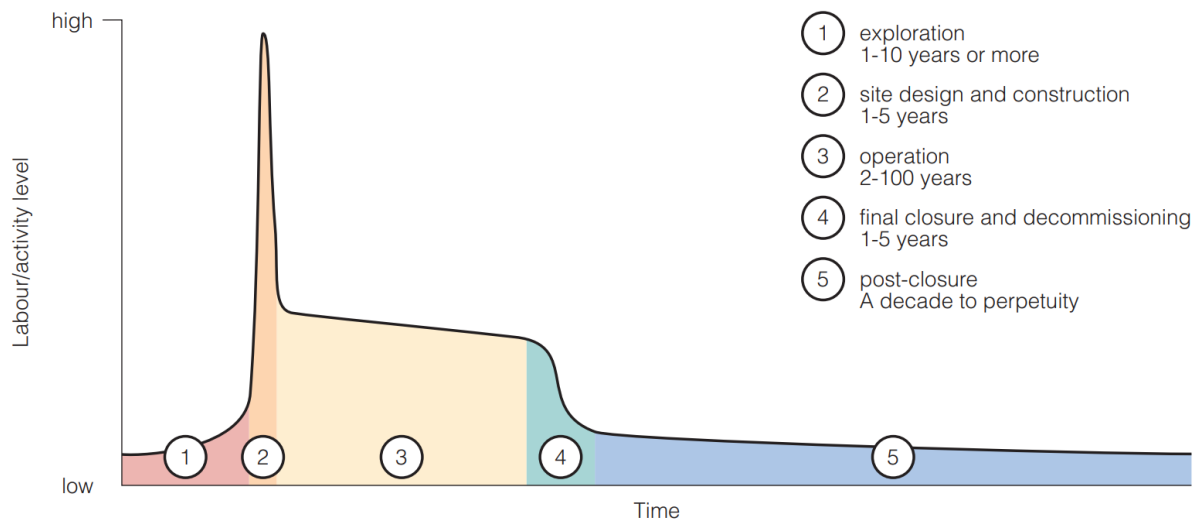


Figure 4.1. Mine project life cycle (ICMM, 2012b)

Over time, reclamation approaches have shifted from narrowly technical interventions toward more integrated, landscape-scale, and socially responsive planning frameworks. Contemporary strategies emphasize ecological restoration,

multifunctional land use, and participatory planning, reflecting broader trends in environmental governance and regional development.

Reclamation issues have a long tradition in Europe. Their level has always corresponded to the social conditions of the time, the relationship to the land as a basis for livelihood and as an important component of the environment. From the outset, however, it has been perceived not only as a technical problem, but above all as a social one. Reclamation strategies have evolved from the level of the soil to the dimension of the landscape, in line with the concept of spatial and technical development of settlements and the entire mining area. The optimization of the use of various reclamation methods is addressed specifically. In the vicinity of settlements, reclamation with high aesthetic value and significant potential for socially useful recreational use is preferred. In open countryside, forestry and agricultural reclamation is preferred (Štýs, 2015).

The development of reclamation tendencies can be divided into the following three stages:

Stage of remediation and planting of greenery, when reclamation was mainly focused on grassy and green areas without major habitat modification, under the motto "clothes make the man, greenery makes the landscape".

Economic-production stage, characterised by improved soil substrate formation, preference for economically productive tree species and a significantly higher proportion of agricultural reclamation.

Greening and revitalisation phase that corresponds to the current period. It is characterised by a preference for an ecological-landscape approach to the reclamation of large areas, where the aim is to achieve a certain level of biodiversity – and a functional connection of the reclaimed areas with the surrounding landscape and its inhabitants.

Current view on reclamation

In the current debate on post-mining landscape transformation, the question of how justified it is to continue prioritizing technically and financially costly reclamation measures over alternative approaches, particularly leaving the area to spontaneous or controlled succession, is becoming increasingly important (Frantál et al., 2024). Natural succession allows for the creation of new, ecologically valuable habitats that not only support biodiversity and provide refuge for endangered species of fauna and flora, but also offer space for aesthetic, recreational, and tourist use (Wiegleb & Felinks, 2001; Sádlo & Gremlica, 2017; Braun et al., 2021). Despite these benefits, its wider application remains limited—both due to rigid legislative frameworks and a lack of practical experience, as well as due to the ingrained ideas of experts, land managers, and the public about what post-mining landscape restoration should look like.

One of the main arguments against succession is its long-term nature and the absence of immediate economic benefits, which makes it less attractive to investors and mine operators (Bradshaw, 2000). The key task therefore remains to assess the suitability of using succession processes in the context of the specific natural, climatic, and socioeconomic conditions of a given location. This assessment should take into account the extent of the disturbed area, its location in relation to settlement structures, the area's potential for ecological and cultural use, and the associated environmental and social risks (Marot & Harfst, 2021; Pešout et al., 2022; Ronyastra et al., 2023).

In order to make effective decisions in these complex conditions, various methodological approaches based on multi-criteria assessment and analysis of land use suitability have been developed in recent years. These tools often integrate the expertise of stakeholders and specific regional experience, thereby supporting participatory and informed decision-making by public authorities, mine operators, and other interested parties (Amaro et al., 2022; Arratia-Solar et al., 2022; Worden et al., 2024).

Options for reclamation and reutilization of dumps

Currently, the most widely applied approaches to the reclamation and subsequent utilization of mine dumps can be broadly categorized into two principal groups: nature-based (Figure 4.2) and socio-economic (Figure 4.3). The first group encompasses land uses aimed at restoring ecological functions and landscape structure—most notably agricultural, forestry, hydric, and renaturalization strategies. These approaches contribute to long-term ecological stability, biodiversity enhancement, and the sustainable reintegration of disturbed sites into the surrounding environment (Bradshaw, 2000; Gairola et al., 2023). The second group includes reutilization-oriented strategies that focus on assigning new socio-economic functions to post-mining landscapes, such as recreational infrastructure, renewable energy installations, industrial zones, or transport corridors (Frantál et al., 2024; Worden et al., 2024).

Agricultural reclamation involves converting the dump's surface into croplands, pastures, or other forms of farmland once stability is secured. This typically requires soil reconstruction, which includes applying salvaged topsoil or amendments to create a fertile soil layer, and regrading the terrain into gentle slopes suitable for farming (Sheoran et al., 2010). When successfully implemented, agricultural reclamation can yield arable land such as permanent grasslands or orchards on former dumps, thereby restoring both economic productivity and ecological function.

Forestry reclamation focuses on establishing tree cover on the dump, either for timber production or for the purpose of ecosystem restoration. Fast-growing pioneer trees and shrubs are often planted, or allowed to seed naturally, to rapidly stabilize the substrate and initiate soil development. This process is typically followed by ecological succession that leads to the formation of a self-sustaining forest. Research indicates that vegetating mine dumps with woody species enhances slope stability, as root systems reinforce the soil and reduce both erosion and water infiltration (Ranjan et al., 2015), while simultaneously creating habitats for wildlife. In some cases, special-purpose forests such as windbreaks or

soil-protective plantations, or short-rotation lignoculture involving fast-growing biomass crops, are established on dumps. These approaches aim to balance ecological benefits with potential economic returns (Skousen & Zipper, 2014). Both agricultural and forestry strategies require careful selection of plant species that are well adapted to the local climate and substrate. The use of native species is widely regarded as best practice, as it accelerates natural succession and supports biodiversity recovery (Gairola et al., 2023).

Hydric reclamation, which involves water-based reclamation, transforms parts of the mine dump or pit into aquatic ecosystems. In this approach, mine voids or subsided areas are either allowed to fill naturally with water or are engineered to function as reservoirs, resulting in the formation of pit lakes, ponds, or wetlands. These newly created water bodies can support aquatic habitats and serve recreational or resource-related purposes, provided that water quality is adequately managed (McCullough et al., 2020). For instance, flooded mine pits have been successfully repurposed for wildlife conservation, fisheries, and public recreation activities such as swimming and boating. They have also been utilized for water supply and flood control (McCullough et al., 2020). Effective hydric reclamation requires ensuring slope stability and addressing potential issues such as acid mine drainage or contamination, in order to ensure that the resulting lake or wetland is both safe and ecologically functional.

Renaturalization, also known as natural succession, represents a passive reclamation strategy in which a dump is rehabilitated through spontaneous ecological processes rather than through intensive replanting. This may involve either unassisted natural revegetation or assisted succession, where a few pioneer species are introduced to initiate the process, after which natural colonization proceeds. Over time, native vegetation establishes itself on the dump, progressing through various successional stages toward a stable and resilient ecosystem. This method can result in the development of novel habitats with high biodiversity, often serving as refuges for native flora and fauna (Bradshaw, 2000; Wiegleb & Felinks, 2001). Studies have shown that allowing natural succession can lead to the

formation of ecologically valuable woodlands or meadows on former mine waste sites, contributing to conservation goals and the creation of new recreational green spaces. However, renaturalization is inherently a long-term process. Its gradual progression and the absence of immediate economic returns, such as those from crop or timber production, have historically made it less appealing to mine operators (Bradshaw, 2000). Nevertheless, this approach is increasingly recognized as a viable and sustainable strategy, particularly in contexts where the primary objective is to create semi-natural landscapes or to enhance biodiversity (Frantál et al., 2024; Marot & Harfst, 2021).

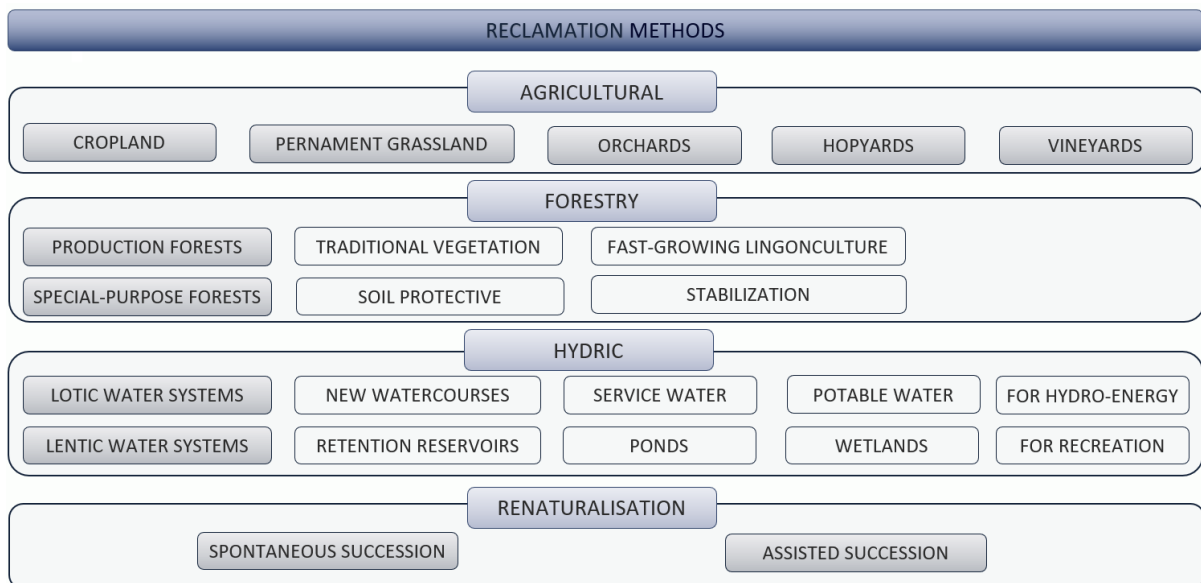


Figure 4.2. Overview of nature-based reclamation methods

Socio-economic reclamation of dumps repurposes these lands for new functions that provide direct public or economic benefits, rather than focusing solely on ecosystem recovery. Three major categories of such reutilization are commonly distinguished: recreational, energetic (renewable energy), and other infrastructure/industrial uses. In each case, the dump must first be rendered geotechnically stable and environmentally safe, but once that foundation is in

place, the land can be transformed to serve community needs or support new industries (Frantál et al., 2024).

Recreational use is one prominent approach, whereby former mine dumps are converted into parks, sports facilities, nature reserves, or other leisure and educational spaces. This strategy can improve landscape aesthetics and public health while also attracting tourism and investment into the area (Marot & Harfst, 2021). For example, turning a dump into an urban green park or botanical garden provides local residents with valuable outdoor recreation space and helps mitigate the scar of mining on the visual landscape. In the Czech Republic and Germany, several former coal or lignite dumps have been re-landscaped into popular recreational parks (with features like hiking trails, lookout points, skiing hills, or even amphitheatres), demonstrating how such projects create socio-cultural value. This approach can spur secondary economic benefits as well, such as jobs in park management or outdoor tourism, and generally enhances the social acceptance of reclamation efforts (Frantál et al., 2024).

Energetic reclamation refers to reutilizing dump sites for renewable energy production. This has become a cutting-edge trend in post-mining landscape planning, aligning land reclamation with climate and energy goals. The flat or terraced plateaus of large dumps and tailing sites are well suited for installing solar photovoltaic (PV) arrays or wind turbines, provided stability and subsidence issues are addressed. Such projects can be beneficial as they find productive use for degraded land and supply clean energy without consuming greenfield space (Frantál et al., 2024). The advantages of energetic reutilization are not only economic (renewable projects create new jobs and revenue streams) but also environmental, by offsetting fossil energy and often by facilitating long-term monitoring of the site (since solar/wind facilities require ongoing maintenance, operators remain engaged with land stewardship). Of course, careful engineering is required to ensure that heavy solar panel racks or turbine foundations do not compromise dump stability. Notably, many mine dumps are near existing grid connections (e.g. power lines or substations from the mine operations), which can

lower the cost of connecting new solar/wind farms to the electricity network (Lin et al., 2023). This synergy makes energetic reclamation both financially and technically attractive in the right contexts.

“Other” reutilization covers a range of additional socio-economic uses of mine dumps beyond ecology, recreation, or energy. Common sub-categories include using the dump or its flat terraces for construction sites, industrial or commercial development, transportation infrastructure, and waste disposal facilities. In some mining regions, dumps have been partially regraded to support buildings – for example, light industry warehouses, logistic centers, even residential developments – once geotechnical studies certify bearing capacity and stability (Worden et al., 2024). Another important reutilization under this category is as engineered landfills or waste processing sites. Because open-cast mining frequently leaves a void or a highly compacted basin, these areas can be adapted (with appropriate liners and environmental controls) to dispose of municipal solid waste or power plant ash, thereby addressing an industrial waste need while also capping and reshaping the dump. Finally, “other” uses can include specialized cases like establishing a campus or research facility on a former dump (e.g. for environmental technology testing, given the unique terrain), or permitting controlled hunting reserves and off-road vehicle courses in large, remote dump areas not suitable for the above uses Frantál et al., 2024).

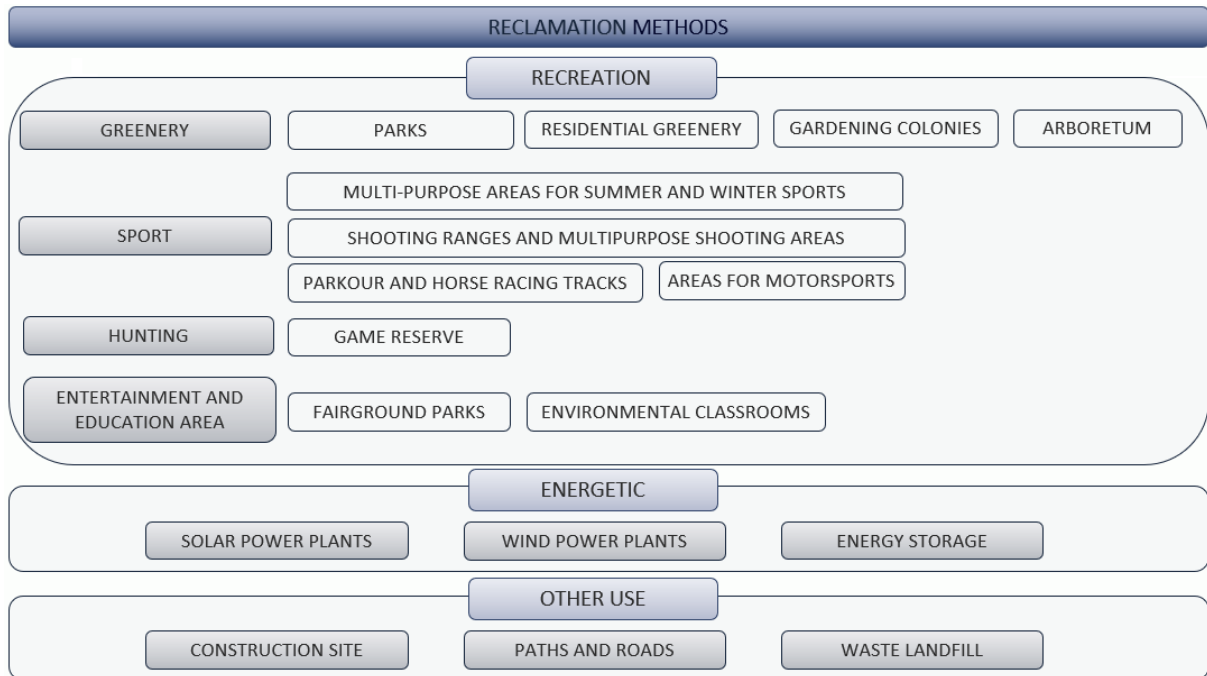


Figure 4.3 Overview of reclamation methods based on socio-economic solutions

Selected cases of reclaimed sites – best practices and common failures

This chapter presents a set of case studies documenting a wide range of approaches to the reclamation and reutilization of post-mining areas. Various types of reclamation measures are included, ranging from nature-based to socio-economic uses of the landscape. In addition to examples of good practice that can serve as inspiration for future projects, there are also cases of problematic implementations, the analysis of which contributes to the identification of risks and lessons learned from past failures.

Greece

Lignite complex of Western Macedonia (LCWM, Ptolemaida–Amynteo mining area), a combination of forestry and agricultural reclamation is proving to be an example of good practice. Over the past 30 years, the energy company PPC has reforested old dumpsites with mainly black locust trees (*Robinia pseudoacacia* L.) – more than 1,500 ha with a density of approximately 2,000 trees/ha. Although black acacia is a non-native and sometimes criticized invasive species, its rapid growth and ability to fix nitrogen and improve poor substrates have proven to be

excellent for the reclamation of degraded soils (Figure 4.4.4). Because of its deep root system, acacia effectively stabilizes the eroded slopes of the dumps and enriches the soil with organic matter, which promotes the subsequent establishment of other tree species (Papadopoulou et al., 2018). At the same time, agricultural reclamation is being carried out on the flat tops of the dumps in LCWM: since 1986, experimental grain sowing has been carried out here to verify the fertility of the reclaimed soils (Figure 4.4). These areas were grassed and then sown with wheat, with PPC leasing them to local farmers for normal farming. Grain yields reach approximately 1–4 t/ha (averaging around 2.2 t/ha), which is comparable to production on the original soils in the region. Furthermore, soil analyses confirm that the reclaimed soils have sufficient nutrients and minimal levels of harmful substances, so that their production capacity is almost on par with unaffected soils.



Figure 4.4 a) *Robinia pseudoacacia* L. plantations used for slope stabilisation and erosion control (Papadopoulou et al., 2018); b) Agricultural lands near Amynteo mine, LCWM, Greece (WINTER Project, 2024)

Germany

One of the largest reclamation projects in Europe is underway in Lusatia: the transformation of dozens of former open-cast mines into a connected area of lakes and recreational areas (Figure 4.4). Since the 1990s, more than 20 large open-cast mines have been flooded, creating the largest artificial lake landscape in Europe with an area of ~155 km². One example is Lake Senftenberg, which was

flooded in the 1970s and around which beaches, marinas, and recreational facilities have been built.

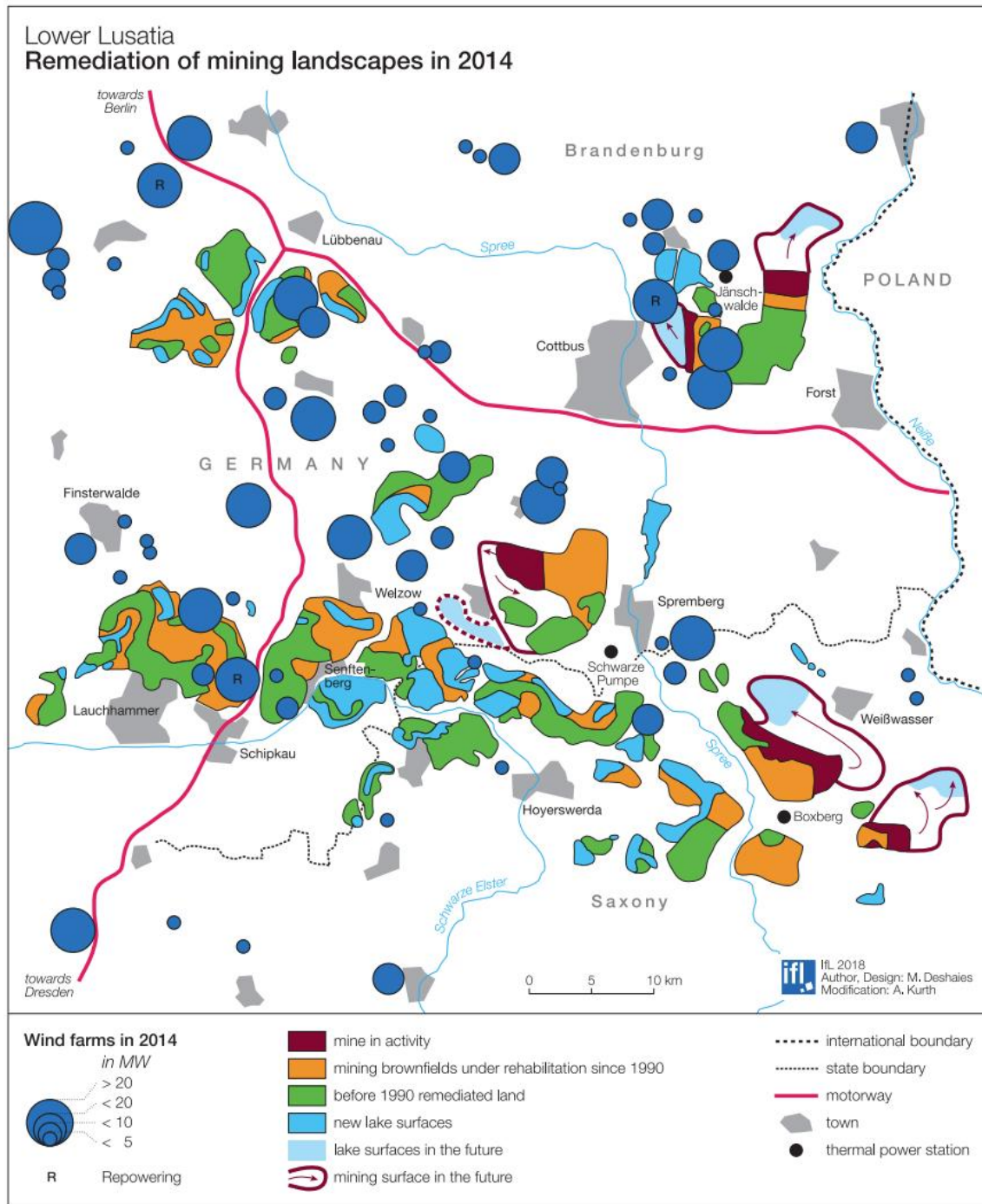


Figure 4.4 Remediation of mining landscapes in Lower Lusatia in 2014; Map: (Deshaies, 2018)

Today, the entire Lusatian Lake District attracts tourists with its cycle paths (1,200 km), water sports, swimming, and new attractions such as observation towers and floating houses (Figure 4.5). The reclamation of Lusatia combines engineering measures (bank reinforcement, slope stabilization, water treatment) with respect for industrial heritage: some preserved mining machines (Figure 4.5) have been left as industrial monuments and tourist destinations (Gannon, 2020). The project has brought new jobs to the region (tourism) and is gradually mitigating the socio-economic impacts of the decline in mining (Wirth et al., 2012; Frantál et al., 2024). Problems that had to be addressed: a number of lakes suffered from water acidity due to pyrite, so continuous water neutralization with lime and aeration is ongoing; some dumps had unstable sediments, which led to isolated landslides (see below "Bergener See" 2010). Overall, however, the Lusatian reclamation demonstrates the possibility of a comprehensive transformation of a mining landscape into a sought-after recreational area (Deshaies, 2018).

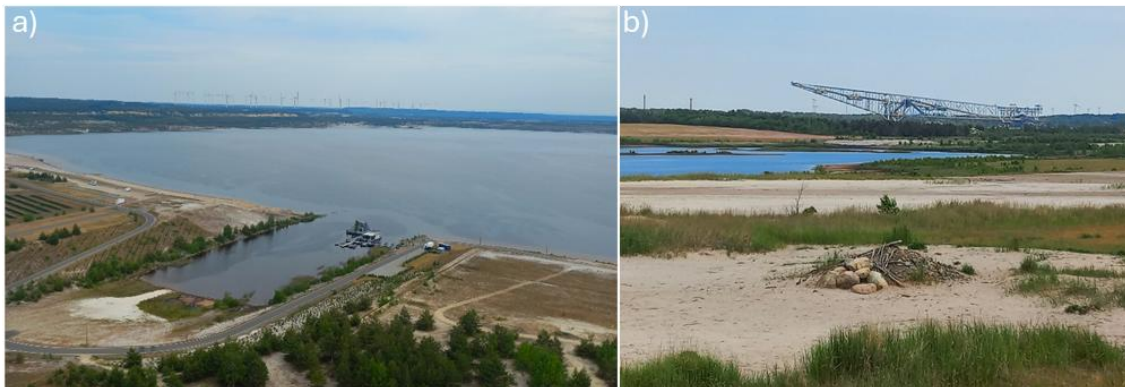


Figure 4.5 a) Linking nature-based and socio-economic reclamation in the Lusatian Lake District; b) The F60 tailings bridge as a monument to mining; Photo: (Dužeková, 2023)

Bergener See in Lusatia – Even in the otherwise successfully reclaimed Lusatian Lake District, a serious incident occurred. On 13 October 2010, a large landslide took place in the area of the future Bergener See, near the village of Spreetal/Bergen. The slide extended for approximately 1.8 km in length and 600 m in width, impacting five trucks working at the site; four drivers managed to

escape, while the fifth was rescued by helicopter (Wikipedia, 2024). The landslide also generated a wave that caused the death of dozens of sheep from a nearby herd. The cause was the instability of the embankments forming the lake shore – water penetrated the sand fill and caused a loss of strength. Engineers from LMBV (the state reclamation organization) subsequently introduced additional measures for other lakes: vibrocompaction of slopes with deep vibrators, creation of stabilizing berms, and controlled blasting to compact the subsoil. The Bergener See case thus shows that even after reclamation, geotechnical risks remain—especially in large-scale hydric reclamation, it is necessary to take into account long-term "settlement" and pay attention to the stability of the banks.

Czech Republic

Lake Most – A similar example of successful reclamation, which also faces certain problems, is the former lignite mine Ležáky near the town of Most, which was flooded and converted into a recreational lake covering an area of ~310 ha. The reclamation took place between 2008 and 2014, resulting in a body of water used for swimming, water sports, and fishing. The adjacent Strimice dump underwent forestry reclamation and today, in conjunction with the flooded residual pit, forms a naturally valuable biotope, especially from an ornithological point of view, as its area of 251 ha makes it the largest bird park of the Czech Ornithological Society. Lake Most has helped to restore the landscape value of the area affected by mining since the surrounding area has been converted into beaches and parks (Figure 4.6). A significant benefit is the improvement of the aesthetic image of the landscape and the creation of new opportunities for sports and tourism (Hlavinková & Vařechová, 2019). However, maintaining the water level remains a challenge – Most has no natural inflow or outflow, and the level was achieved by pumping water from the Ohře River. As a result of warming and drought, evaporation losses are higher than originally anticipated; it is necessary to continuously replenish the water through pipes, which costs approximately €400,000 per year. This fact shows that despite the overall success of the hydric reclamation, the lake requires long-term technical support (Frantál et al., 2024).

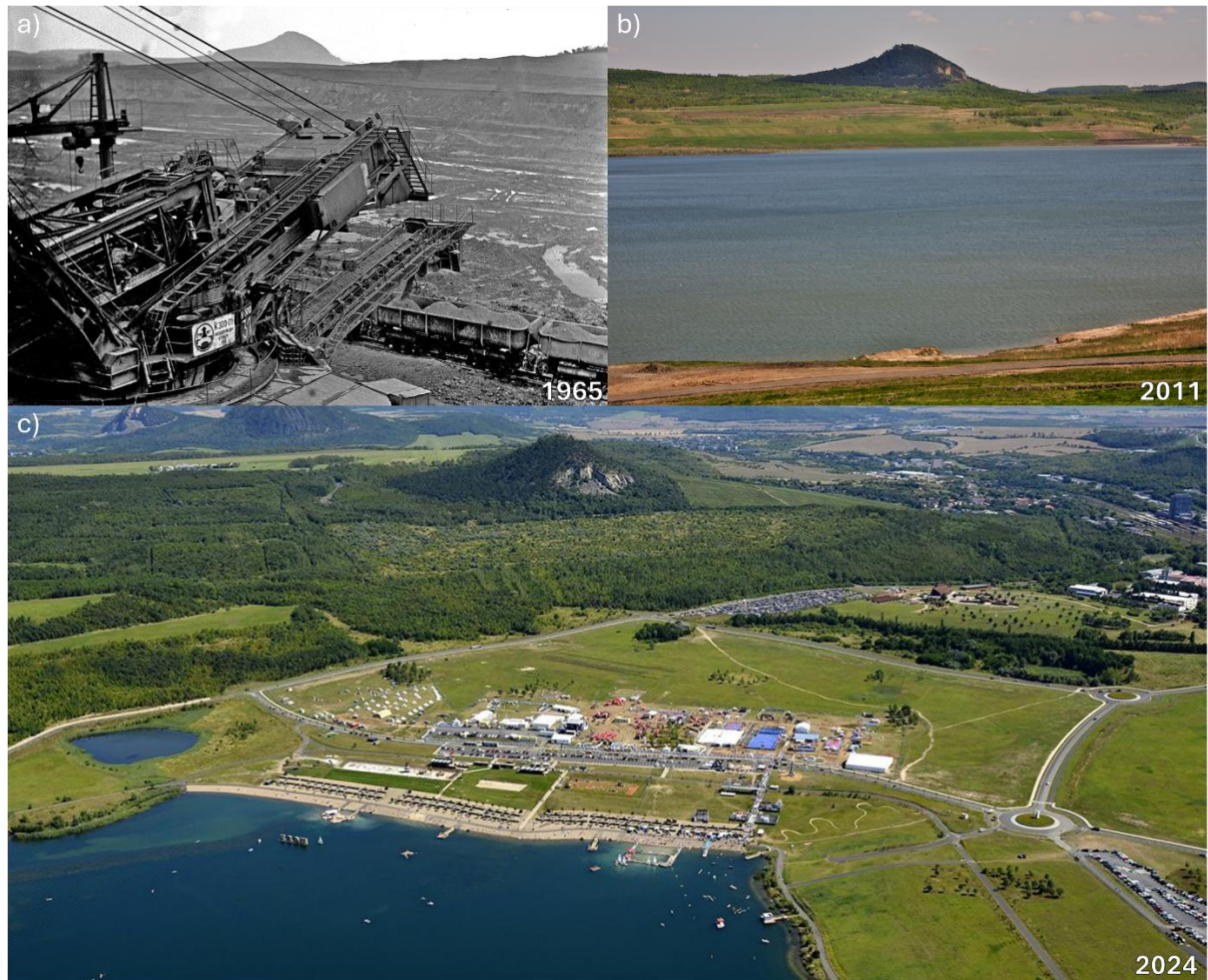


Figure 4.6 Transformation of the former Ležáky open-cast mine: hydric reclamation of the residual pit and forestry reclamation of the adjacent Střimice dump; Photo: a) b) (Štýs, 2015), c) (Město Most, 2025)

Poland

Sieniawa open-cast mine - Experts consider the reclamation of the Sieniawa lignite mine in the Lubuskie region to be a model example of sustainable reclamation. This small lignite mine (in operation since the 1970s, closed in 2002) continuously reclaimed the mined areas, mainly through forest reclamation using native tree species. Even during operation, some of the reclaimed areas were transferred to state forests (e.g., ~20 ha were afforested and transferred around 1975). After mining ceased, most of the mine area was completely afforested (mixed deciduous and pine trees) with the aim of blending in with the surrounding landscape (Figure

4.8). Part of the dumps with less fertile soil were converted into wetlands and small water areas, which increase biodiversity. Thorough soil preparation (topsoil filling, landscaping) and cooperation with local authorities and foresters have resulted in Sieniawa now being mostly covered by functional forest, and the reclamation is considered effective and properly executed (Galiniak & Bik, 2012).

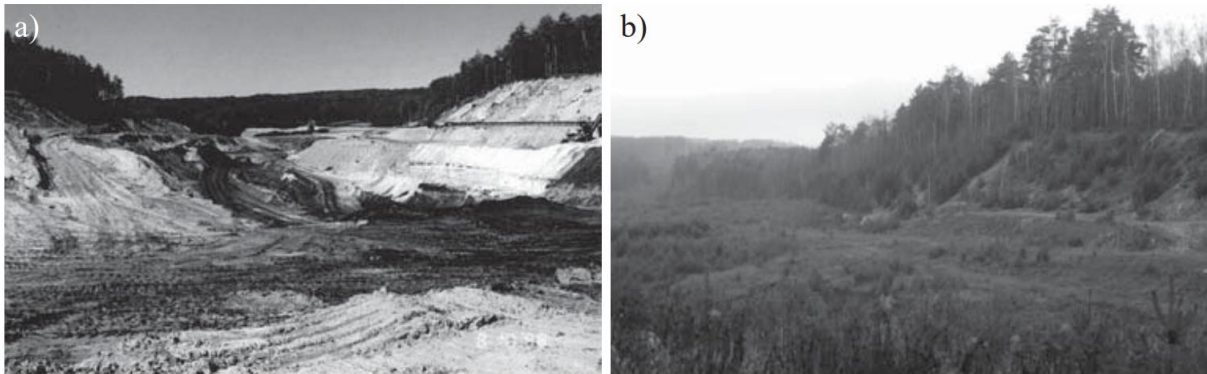


Figure 4.8 Successful reclamation in Saddle VI (open-cast exploitation) a) exploitation (in October 1998); b) reclamation (October 2010); Photo: KWB Sieniawa

Poland

Sieniawa open-cast mine - Construction of the Pątnów mine began in 1957 and mining operations ceased in 2002. The Pątnów mine deposit was located near the Gosławskie, Pątnowskie, and Mikorzyńskie lakes. As a result, the poor water conditions in the area deteriorated, and the direction of water environment restoration was adjusted. The development of the areas after mining in the Pątnów surface mine was beneficial for both industrial plants and the community living in the region. The following facilities were built on the site of the former Pątnów open-cast mine: an external dump for another open-cast mine – Józwin, a dump for ash and gypsum from the Pątnów power plant, a dump for clay and sand for the "Wienerberger" brickworks, a municipal waste dump for the municipality of Ślesin, agricultural land, and a water reservoir. By increasing the height of the dump, the external dump of the Pątnów mine was used as an area for the external dump of the Józwin open-cast mine. This decision, which made it possible to save space and not take up additional land, proved to be partially incorrect in the case of the

mass formations of the Józwin open-cast mine (gyttja and aquifers). A series of landslides occurred in the dump area, causing numerous technical problems that continue to this day (more than 30 years have passed since then) and requiring further reclamation work on the slopes of the dump. The water reservoir (Figure 4.7) in the former Pałnów surface mine was built for recreational and sports purposes (WINTER Project, 2024).



Figure 4.7 Final pit lake and its surroundings (WINTER Project, 2024)

Czech Republic

The Radovesice dump, one of the largest dumps in the Czech Republic, is an example of comprehensive and long-term successful reclamation of a post-mining landscape. Since the 1960s, overburden soil from the Bílina open-cast mine has been deposited here, and systematic reclamation began in 1986 in more than 17 stages. A key engineering measure was the use of calcareous marl to improve the physical and chemical properties of the soil profile, which enabled substrate stabilization and subsequent afforestation (Řehoř et al., 2022). Another important element was leaving two large areas (totalling 52 ha) to natural succession (Figure 4.8), which today serve as reference sites for research into the spontaneous

development of ecosystems. Long-term pedological and biological monitoring of these areas has demonstrated the formation of functional soil horizons, diversification of vegetation cover, and the occurrence of wetland and steppe biotopes (Říhová, 2011). The results show that, under suitable conditions, natural succession can be as effective as technical recultivation, especially in terms of biodiversity and ecological stability. Today, the dump fulfils not only ecological but also recreational and landscape functions, making it a model example of sustainable reclamation of mining-disturbed areas (Zemánková, 2016).



Figure 4.8 Transformation of the dump with natural succession areas: Střimice dump; Photo: a), b), c) (ČUZK, n.d.), d) (VUHU, 2025)

Czech Republic

Lipiny Golf Course near Karviná – Not all reclamation projects face technical problems since sometimes they fail in terms of socio-economic sustainability. An example is the reclamation of dumps (Figure 4.9) between the ČSM and Darkov mines in the Karviná region. Originally, afforestation or agricultural use was planned, but around 2007, politicians pushed through an ambitious plan for a golf course (Golf Resort Karviná-Lipiny). The complex opened in 2012 and includes a stylized "mining tower" as a reminder of mining. However, the project did not meet expectations since locals perceived it as elitist, and it lacked the necessary customers. From the beginning, the operation generated losses—the maintenance costs of the 9-hole course far exceed its revenues. In addition, the planned cycle paths and connection to the recreation area did not materialize due to the bankruptcy of the mine owner OKD. Due to complex property relations (the land is owned by the state, and the operator pays high rent), it has not been possible to put the complex to another use. In 2020, the resort was offered for sale, but no buyer was found thus today the complex is at risk of degradation (Frantál et al., 2024). The case of Lipiny shows that reclamation must correspond to the real needs of the region – otherwise, even a technically successful transformation can end up being economically unsustainable. Lipiny has become a clear example of how public involvement and demand assessment are crucial for socio-economic projects (Marot & Harfst, 2021).



Figure 4.9 Transformation of the dump into recreational landscape: Lipiny Golf Course near Karviná; Photo: a), b), c) (ČUZK, n.d.), d) (Golf Resort Lipiny, 2024)

Romania

In the wider region known as the Oltenia Mining Basin, over time a series of surface and underground mining operations have been developed, affecting almost 20,000 ha of land. On these lands affected by mining (lignite mines and internal/outer dumps), various ecological reconstruction works have been carried out, which aimed at restoring the original natural setting (through forest plantations or pasture restoration), transforming them into agricultural land, establishing experimental

fruit tree or vine crops, or creating new habitats that also include the formation of lakes in the remaining voids of the open pits. In this regard, two recent cases of ecological reconstruction of the Urdari and Peșteana South mining perimeters, both located in the Rovinari mining sub-basin, are presented.

Urdari mining area (Figure 4.12) was closed during 2003 and the lake with the same name began to form at the end of 2003 - beginning of 2004, in the gap formed between the final slopes of the open-pit and those of the inner dump (Lazăr & Faur, 2012). Therefore, it may be considered a young lake, which was barely studied from an ecological perspective during the period between 2010 and 2019.

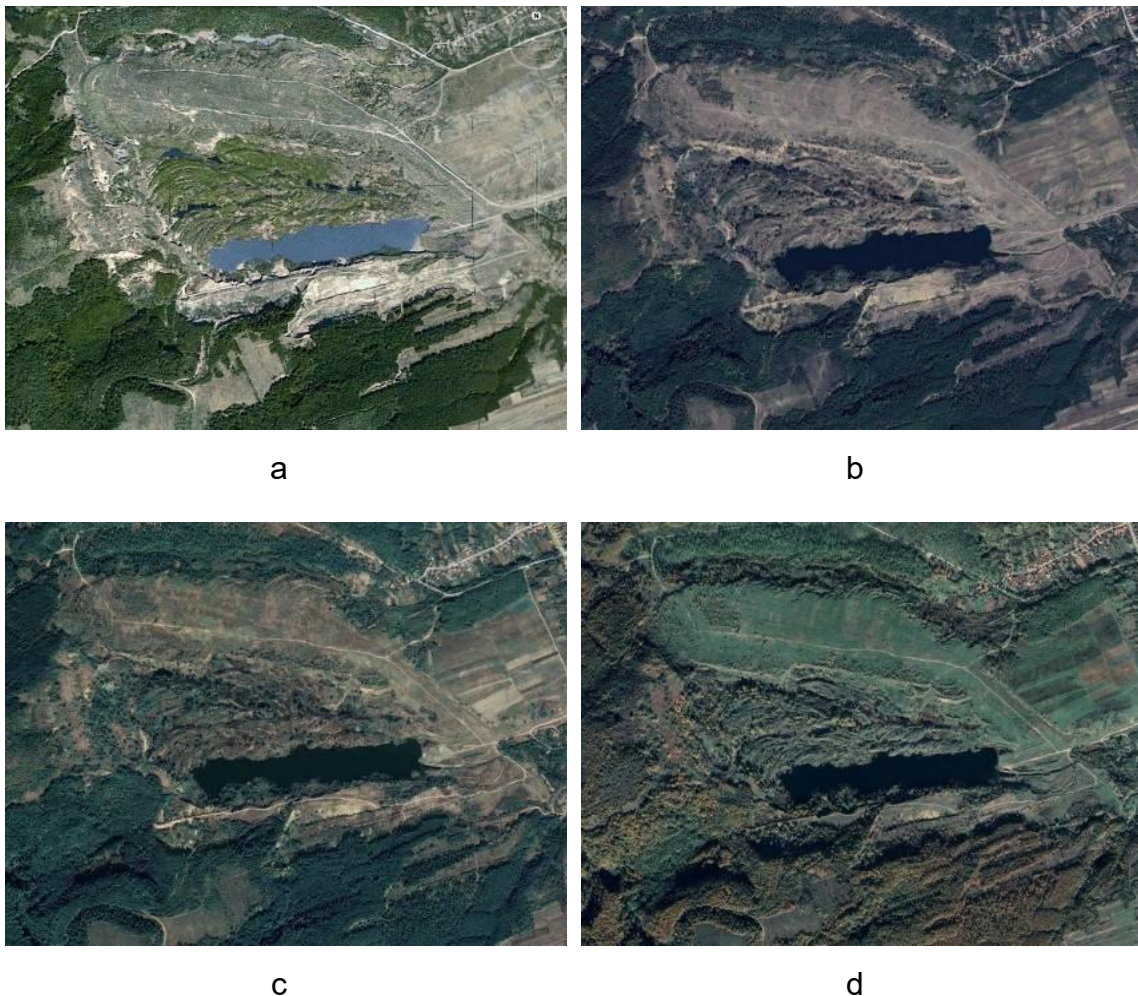


Figure 4.12 Transformation of the open pit area by natural succession: a) in 2013; b) in 2017; c) in 2019, d) in 2022 (Google Earth Pro. www.google.com/intl/ro/earth/versions/)

This mining area has not been subject to any specific ecological reconstruction (revegetation) work, making it a classic example of unassisted naturalistic rehabilitation. The remaining gap occupies approx. 19 ha, has an elevation at the bottom between +145 and +152 m, has a length of 950 m, a maximum width of 220 m, the elevation of the water level being at approx. +165 m (maximum depth, of about 20 m, being reached in the central-eastern part) (Lazăr & Faur, 2012; Faur et al, 2022 a). In the excessively dry years, the water level dropped to approx. +160 m.

The lake is bounded to the north by the inner dump of the open pit, to the south by the final benches of the pit, to the east by the Săscuia Valley, and to the west by a hilly area characterized by highly rugged terrain. As can be seen from Fig. 4.12, over time, the lake formed in the remaining gap has not undergone significant changes in terms of size and morphology. This is mainly due to factors related to the evolution of vegetation spontaneously installed on the final slopes of the open-pit and the inner dump and the arrangements existing since the active period of lignite exploitation.

The relatively rapid spontaneous installation of grassy, shrubby and arboreal vegetation on the slopes prevented the occurrence of accentuated rain erosion, or even the triggering of landslides, which could have significantly changed the shape of the lake shores on the one hand, and on the other hand, it prevented the massive transport of disaggregated materials from these slopes, which could have led to the clogging of certain areas.

On the east side of the lake there is a drainage channel that initially had the role of directing the waters coming from the precipitations and from the aquifers intercepted by the mining works towards the Jiu River. In this way the mining operations could be carried out in optimal conditions from the technical point of view and regarding the safety of the workplace. Currently, this channel ensures the drainage of excess water from rainfall and surface runoff from the slopes, thus maintaining a relatively constant level of water in the lake. The lake basin is formed

by the clay layer beneath the lignite layer, thus favouring the accumulation of water in the remaining gap (Faur et al., 2022 b).

An assessment on the water quality was performed in 2019 using standard methods of sampling, transportation and analyses (SR EN ISO 5667-1, 2007). Thus, according to the analyses results, it is found that from a qualitative point of view, the water in the Urdari Lake falls into the second quality class, which corresponds to a good ecological status according to Directive 2000/60/EC (Apostu et al., 2020).

The lake Udari (Fig. 4.13) was populated with different species of fish and attracts also a wide variety of small insects, amphibians, reptiles, small mammals and birds.



Figure 4.13 Urdari Lake in 2022

Even if the Urdari Lake was formed in the remaining void of a former lignite open pit, the research shows that it is at present and evolves similarly to the natural eu-mesotrophic lakes located in different hilly and plain areas in Romania (Faur et al., 2022 a and b).

The ecological conditions from around Urdari Lake have favoured the installation of an important vegetation in which we can find phytocoenoses with a conservative value, as well as a diverse fauna. The area is suitable for sport fishing and leisure.

Romania

In Peșteana South mining area (Fig. 4.14 a) the production activities were stopped in the summer of 2015. After a period of time necessary to remove the equipment from the open-pit, as a significant part of the drainage system became non-operational, the remaining void begun to be flooded (Fig. 4.14 b).



Figure 4.14 Peșteana South open pit: a) in operation (cca. 2014); b) during flooding (cca. 2018)

South Pesteana open pit is part of the Getic Plateau. Situated at the junction between Jiu and Jilț rivers, the area comprises the Jiu Plain (meadow) about 2.5 km wide, with elevations ranging from +153 m to +130 m, with inclinations from west to east (to the Jiu riverbed) and from north to south. The relief is presented in the form of plain and lower terraces in the area adjacent to the Jiu River. The hills that surround the region have a pronounced platform aspect, characteristic of the Getic Plateau, with altitudes below +300 m and slopes up to 30°.

The aquifers horizons identified by the hydrogeological exploration works within the South Pesteana area have been classified, depending on the conditions of the deposit, as free-level (groundwater or phreatic) aquifers and under pressure aquifers with ascending or artesian levels. The water level of the lake (70 – 75%

of the initial design) is maintained by operating a pump station and by pouring water into the Jiu River through a drainage channel. The current surface of the lake is of approx. 140 ha. These measures are needed to protect households in the area of influence from flooding and/or landslides (Lazăr et al., 2020).

The total area of the licensed perimeter is 628.31 ha. The area occupied until 30 June 2015 (when the open pit was closed) was of 480.20ha (surface not affected by mining works is 148.11 ha) (Fig 4.15).

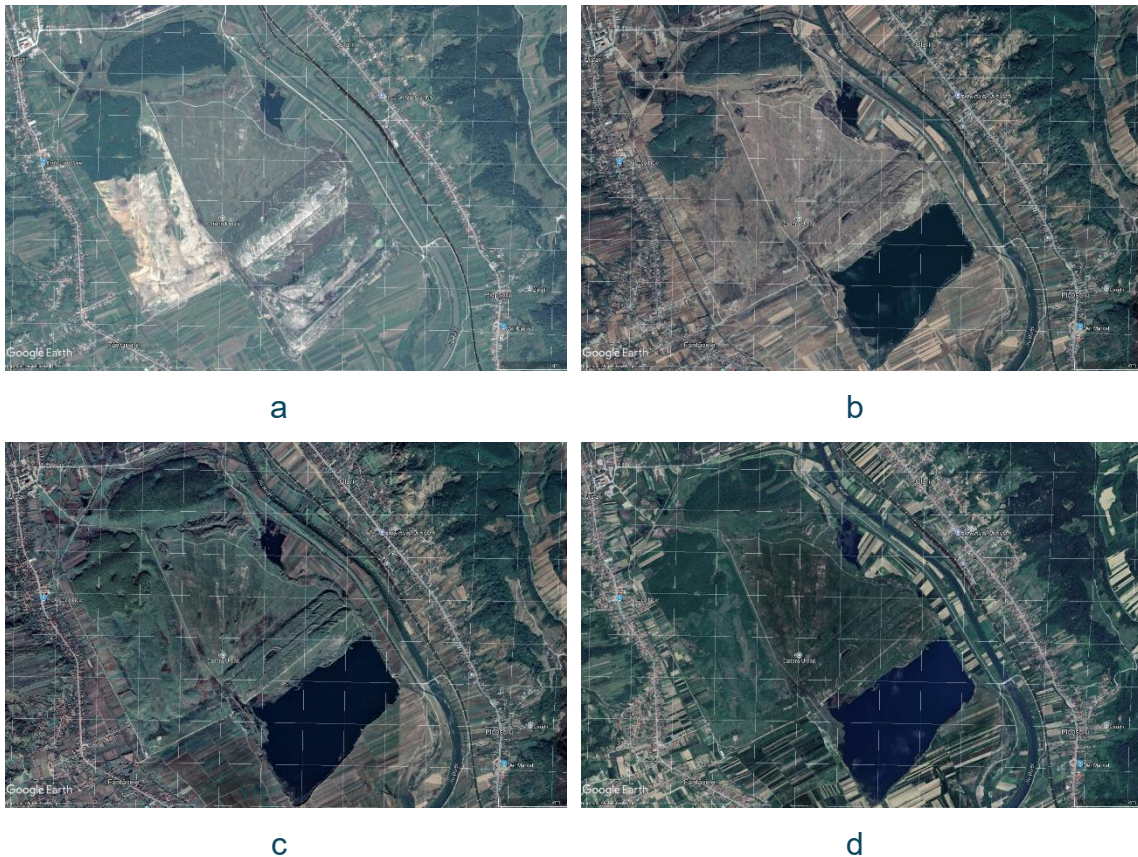


Figure 4.15 Evolution of Peșteana South open pit: a) in 2014 (in operation); b) in 2019; c) in 2022; d) in 2025 (Google Earth Pro. www.google.com/intl/ro/earth/versions/)

The water in Peșteana South Lake is classified as second quality class (Apostu et al., 2020), corresponding to a good ecological status under Directive 2000/60/EC. Similar to Uradri Lake, it has been populated with various fish species and supports

a diverse fauna, including small insects, amphibians, reptiles, small mammals, and birds.

The total area proposed for productive reuse is 202 ha (Lazăr et al., 2020), comprising 76.0 ha designated for agricultural use on the inner dump and 126.0 ha allocated for forest plantations. In addition, approximately 65 ha are occupied by various enclosures, while the Peșteana South Lake, when fully flooded, will cover an area of about 213 ha (Fig. 4.16). This is a good example of mixed ecological reconstruction, with productive areas and the creation of a new, water based, ecosystem. The area is suitable, to a certain extent, for sport fishing.



Figure 4.16 Lake Peșteana South in 2021

4.4 Best practices for community and stakeholder involvement

Successful reclamation and subsequent use of post-mining areas require the systematic involvement of all key stakeholders – from local governments and state authorities, through mining companies, professional institutions, and non-profit organizations, to the residents of the affected regions themselves. Good practice emphasizes the timely and transparent involvement of these actors in the planning process in order to increase the legitimacy and sustainability of the proposed

solutions (Bainton & Holcombe, 2018; Marot & Harfst, 2021). In this chapter, we describe a proven methodology for participation: (1) how to identify and involve key stakeholders, including methods such as interviews and thematic workshops; (2) participation of the general public through questionnaires and public meetings; (3) evaluation of the results and main findings from these processes; and (4) incorporation of the feedback obtained into spatial planning and regional development, including current obstacles and possible improvements.

Within the MiDSafe project, we focused on stakeholder and public involvement as a key aspect of the reutilization of dump sites and their sustainable development. The Most Basin in the Czech Republic was selected as a case study, where a process of transformation and intensive participation in the planning of post-mining areas is currently underway. During the project, interviews with stakeholders were conducted in cooperation with the regional development agency. A series of workshops was also held in the region, during which participants were presented with the results of an initial comprehensive analysis of the Most Basin area. This included, among other things, an overview of limitations and development potential, a typology of post-mining areas, and possible options for their reclamation. At the same time, an online public questionnaire survey was conducted, in which more than 700 respondents took part.

Below is a general description of the recommended procedure for the participatory process. Specific results of participation—including stakeholder involvement, outputs from the public questionnaire survey, and their connection to spatial planning tools—will be detailed in Deliverable 5.3.

Methodology for involving key stakeholders

The first step is to map key stakeholders, i.e., to determine who has a legitimate interest in or influence over surface mines and dumps after mining has ceased. Typically, these include local and regional authorities (mayors, regional representatives), central authorities (ministries, state mining administration, environmental departments), mining companies (or their successor organizations responsible for reclamation), specialized institutions (research institutes,

universities), business entities (e.g., companies operating in the affected area or potential investors in new projects), non-profit organizations (environmental associations, historical and cultural initiatives), and, of course, community representatives (local communities associations, clubs, prominent informal leaders). In some cases, this group also includes trade unions of mining company employees or regional development agencies (Everingham et al., 2020; Kozłowska-Woszczycka & Pactwa, 2022; Frantál et al., 2024). From a practical point of view, it has proven useful to create a working group or forum (platform) for the reclamation and development of the area, where these actors are formally associated (e.g., regional transformation teams in mining regions) and can meet regularly (Marot & Harfst, 2021; Worden et al., 2024).

Best practices include a combination of individual consultations and group meetings. In the initial phase, it is advisable to conduct semi-structured interviews with representatives of key institutions (mayors, directors of organizations, etc.) to map their attitudes, expectations, and possible concerns. Subsequently, workshops and round tables are used – thematic discussions where individual groups can express their views on proposals and seek consensus together (Kozłowska-Woszczycka & Pactwa, 2022; Pavludakis et al., 2020). It is important that these meetings are led by an experienced facilitator who will ensure that the discussion is constructive and that the voices of all parties are heard, not just the loudest participants. The presentation of expert background materials (territorial analyses, feasibility studies, scenarios for possible development) serves as a starting point for discussion – stakeholders should have access to clearly presented data and map outputs so that they can comment on the proposed options in an informed manner (Monosky & Keeling, 2021).

Methodology for public involvement

In addition to intensive work with key stakeholders, it is equally important to involve local residents and the wider public, i.e., to ensure bottom-up participation. Residents have unique local knowledge and a personal relationship with the landscape in question—their opinions can therefore reveal practical needs and

values that would otherwise be overlooked by planners (Bainton & Holcombe, 2018; Svobodová et al., 2023). At the same time, if people from the region are invited to participate in planning at an early stage, acceptance of future changes increases and the risk of resistance or mistrust towards the planned projects decreases.

One of the most effective tools for public involvement is a survey of residents, typically in the form of a structured questionnaire (nowadays usually online, supplemented by printed forms for older citizens). The questionnaire should include demographic data (for a basic profile of respondents: age, place of residence, relationship to the area – e.g., whether the person worked in the mine, etc.), as well as a set of questions mapping people's relationship to the area and its identity (how they perceive the current landscape, how much it is connected to their home, employment, recreation, etc.), their ideas about future use (e.g., preferred types of reclamation: water reservoir, forest park, industrial zone, photovoltaic power plant, residential construction, etc.) and attitudes toward various forms of revitalization (whether they support ecological restoration vs. economic development of the area, how they perceive leaving dumps to natural succession, etc.). An important part is the question of the public's willingness to get further involved – whether they would be interested in participating in public meetings, volunteer work during reclamation, community planning, etc. A properly targeted questionnaire not only collects opinions but also activates residents to further activities (Holcombe et al., 2024).

To ensure representative coverage of different population groups, attention must be paid to distribution of the questionnaire: it is best practice to combine online distribution (municipal websites, social networks, e-mail mailings) with physical distribution of information (flyers in mailboxes, posters in public places, information stands). In mining towns, for example, cooperation with local associations or mining unions can help to reach former mine employees and their families (Marot & Harfst, 2021). Citizens are more motivated to complete the questionnaire when they know how their opinions will be used – it is therefore advisable to clearly

explain the purpose in the introduction (e.g., "The results of the survey will be used to create a development plan for the lake and surrounding landscape") and later publicly present the summary results so that respondents can see that their vote has been recorded.

In addition to questionnaires, which capture a wide range of opinions, open public meetings should also be held. These can take the form of public discussions (a traditional format in which experts present a draft plan and citizens comment on it in the form of questions or comments) or more interactive formats such as workshops for the public (Arnstein, 1969; Everingham et al., 2020).

Conclusion

This report has demonstrated that mine dump stability is governed by a complex and interdependent set of geotechnical, hydrological, environmental, and anthropogenic factors. Experience from across Europe, supported by substantial research efforts, indicates that proactive monitoring, systematic assessment, and ongoing maintenance are essential components of effective risk management for these structures. Advances in monitoring technologies—ranging from in-situ sensor networks to satellite-based radar interferometry—have substantially improved the capability to detect early-stage deformation and adverse hydro-mechanical trends, thereby enabling timely intervention and the implementation of stabilisation measures before critical failure conditions develop.

At the same time, the increasing interest in the re-utilisation of mine dumps for beneficial post-mining land uses, including renewable energy generation, recreation, and development, necessitates a cautious and technically robust approach. Successful re-utilisation requires that long-term safety, environmental remediation, and regulatory compliance are treated as primary objectives, supported by coordinated planning and collaboration among all relevant stakeholders. Case studies from Europe and other regions illustrate a wide range of viable outcomes, such as the installation of wind energy infrastructure on rehabilitated dumps, the conversion of former spoil heaps into public green spaces,

and the establishment of agricultural activities on suitably remediated materials. Conversely, these examples also highlight the potential consequences of inadequate characterisation, insufficient monitoring, or neglect of historical failure mechanisms, underscoring the importance of incorporating lessons learned into future design and management strategies.

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