Post-Mining Multi-Hazards evaluation for land-planning

PoMHaz

WP 3: Post-mining risks assessment methodology and decision support systems

D11 - Deliverable D3.3: DSS tool and report detailing its application

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Content

List of Figures

List of Tables

Acronyms

AHP	Analytic Hierarchy Process
AOI	Area of Interest
BauGB	Baugesetzbuch
BBergG	Bundesberggesetz
BBodSchG	Bundes-Bodenschutz-Gesetz
BImSchG	Bundes-Immissionsschutzgesetz
BNatSchG	Bundes-Naturschutzgesetz
CAD	Computer aided design
CBA	Cost Benefit Analysis
DB	Database
DBMS	Database Management System
CERTH	Centre for Research & Technology Hellas
CPU	Central Processing Unit
CSV	Comma-separated values
DEM	Digital Elevation Model
DMT-THGA	DMT-Gesellschaft für Lehre und Bildung mbH – Technische Hochschule Georg Agricola University
DSS	Decision Support System
EAR	Exposed Elements at Risk
GDB	Geodatabase
GDP	Gross Domestic Product
GDPR	General Data Protection Regulation
GeoJSON	Geographic JavaScript Object Notation
GeoTIFF	Geographic Tag Image File Format
GIG	Główny Instytut Górnictwa
GIS	Geographic information system
GNSS	Global Satellite Navigation System
GPU	Graphics Processing Unit
GUI	Graphical User Interface
Ineris	Institut national de l'environnement industriel et des risques
KML	Keyhole Markup Language
KrWG	Kreislaufwirtschaftsgesetz
Laser	Light Amplification by Stimulated Emission of Radiation
LiDAR	Light Detection and Ranging
LU/LC	Land Use/Land Cover
MCDM	Multi-Criteria Decision-Making
MHI	Multi-Hazard Index
NPV	Net Present Values
POMHAZ	POst-mining Multi-Hazards evaluation for land-planning
PPC	Public Power Company
Radar	Radio Detection and Ranging
RAM	Random-Access Memory
RDBMS	Relational Database Management System
RGB	Red, Green, Blue

ROG	Raumordnungsgesetz
sDSS	Spatial Decision Support System
SoVI	Social Vulnerability Index
SQL	Structured Query Language
SHP	Shapefile
TU BAF	Technische Universität Bergakademie Freiberg
UAV	Unmanned Aerial Vehicle
UVPG	Gesetz über die Umweltverträglichkeitsprüfung
UI	User Interface
USchadG	Umweltschadensgesetz
UTM	Universal Transverse Mercator
VI	Vulnerability Index
VwVfG	Verwaltungsverfahrensgesetz
WHG	Wasserhaushaltsgesetz

Executive summary

This deliverable is part of the POMHAZ project, Post-Mining Multi-Hazards evaluation for land-planning.

The main objective of POMHAZ is to identify the interaction between the post-mining hazards for coalmines in Europe and to develop tools for facilitate the management of the post-mining hazards in coal region.

In the POMHAZ project, the present deliverable is part of the WP3 that is dedicated to post-mining risk assessment methodology and decision support systems. This WP provides both methodology for assessing post-mining risks and the tools for decision-makers and coal communities facing multi-hazards and multi-risks.

This deliverable related to Task 3.3 “Development of a DSS for Risk management” focuses on the development and implementation of a Spatial Decision Support System (sDSS) to manage multi-hazard risks in post-mining regions. Building on the specifications established in Deliverable 3.2, this deliverable provides a detailed account of the sDSS tool, its methodology, technical architecture, and application in real-world scenarios.

The sDSS employs a multi-criteria decision-making framework to assess risks based on three core factors: Multi-Hazard Index (MHI), Exposed Elements at Risk (EAR), and Vulnerability Index (VI). These factors are calculated using spatial data, expert input, and automated processing, generating actionable risk assessments for specific post-mining sites. The system then categorizes risk levels and proposes tailored actions, such as monitoring, mitigation, or land repurposing, depending on the severity of identified risks.

The sDSS is hosted on a high-performance server and uses a Flask-based API integrated with a PostgreSQL database enhanced by PostGIS for geospatial analysis. Its user interface, built with Leaflet, enables dynamic interaction with risk maps and supports the customization of scenarios by stakeholders. The tool is designed for scalability and replicability, accommodating diverse regional datasets and enabling iterative improvements through stakeholder feedback.

The development process included rigorous testing in case studies, such as the Southern Ruhr area, demonstrating the system's robustness and adaptability. The sDSS successfully processed large datasets and provided detailed multi-risk assessments, guiding decision-making for urban planners, environmental agencies, and local authorities.

The deliverable concludes that the sDSS is a valuable tool for post-mining hazard management, combining scientific approaches with practical usability. Recommendations for future development include expanding data integration capabilities, enhancing predictive analytics through AI, and establishing comprehensive user training programs to maximize the system's impact. This innovative tool underscores the potential of GIS-supported technologies in transforming post-mining risk management and land-use planning.

1 Introduction

The POMHAZ project aims to enhance hazard assessment and risk management for abandoned coalmines. Its primary goal is to advance methodological knowledge for effectively conducting multi-hazard analyses at the scale of a mining basin, with particular focus on the key hazards associated with post-mining activities. The primary hazards associated with post-mining activities include ground subsidence, contamination of groundwater, soil instability, gas emissions, and surface water pollution. These hazards can have significant impacts on urban development, leading to issues such as damage to infrastructure, compromised public safety, and the potential contamination of water sources.

Addressing these complex risks requires a systematic approach like a Decision Support System (DSS) [1–6] that integrates various data sources, models hazard interactions, and provides clear decision-making frameworks for effective risk management. During the development process, the DSS tool was highly improved with a spatial component, creating a spatial Decision Support System (sDSS). The systems objectives, functional and non-functional requirements, as well as constraints on its development and use are shown and discussed in POMHAZ deliverable D3.2, while this deliverable 3.3 focuses on the tool itself, its development and usage.

2 The DSS in the overall concept of the project

The DSS is a central component in achieving POMHAZ's objectives in post-mining hazard management, according to the project plan. Its development and successful implementation are integral to achieving the project's broader goals of sustainable and informed decision-making in areas affected by abandoned coal and lignite mines [7]. The DSS aims to facilitate well-informed decisions based on a thorough analysis of complex data, including natural and post-mining hazards and other risk factors. These decisions could range from high-level strategic decisions by urban planners and policymakers to more operational decisions by local authorities and hazard management teams.

Deliverable D3.2 "DSS specifications related to post-mining hazard management" establishes the detailed specifications for the DSS, defining the functionalities, data sources, interfaces, and constraints that guide the development and implementation phases. In this deliverable D3.3 the implementation of the specific DSS for project POMHAZ will be explained in detail, including a documentation on its usage. D4.2, D4.3 and D4.4 are dedicated to the linking of DSS and GIS system and the validation of the system, while D5.3 will test all component on real case studies.

3 DSS methodology

The methodology for the Multi-Risk assessment is comprised of several steps and necessitates the initial collation, classification and pre-processing of data by multi-disciplinary experts [8] in order to facilitate the subsequent automatic calculations of a multi-risk index. A multi-risk index reflects the level of the impact of the multi-hazards. The methodology used in the sDSS was developed within the project POMHAZ in different tasks in the work packages WP2 “Post-mining hazards and multi hazards identification and assessment methodology“ and WP3 “Post-mining risks assessment methodology and decision support systems” and was completed and outlined in detail in the deliverable D3.1 “Methodological guidelines about risk management”.

It is necessary for a mining site to gather and prepare data on a range of factors, including hazards, the environmental context, infrastructure, and geotechnical aspects, in formats that can be read by a geographic information system (GIS). Vector formats, such as Shapefiles or GeoJSON, may be employed for the initial processing. However, for the subsequent calculation of pixel-wise Multi-Risk values [9,10], all data must be rasterized. The following equation illustrates the calculation of the Multi-Risk value for each pixel and scenario.

$$Risk = \sum Hazard^{*} \times Exposed\ element\ at\ risk \times Vulnerability \qquad (1)$$

* Hazard corresponds to adjusted hazards identified on a mining site.

To ensure the consistency of the data, it is advisable to select a uniform grid resolution. In the test case study, a resolution of 10 x 10 m was selected, corresponding to the resolution of the Land Use/Land Cover derived from the Sentinel-2 data [11]. This resolution allows for effective computing performance over larger areas while maintaining sufficient resolution for subsequent analyses, making it a suitable standard for different mining sites.

After the multi-risk assessment, different courses of action are proposed based on the level of risk (**Figure 1**). The decision support system should help to use the appropriate mitigation or/and land use of the mining site. This ranges from no action for no risk areas, monitoring for low risk, risk mitigation for medium risk and changes in current or future land use by land planning methods for high-risk areas, depending on the national and regional regulations.

To enable the automated calculation of the Multi-Risk for each cell, the three components must first be defined and subsequently calculated, or alternatively, suitable values must be selected by an expert user. In order to accommodate the varying requirements of the stakeholders and the numerous interactions between multiple post-mining, natural and technical hazards, it is possible to utilize more than one scenario throughout this process. This allows for more suitable results.

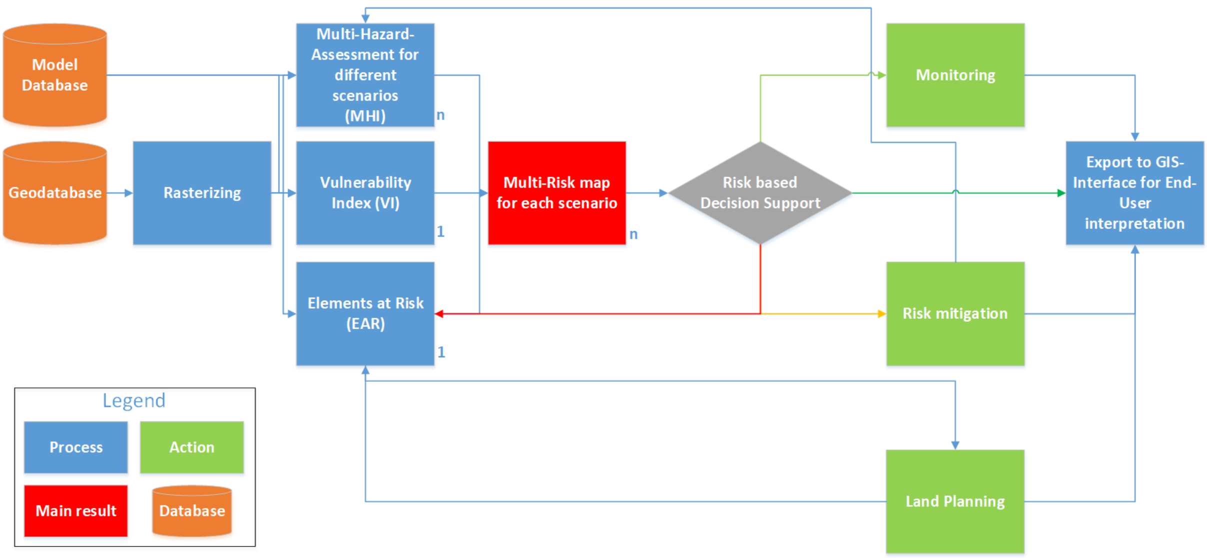

Figure 1: The Multi-Risk calculation process. The pre-processed data is stored in the model- and geodatabase, rasterized and then used to calculate the three factors and subsequently the Multi-Risk value for each cell, leading to different causes of action.

3.1 Multi-Hazard Index (MHI)

The principal of the calculation to determine a value to assess how much the interaction is important. Following an examination of various multi-criteria decision-making (MCDM) and indicator-based techniques for calculating a MHI from multiple single hazards, the factor multiplication method, as developed by Liu et al. [12], is employed in the context of both natural and technological hazards [10,13], with specific consideration of their potential interactions.

The method comprises four principal stages [13]. The initial stage of the process entails the identification of the post-mining hazards and the assignment of an initial intensity rating on a scale of 1 to 5[1], which indicates the severity of each independent hazard. Subsequently, in the second step, an interaction matrix is constructed, with primary hazards positioned on the vertical axis and secondary hazards triggered by the primary ones on the horizontal axis. Each multi-hazard scenario includes both primary and secondary hazards. The matrix comprises a series of cells, each representing a potential interaction between a primary and secondary hazard. The categories indicate the probability of potential interaction between the corresponding hazards, with low and high probability representing the two extremes. The third step is to adjust the intensity of secondary hazards based on their interaction with primary hazards. Hazards with high potential interaction probabilities are assigned increased intensities, whereas those with low or no interaction retain their initial values. This adjustment process entails multiplying the original intensity by specific adjusted

[1] The intensity scale for post-mining hazard can be different from a country to another. We can consider the maximum number of scales can vary from 3 to 6.

principles, which were developed for post-mining hazards and take into account interactions among natural, mining, and technological hazards [14].

$$H_{adj-i} = H_{ini-i} \times \sum_{1}^{3} L_k \times N_{ik} \tag{2}$$

where H_{adj-i} is the adjusted hazard level of hazard i, H_{ini-i} the initial hazard intensity of hazard i, L_k the hazard interaction level with k varying from 1 to 3 and N_{ik} the number of different interactions (with other hazards) for each interaction level.

The final step in this method is calculating the MHI by summing the adjusted intensities of all hazards in each scenario:

$$HI = \sum_{1}^{n} (H_{adj-i}) \tag{3}$$

where n is the number of hazards identified on the studied site. This index offers a comprehensive assessment of the collective impact of multiple hazards, facilitating a comparative analysis across diverse multi-hazard scenarios [13]. For the sake of comparison, the MHI has to be normalized from 0 to 9.

3.2 Exposed Elements at Risk (EAR)

The identification of EAR can be achieved by determining which elements are present in hazard zones and which of these elements are susceptible to potential losses [10,15]. Given that the losses in question can be of both quantitative and qualitative value, the data pertaining to this factor may vary depending on the specific regional or national regulations that apply. To ensure consistency across case studies, Land Use/Land Cover data (LU/LC) derived from Sentinel-2 data was employed [16]. The expert user is required to define a risk level (ranging from 1 to 9) for each class. However, the integration of more detailed datasets, if available, can facilitate the EAR factor.

3.3 Vulnerability Index (VI)

Vulnerability is a pivotal element in multi-risk analysis, signifying the extent to which specific EAR (persons, structures, and infrastructures) are susceptible to risk [10]. It incorporates a multitude of factors, including demographics, infrastructure, socio-economic conditions, and community resilience. The Vulnerability Index (VI) for POMHAZ was derived from the context of a Social Vulnerability Index (SoVI), that represents a state-of-the-art approach and a potential method for assessing vulnerability. These indexes, developed by different authors [17,18], evaluate vulnerability through a composite index that includes a range of socio-economic and demographic variables, such as income levels, age distribution, education, and housing quality. These factors can affect a community's ability to cope with and recover from hazards.

For the POMHAZ project, a specific post-mining SoVI was developed [19] and later adjusted to a more holistic Vulnerability Index (VI), that includes social and physical vulnerability. It is calculated from 4 weighted classes with 10 subclasses:

- Socioeconomic status
  - Unemployment rate
  - GDP per capita
- Household composition
  - Population < 15 y.o. / > 64 y.o.
  - Population density
- Environment
  - Settlement area
  - Agricultural area
- Infrastructure
  - Building Age
  - Building material
  - Building geometry
  - Traffic area

After normalization of each subclass from 1 to 9 and calculating the average for each class, the VI can be calculated for each zone (e.g. municipality) and then rasterized:

$$VI = \sum_{1}^{4} (IV_n \times W_n) \tag{4}$$

where IV_n is the normalized, average index value for each class and W_n the adjustable weight for each class, calculation a sum for the four classes. The standard weights are 0.3 for socioeconomic status, 0.4 for household composition, 0.1 for environment and 0.2 for infrastructure [13].

The full calculation with exemplary data from cities in the German Ruhr area and comparison data from Germany, the EU and the world can be seen in Annex A.

4 User structure

A user concept was developed to meet the requirements of the various stakeholders and to achieve an appropriate level of data protection and user support (**Figure 2**). In addition to a site admin (provided by DMT-THGA in the implementation for the POMHAZ project), this also includes additional administrations for the various mining sites to be investigated. These include the respective expert users, as well as access for administrations and the interested public. A corresponding anonymization of the data, for example by strongly reducing the resolution, can be realized via the GIS tools (deliverables D4.2, D4.3).

Figure 2: The different user and support levels for the sDSS

5 Data Input

The data input results from the methodology presented in chapter 3. For the calculation of the Multi-Hazard Index (MHI), polygons must be prepared by the expert users and uploaded in the backend by the admin (see Annex C). The hazard level can be specified for each hazard (post-mining, natural, technical) in an interval of 1 to 5. For example, the hazard of a sinkhole emanating from an old shaft can decrease in relation to its distance. Another example would be the decrease of the hazard level of a flood with the decrease of the relative frequency of the event (10 years, 100 years, 1000 years). The assessment of individual hazards must be made by experts with local knowledge and is not part of the automated sDSS process.

For the Element at risk (EAR) no input from the user is needed. The standardized values from 1 (low risk element) to 9 (high risk element) is derived from the current or planned land use / land cover (LU/LC). The expert user chooses risk levels based on their own experience, local knowledge and national regulation.

Examples could be 1 for bare ground or 9 for build area. The LU/LC data is uploaded in the backend by the admin user (see Annex C).

The Vulnerability Index (VI) is calculated by the experts using the prepared spreadsheet in Annex A, attributed to the city polygons and uploaded by the admin (see Annex C). The expert user can vary the weighting of the four factors (see Annex B).

The complete workflow, including the data pre-processing and input can be seen in **Figure 3**.

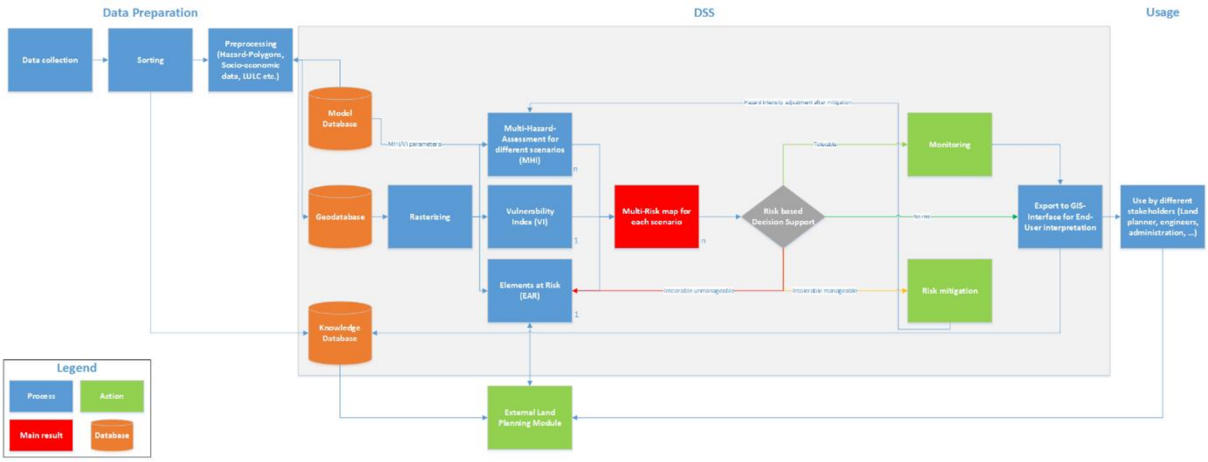

Figure 3: The complete sDSS workflow, including data preparation, input and usage

6 Interfaces and Export

The sDSS provides export capabilities in each of its modules, enabling users to download data after completing the assessment. Depending on the layer displayed in the GUI, the exported file will be in either raster format, where each grid cell represents the risk level of a specific factor, or in vector formats such as Shapefile or GeoJSON. This functionality allows experts to perform further analysis on individual risk factors or the final risk map using external tools. Additionally, these exports can be seamlessly integrated into the GIS toolbox (see Deliverables 4.2 and 4.3) for enhanced processing and visualization.

It is important to note that the quality and relevance of the exported results depend heavily on several key inputs: the level of hazards and interactions defined, the significance assigned to each class of the exposed elements at risk, the weighting of the vulnerability indicators, and the final scenario assessment used to generate the risk map.

7 Utilization of the multi-risk results

In accordance with its intended use, the sDSS creates various recommendations for dealing with the calculated spatial risk areas. The intervals of the four risk classes can be individually adjusted by the respective user based on their own knowledge and national regulations.

7.1 No risk – No action

Areas with a value of 0 (no risk) can be reported after the calculation. This is the standard case for most areas, as there is no risk if there is no hazard in the specific cell. However, depending on the data basis used, residual risks may still occur here due to outdated or inaccurate sources.

7.2 Low risk – Monitoring

Instead of expensive risk mitigation or land repurposing, most risks with low values are tolerable and can be managed using different observation or monitoring techniques (depending on the national regulations). Regarding the classification, evaluation and use of a wide range of monitoring techniques for active and abandoned mining, various projects have been carried out at the Research Center of Post-Mining at DMT-THGA in recent years [20]. The results were also presented in a "3D monitoring cube" showing the relationships between mining elements, monitoring methods and parameters [21].

In a further step, the Research Center of Post-Mining conducted research to additionally divide these methods into active and passive monitoring [22]. The data presented here for POMHAZ Task 2.2 condenses these different research results and has been adapted to the risks identified in Task 2.1.

7.2.1 Terrestrial Methods

Over the last centuries, many different terrestrial methods have been developed and used to monitor the hazards of mining operations [23]. This list shows examples of these methods still used in today's mining and post-mining environment:

- Ground-Based Surveys:
    - Traditional surveying techniques involving the use of instruments such as total stations, GNSS rovers and levels.
- Geotechnical Monitoring
    - Installation of instruments like inclinometers, piezometers, extensometers and strain gauges.
- Hydrological and geochemical Monitoring:
    - Discharge volume measurements, permeability measurements, water chemistry analysis and multi-parameter probes.
- Seismic Monitoring:
    - Seismometers and accelerometers.

7.2.2 Remote Sensing Methods

In order to complement the above-mentioned measurements, which can usually only be used at specific points and not over a larger area, many remote sensing methods are also used today in the field of active and post-mining. The application of modern remote sensing methods has proved very successful when it comes to meeting the necessary requirements for such a monitoring regime in terms of spatial and temporal coverage.

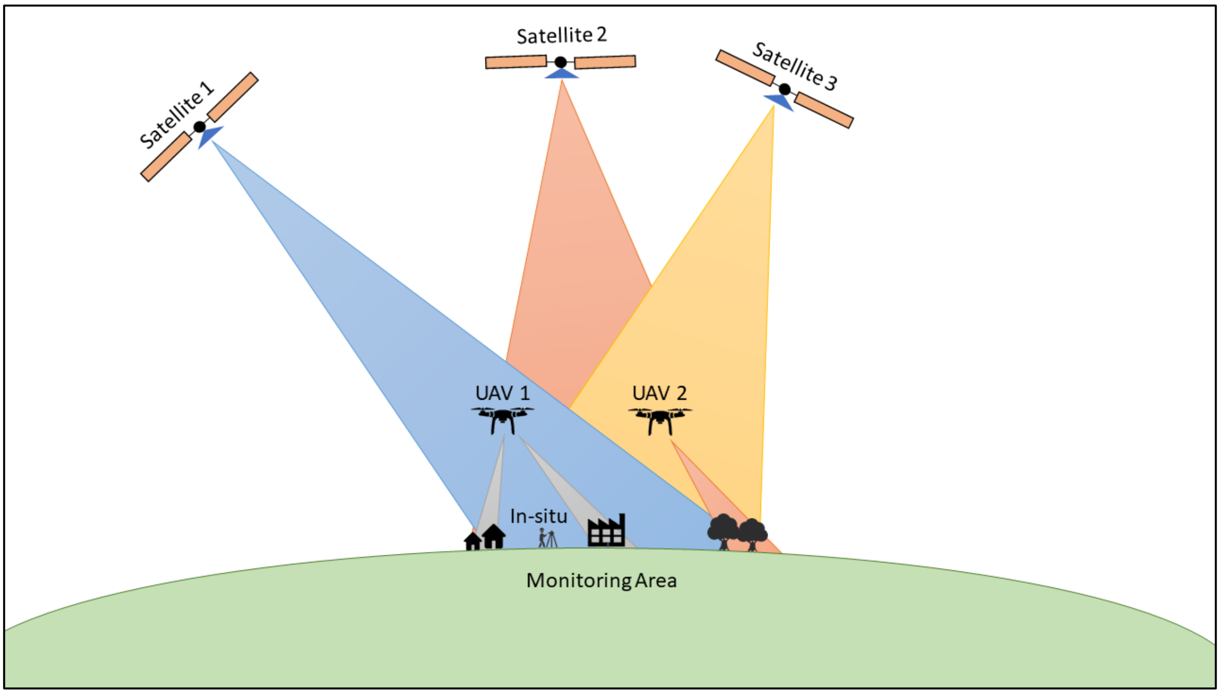

Figure 4: Multilevel geomonitoring using different remote sensing platforms and terrestrial methods [24]

The freely available data from various European and American satellite missions have significant potential to offer. These temporally high but spatially low-resolution data can be supplemented, for example, by the cost-effective use of drones, which can cover smaller areas but at very high resolution [24]. The sensors of the platforms are so similar that the data can complement and mutually validate each other through their high-precision georeferencing (**Figure *4***) [25].

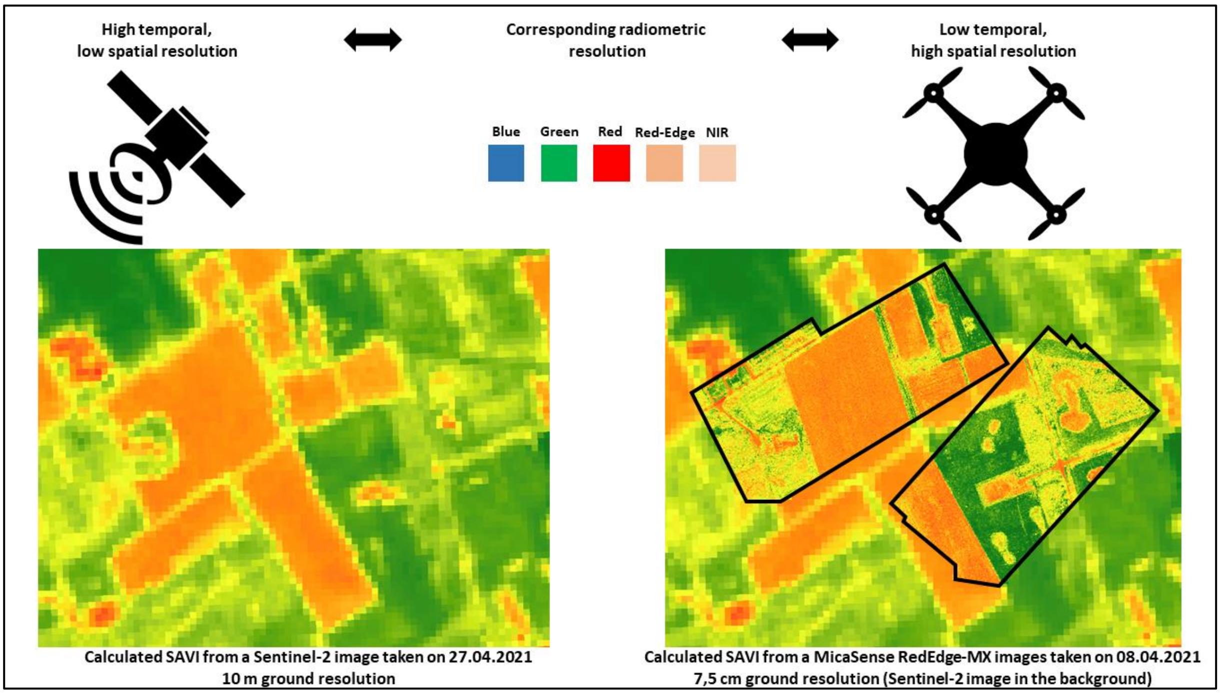

Figure 5: Comparison and combination of spatial, temporal and spectral resolutions from Sentinel-2 satellite data and a UAV-based MicaSense RedEdge-MX camera using a Soil-Adjusted Vegetation Index (SAVI) [25].

The list of remote sensing methods is split into platforms and sensors. In principle, the same type of sensor, e.g. a multispectral camera, can be used on different platforms, thus balancing spatial and temporal advantages and disadvantages (**Figure *5***) [25].

- Remote sensing platforms
  - Satellites
  - Aircrafts
  - Helicopters
  - Unmanned Aerial Vehicles (UAV)
  - Mobile Mapping Systems (Cars, trains, backpacks, handhelds, apps, …)
- Remote Sensing sensors
  - Active sensors
    - LiDAR and Laser
    - Radar
    - Electromagnetic Sensors
    - Ultrasound
  - Passive sensors
    - RGB cameras
    - Thermal Infrared cameras
    - Multispectral cameras
    - Hyperspectral cameras
    - Magnetometer

  - Gravimetric sensors
  - Gamma spectroscopes

Various monitoring methods can be derived from the combination of platform and sensor (or even sensor combination), which would go beyond the scope here. Not all sensor types are being used for mining hazard monitoring yet, therefore the assignment of sensors/platform combinations as monitoring techniques for mining hazards will be limited to those currently in use. The development of monitoring methods based on the available data sources or the assignment of methods to different hazards and risk is not part of project POMHAZ.

7.3 Medium risk – Risk mitigation

Risk mitigation for post-mining hazards and risk can involve several strategies designed to address environmental, structural, and ecological issues arising from abandoned or decommissioned mining sites. This includes e.g.

- Geotechnical Stabilization
- Environmental Rehabilitation
- Water Management
- Gas and Air Quality Management

The type and extend of the mitigation however depend on the national and regional regulation, that can vary drastically across European countries. As an example, the German approach is outlined below.

7.3.1 Example: German approach

As with monitoring, risk mitigation is not a designated component of the POMHAZ project. However, for purposes of completeness, the German approach is explained here as an example in order to facilitate a more comprehensive understanding of the impact of the sDSS results.

The primary responsibility for addressing post-mining hazards lies with the (former) mine operators and legacy companies. Under German law, this responsibility is considered perpetual liabilities, meaning it does not expire. However, when companies undergo changes such as sale, merger, or division over time, ownership and responsibility can become significantly unclear. It is not uncommon for old mining sites' responsibilities to be transferred to foreign corporations during takeovers, leaving them either uninformed or unaware of their associated obligations. In cases where no responsible party can be identified, the respective mining authority of the country assumes the responsibility for these ongoing tasks as a substitute.

7.3.1.1 Risk Mitigation after mine closure

Risks are systematically identified and assessed throughout the entire mining life cycle. Anticipating risks that extend beyond the active mining period, proactive measures are taken to address them well in advance of production cessation. By law, mining operators are obligated to allocate provisions for the post-mining phase, ensuring adequate resources are set aside for potential challenges, repairs and financial compensation.

To undertake land use planning on previously used mining grounds and initiate a reclamation process in Germany, the primary law to consider is the Federal Mining Act (BBergG) [26]. This law outlines the mine closure plan, which includes measures to prevent damage to the surrounding area resulting from the decommissioned mine and associated structures and activities. The mine closure plan also covers the reclamation of the surface. However, the BBergG serves more as a process framework for the establishment, execution, and closure of mining activities. Multiple legislations must be considered when assessing and approving mine operation or closure plans, such as soil protection law, environmental and nature protection law, waste management law, water law, and occupational health and safety.

The ultimate goal of a mine closure plan is to release mining supervision by the responsible mining authority by achieving a sufficient state of reclamation. Competent authorities participate in the procedure to enforce specialized issues such as those listed above. Municipal affairs are also impacted since the municipality acts as the responsible planning authority and shapes future land use. Clarifying the land use perspective with local authorities can help access the necessary reclamation measurements early on.

It should be noted that in Germany, a federal republic with 16 states, legislative authority could be on both federal and state levels. For some types of competence, there is exclusive jurisdiction, where only the federal government or a state government can enact a law on a specific topic. The Federal Mining Act falls under this category. Other issues, such as spatial planning and land law, fall under competing jurisdiction, where both federal and state governments are authorized to pass laws within the same legal sphere. Therefore, there are various regulations on specific issues such as distance regulations for wind energy plants. In the case of colliding norms, the federal one is favored by the judicial branch.

The mining-related legislation in Germany is primarily governed by the Federal Mining Act at the federal level. In the post-mining sector, it is supplemented by various other environmental and construction laws. However, the responsibility for overseeing these laws lies with the state ministries. Depending on the size and number of mining companies in a particular state, the direct implementation and monitoring may be delegated to a subordinate authority.

7.3.1.2 Overview of mining and post-mining laws in Germany

- Federal mining law
    - Bundesberggesetz (BBergG)
- Environmental laws
    - Bundes-Bodenschutz-Gesetz (BBodSchG)
    - Bundes-Immissionsschutzgesetz (BImSchG)
    - Bundes-Naturschutzgesetz (BNatSchG)
    - Kreislaufwirtschaftsgesetz (KrWG)
    - Gesetz über die Umweltverträglichkeitsprüfung (UVPG)
    - Umweltschadensgesetz (USchadG)
    - Wasserhaushaltsgesetz (WHG)

- Spatial laws
    - Baugesetzbuch (BauGB)
    - Raumordnungsgesetz (ROG)
    - Verwaltungsverfahrensgesetz (VwVfG)

7.3.1.3 Social aspects, transition and reactivation

Alongside the geotechnical and environmental considerations in risk management, Germany also addresses the social aspects and challenges related to transition and reactivation. The country has established a dedicated research branch within the Research Center of Post-Mining to focus on these areas. A notable example of this commitment can be seen in the upcoming coal phase-out:

The " The final report of the commission “Growth, Structural Change and Employment” (“Wachstum, Strukturwandel und Beschäftigung”) [27] outlines a plan for the phasing out of coal mining in Germany and the transformation of the affected regions towards more sustainable and diversified economic structures.

The agreement includes provisions for the shutdown of all coal-fired power plants in Germany by 2038 at the latest, as well as financial support for the affected regions to invest in infrastructure, education, research and development, and other economic activities. The total funding for the structural transformation of the regions is estimated to be around €40 billion.

The aim of the agreement is to ensure a socially just and economically viable transition away from coal mining and towards a more sustainable future for the affected regions and their communities. It is seen as a key step in Germany's efforts to meet its climate targets under the Paris Agreement.

7.4 **High risk – Land repurposing**

To encompass the most comprehensive socio-economic and sustainability aspects, the POMHAZ methodology is developed based on the Triple Bottom Line (TBL) framework, pertaining to economic, environmental, and social factors. Outcomes from European funded projects (MERIDA, TRIM4Post-mining, RECOVERY, TRACER [28–31]) are extensively used to build the core elements of the methodology. One specificity of POMHAZ lays in the land feasibility maps construction, taking into account the outcomes of the Work packages 2 and 3 on multi-hazards and multi-risks.

Annex D presents in detail the socio-economic methodology developed in the frame of POMHAZ project.

According to the WP 5.1 objectives, the requirements formulated by the end users/administrators of the selected test sites are included in the DSS methodology and tool. Different specialized agencies and experts need to collaborate through using the DSS (POMHAZ proposal description). The method, presented in the annex D, is intended to be smart, to be suitable for any land repurposing cases, and any type of governance. For example, the role of each stakeholder could be set, e.g. for weighting criteria. Another specificity is to perform a Cost Benefit Analysis (CBA) for provisioning services and a global CBA for provisioning and non-provisioning services to assess the Net Present

Values (NPV). A global positive NPV with a negative NPV for provisioning services can justify public subsidiaries.

To implement the spatialized DSS, a flow chart is proposed (**Figure 6**). Chapters 4 to 7 of the annex D, depict each step of the flowchart, with detailed flowcharts. Finally, the chapter 8 depicts the possible interactions between the databases needed to implement a land planning repurposing.

The first step of the process under the following proposed MCDA methodology is to gather stakeholders and define land use needs and objectives.

The second step will map the area to be repurposed according to the feasibility of setting up the different land uses identified during the first step. It takes into account the multi-hazards assessment (WP 2), risks acceptance associated with vulnerability of each land use, land features, physical events monitoring, risks mitigation efficiency and the associated sunk costs e.g. polluted land removing (WP 3), compared to market price.

The third step assesses the impacts of land use on environment, social and economic aspects. It compares the initial state to future land uses. It includes a Cost-Benefit Analysis (see Annex D). and a CBA for non-provisioning services.

In the last step, conflicts of land uses are described, and a multi-criteria decision analysis (MCDA) will allow to trade-off the different land use needs claimed in step one, combining risk mitigation and sustainability criteria and costs. To implement MCDA, a multi-criteria decision method based on AHP is applied, with the most transparent fashion.

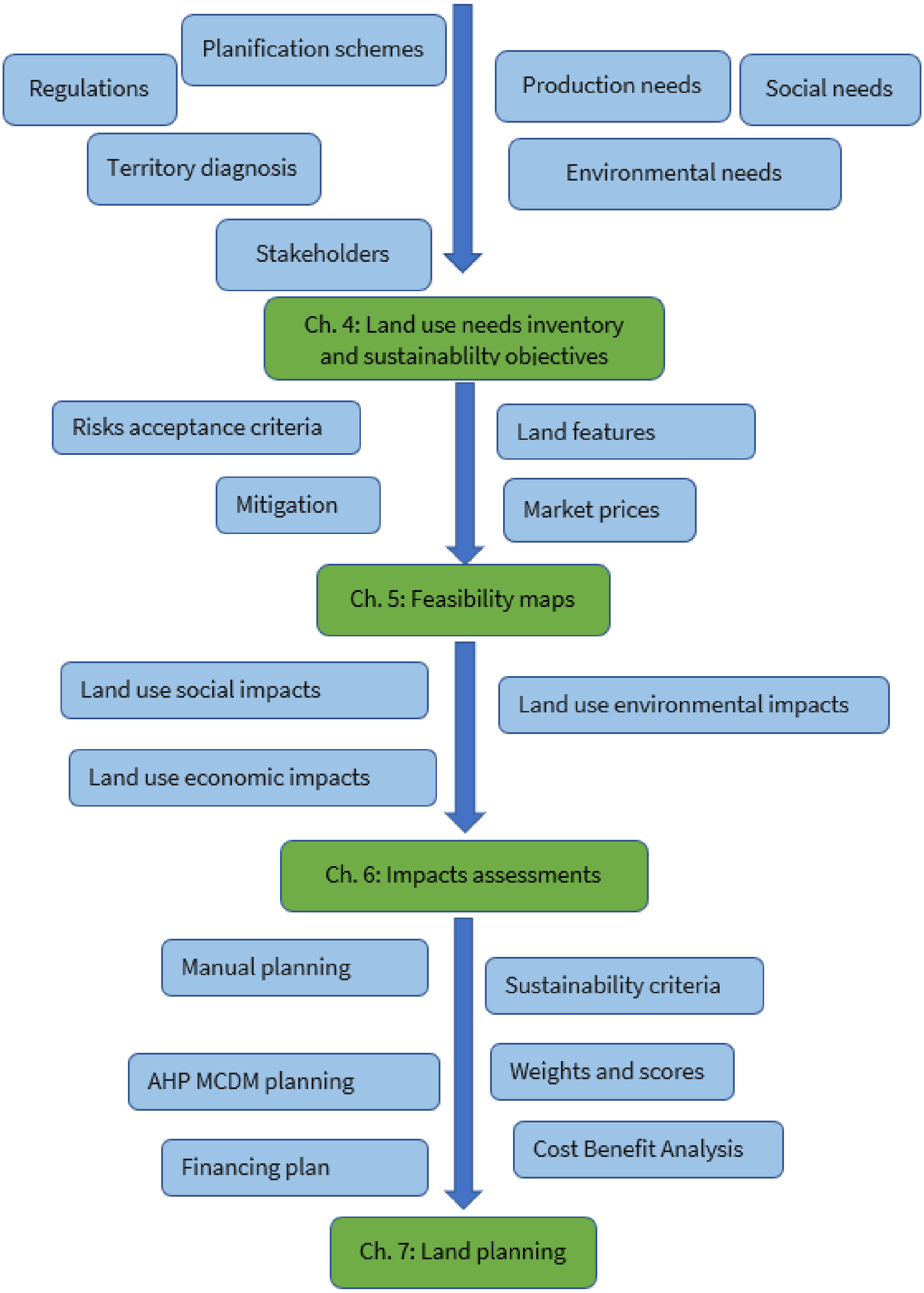

Figure 6: General flowchart of land planning repurposing. Numbers refer to chapters in annex D

8 Technical Development of the sDSS

The SDSS API was developed using Flask, a lightweight and flexible Python web framework, enabling efficient communication between the backend and the user interface. Leaflet, a powerful JavaScript library for interactive maps, was integrated to visualize the outputs and results dynamically. For data management, a PostgreSQL database with PostGIS extension was utilized to store and process geospatial data related to the study cases, ensuring efficient handling of spatial queries and analysis.

The Graphical User Interface (GUI) provides users the flexibility to interact with the system by either working with the pre-existing study cases or adding new data to define and analyze the multi-risk assessment problem in post-mining sites.

8.1 Hardware and hosting

In order to meet the technical requirements of the sDSS (see D3.2), it was developed and hosted on a high-performance server in the DMT-THGA data center. The server has the following parameters in order to perform the corresponding calculations quickly and efficiently.

Table 1: Specifications of the hardware server used for hosting the POMHAZ sDSS

Mainboard	PowerEdge R740-/R740XD
CPU	2x Intel Xeon Gold 5222 3,8 GHz
RAM	4x 16 GB RDIMM, 3.200 MT/s, Dual Rank
Storage 1	2x 480GB SSD-SATA 6 Gbit/s
Storage 2	2x 960GB SSD-SATA 6 Gbit/s
Ethernet	Broadcom 57416, 2x 10Gb BASE-T
Internet connection	High speed connection via university access

The Hosting is realized via a reverse proxy that enables secure use from outside the university network via the Internet.

8.2 Flask API Architecture

The Flask API is modular in design, consisting of five core routes (**Figure *7***). Each route corresponds to specific components within the sDSS workflow and are defined based on the equation for the multi-risk index calculation. Each module interacts with the backend to perform the specific process defined by the expert. Depending on the user's input in the GUI, the data is processed and passed through the relevant modules to compute intermediate results for each one of the risk factors indices (multi hazard index (MHI), reclassified LU/LC, vulnerability index (VI)). These results are then combined in the Risk Assessment Module to generate the final risk assessment map, where the Risk Interval route allows the expert to reassess the level of risk in each site.

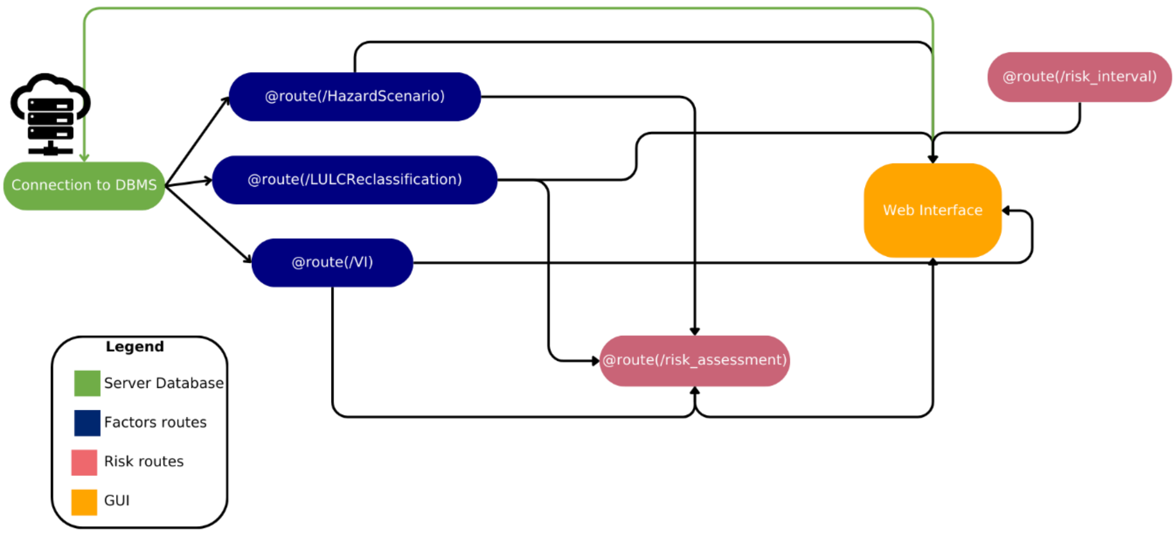

Figure 7: sDSS Flask routes

8.2.1 Hazard Scenario route

This route is associated with the Hazard factor and provides the expert with the flexibility to establish multiple scenarios for risk assessment. Depending on the selected site, the expert can access pre-assessed hazards already developed within the POMHAZ project. Within this route, the expert can define the intensity level of each hazard and specify the interactions between different hazards.

Once the input is provided, the information is sent to the backend route. The backend connects to the database to retrieve the hazard data selected by the user. It then applies an adjustment principle to reweight the hazards based on their intensity levels and interactions. Finally, the route calculates the Multi-Hazard Index (MHI) for the study site, and store the information to be used in the risk assessment route.

8.2.2 LU/LC Reclassification route

This route corresponds to the Exposed Elements at Risk factor. Through the GUI, the expert can define the level of significance for each of the eight classes established by the LU/LC global map for the risk assessment study.

Once the input is provided, the information is passed to the LU/LC Reclassification route, which retrieves the spatial data for the site selected by the user. The route then reclassifies the LU/LC map of the area based on the significance levels specified. The resulting reclassified raster is saved in the database for integration into the Risk Assessment route. Additionally, the updated map is sent back to the front end, where the user can view the results interactively on the Leaflet map.

8.2.3 Vulnerability Index (VI) route

The Vulnerability Index route corresponds to the assessment of the Vulnerability factor. This module enables the expert to assign weights to each of the vulnerability indicators, tailoring the analysis to the specific needs of the risk assessment. The flexibility to adjust weights ensures that the vulnerability assessment reflects the unique characteristics and priorities of the study site.

Once the weights are defined, the information is sent to the backend VI route, which retrieves the relevant vulnerability indicators from the database for all cities within the boundaries of the selected study site. Using the weights provided by the expert, the route performs the calculation of the Vulnerability Index (VI).

The resulting VI raster is saved in the database to be integrated into the Risk Assessment route. Additionally, the GUI displays the vulnerability indicators corresponding to the study site and the calculated Vulnerability Index, allowing the expert to review the results and ensure they align with the input parameters

8.2.4 Risk Assessment and risk interval routes

The Risk Assessment Route serves as the integrative module that combines the results from the Hazard Scenarios, Exposed Elements at Risk, and Vulnerability Index routes. This integration enables the generation of a comprehensive risk map for each scenario established in the assessment. The backend gathers the results from the previous modules, processes the data using the multi-risk equation, and produces a new raster that represents the spatial distribution of risk levels.

Once the risk map is prepared, the raster is sent to the front-end and displayed using a Leaflet map. The interface allows the expert to interact with the data by defining four interval classes through the use of three sliders. These sliders enable the user to set thresholds for the classification of the risk levels:

- No Risk Class: Represents areas with no detected hazards or insufficient data for hazard assessment.
- Low Risk Class: Defined based on the expert's input through the first slider.
- Medium Risk Class: Determined using the second slider, representing moderate levels of risk.
- High Risk Class: Defined using the third slider, indicating areas with significant risk requiring immediate attention.

The classification intervals selected by the expert are sent to the backend via the Risk Interval Route, where the system processes and generates corresponding interval-specific maps. The expert can download these maps for further analysis or reporting.

In addition to generating interval-based maps, the sDSS API provides suggestions for managing risks based on the risk classification (see chapter 7):

- Low Risk Areas: Monitoring techniques are recommended to track potential developments. These techniques include terrestrial and remote sensing methods such as Unmanned Aerial

Vehicles (UAVs) and satellite imagery to monitor hazards associated with post-mining activities.

- Medium Risk Areas: Risk mitigation strategies are suggested to address environmental, structural, and ecological challenges arising from abandoned or decommissioned mining sites. These may include geotechnical stabilization, water management, and ecological rehabilitation measures.
- High Risk Areas: A land repurposing methodology is advised. The sDSS provides an overview of potential land repurposing techniques, which involve transitioning high-risk sites into safe and sustainable uses, such as recreational areas, renewable energy installations, or urban development projects.

9 Usage of the sDSS tool

The sDSS tool is online available under https://dss.fzn.thga.de. All data access is restricted with user name and password, accounts for testing and evaluation can be created by contacting Benjamin.haske@thga.de or Vinicius.Inojosa@thga.de.

The usage of the sDSS is explained in detail in Annex B for expert users and Annex C for admin user. These manuals serve as a well-defined guideline to ensure efficient and accurate risk assessment in post-mining areas. They indicate a proper understanding for expert and admin users to fully leverage the system's capabilities. From the specified data formats, file naming conventions to module workflows, the manual ensures an integration of new data and enhances the accuracy of risk assessments. By empowering both user groups to update and refine datasets, the sDSS promotes dynamic and adaptive risk evaluation methodologies, accommodating new information as it becomes available.

Furthermore, the manuals highlight additional features like download options, interactive maps, and scenario adjustments, offering flexibility and accessibility for both expert users and stakeholders.

Further use by different stakeholders and the possibility of using anonymized datasets for the general public will be assessed during Work package 5 "Application on real case studies".

The use of the interfaces and tool boxes is described in the deliverables D4.2 and D4.3.

10 Testing and case Studies

The sDSS underwent rigorous testing in the development phase to ensure its functionality, reliability, and user-friendliness. The following testing protocols were implemented:

- **Functional Testing:** Validated the accuracy of calculations in each module (e.g., Multi-Hazard Index, Vulnerability Index).
- **Performance Testing:** Assessed the system's ability to handle large datasets and multiple user requests simultaneously.
- **User Acceptance Testing:** Collected feedback from stakeholders in the study areas to refine usability and ensure practical application.
- **Extensive testing:** Generated and analysed recommendations of decisions on fictive cases of different land covers for a set of MHI and VI values to assess sensibility and stakeholders' feedback.

10.1 Test case – Southern Ruhr area

To test the methodology and the developed sDSS, open source, public and archival data of the Ruhr Area case study was used. In the 1000 km^2 area of interest (**Figure *8***) data for several post-mining and natural hazards alongside socioeconomic data for the VI calculation was collected: Sinkhole (local collapse) hazards where derived from shafts [32], adits [33,34] and coal seams [35] with their intensity decreasing with distance to the object or the surface; Subsidence hazards from the legacy mining company RAG AG [36]; Flood hazards from open source flood maps [37] (intensity increasing with reoccurrence intervals); rockfall and landslide hazards from open source digital elevation models (based on angle and curvature) [38]. It should be noted at this point that this is only an initial test data set as part of the sDSS development, not an anticipation of the extensive application as part of WP5 "Application on real case studies".

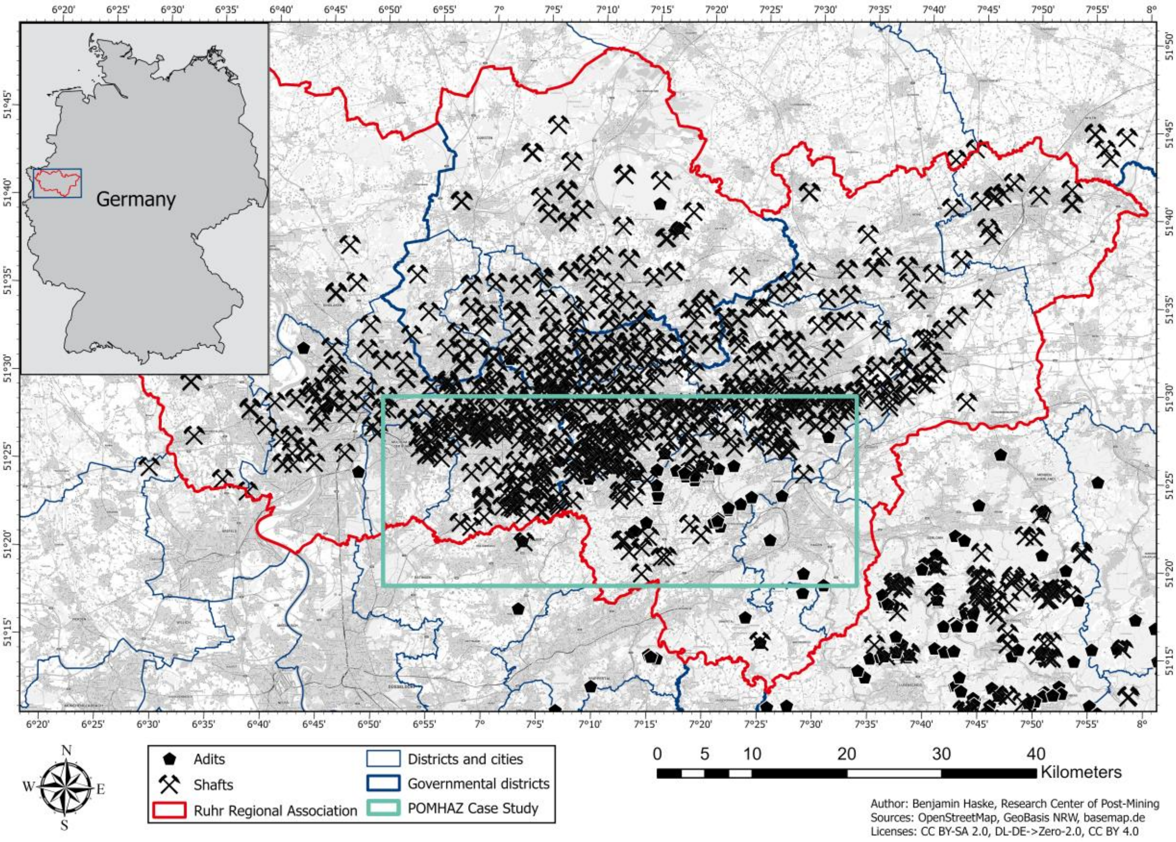

Figure 8: The test case study "Southern Ruhr Area" with open and archival data on shafts and adits alongside administrative boundaries

For data protection reasons the following maps only show parts of the Area of Interest (AOI) without scale and coordinates. For subsequent applications, the sDSS will also be supplemented with more confidential company and administrative data, resulting in enhanced outcomes. Stringent data protection protocols are implemented to prevent any unauthorized use or disclosure of the data.

Using the four hazards “Subsidence” (SU), “Sinkhole” (SH), “Gas Emissions linked to Mining” (MG) and “Hydrological disturbances, mining induced floods (surface)”[2] (FL), two basic scenarios with potential interactions were tested[3]:

- Scenario 1: Sinkholes opening new ways for mine gas emissions
- Scenario 2: Subsidence creating hydrological disturbances and/or floods

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[2] Natural flood risks were employed as a surrogate, albeit with the caveat that these can be intensified by the impact of mining.

[3] As this is merely a test case utilizing open data, the presented scenarios should only be regarded as illustrative examples to assess the methodology. A comprehensive investigation of the area, the existing hazards and their interactions will be conducted with more precise data in WP5.

10.1.1 MHI calculation

In accordance with the identified hazard sources, hazard polygons were devised, to which a range of factors (see above) were assigned intensity values from 1 to 5. These were subsequently transformed into 10 x 10 m cells. By employing the formula and the corresponding interaction levels (SU = 2, SH = 3, MG = 1 and FL = 3), it is possible to calculate and visualize the spatial MHI for the two scenarios (**Figure *9***).

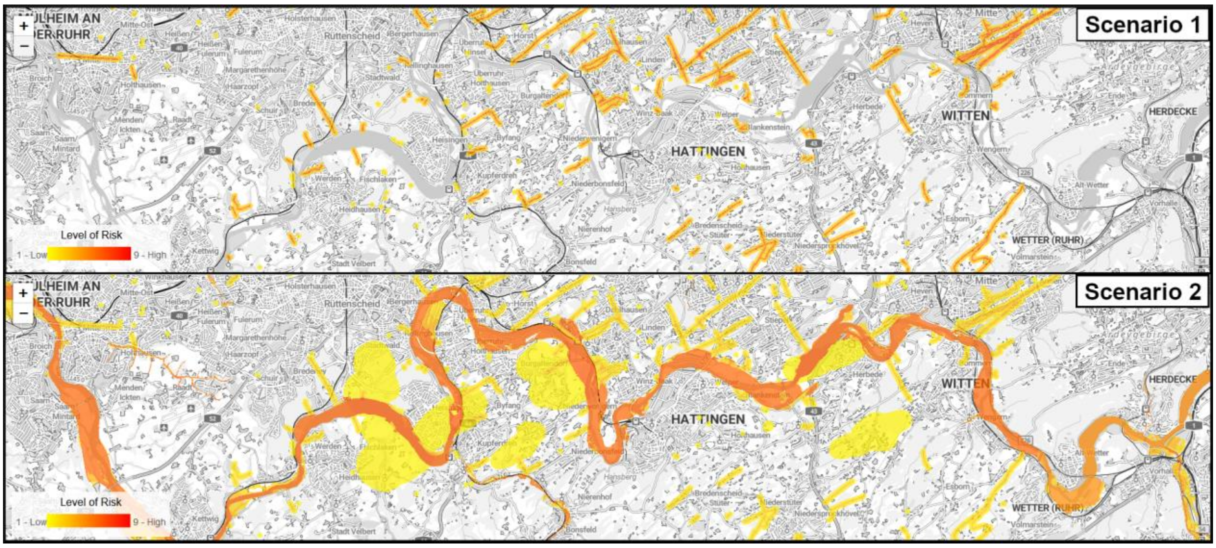

Figure 9: The spatial MHI from 1 to 9 for both test scenarios (progressive scale)

10.1.2 EAR assessment

In order to conduct the EAR assessment, open LU/LC data was employed [11]. As with the MHI calculation, the use of more precise data from stakeholders can facilitate the generation of superior results in later uses. The land use values were reclassified in **Table *2*** in order to represent their respective risk levels. The result of the reclassification is shown in **Figure *10***, highlighting higher risks for elements on the surface in denser populated areas in the northern part of the AOI.

Table 2: Reclassification of land use classes using an EAR risk level

Land use	Risk level
Water	2
Trees	5
Flooded vegetation	3
Crops	7
Built area	9
Bare ground	2
Snow/Ice	1
Rangeland	7

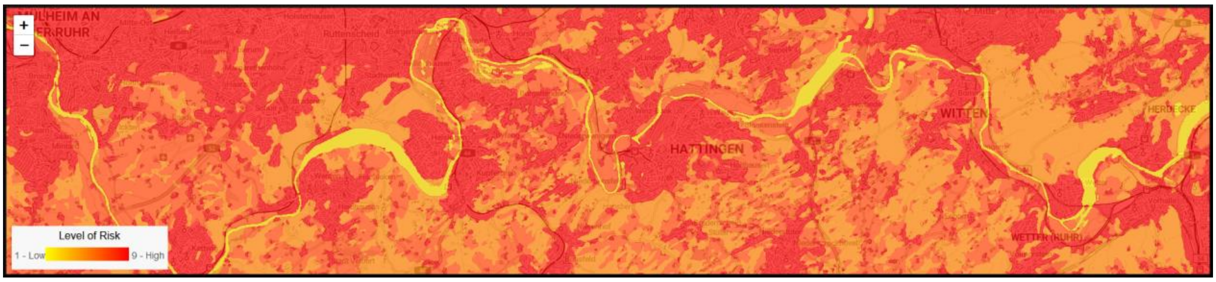

Figure 10: The reclassified LU/LC values showing the spatial EAR risk levels in the AOI

10.1.3 VI calculation

The calculation of the VI utilizing the four classes was conducted for each municipality within the AOI, representing the lowest data resolution available. The open data [39–41] allowed for the gathering of values for each subclass, which were then normalized from 1 to 9 in comparison to national averages. The class value was calculated as the mean of the subclasses, weighted and used as a factor for the overall VI calculation using the equation shown earlier. **Table *3*** shows the values for the cities in the case study AOI, while **Figure *11*** provides a visual representation of this data.

Table 3: Calculation of the VI for different cities in the AOI using open data and the standard weights

City	Socioeconomic factor	Household factor	Environmental factor	Infrastructure factor	VI
Bochum	5,5	7	5	3,5	**5,65**
Breckerfeld	4	4	5	3,125	**3,925**
Dortmund	6	7	5	3,5	**5,8**
Ennepetal	4,5	5,5	4	3,125	**4,575**
Essen	6	7	5	3,25	**5,75**
Gelsenkirchen	6,5	7	5	3,5	**5,95**
Gevelsberg	4	6	5	3,375	**4,775**
Hagen	6	3,5	1,5	3,175	**3,985**
Hattingen	4,5	6	3,5	3,125	**4,725**
Heiligenhaus	4	6	5	3	**4,7**
Herdecke	3,5	6,5	4	3,375	**4,725**
Mülheim a. d. R.	5	6,5	5	3,25	**5,25**
Oberhausen	7	7	5	3,5	**6,1**
Ratingen	3,5	6	5,5	3	**4,6**
Schwelm	4,5	6,5	5,5	3,375	**5,175**
Schwerte	4	5,5	5	3,375	**4,575**
Sprockhövel	3,5	6	5,5	3,125	**4,625**
Velbert	4,5	6	4,5	3	**4,8**

Wetter (Ruhr)	4	5,5	4	3,125	**4,425**
Witten	5	6	5	3,25	**5,05**
Wülfrath	4	6	4,5	3,125	**4,675**
Wuppertal	6	7	5	3,425	**5,785**

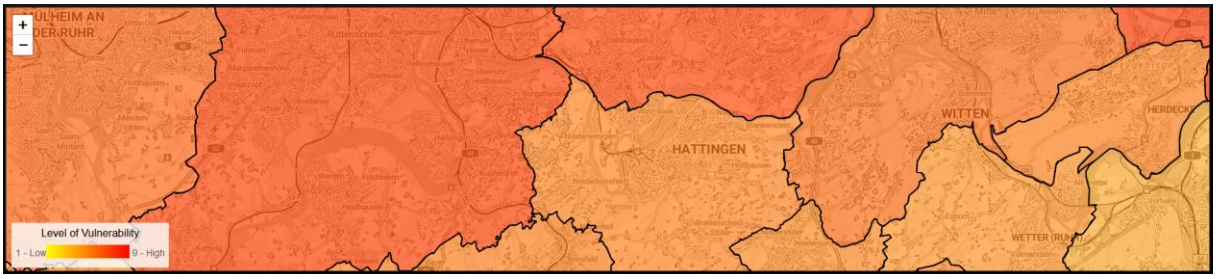

Figure 11: Spatial VI representation in the AOI of the southern Ruhr area

It is evident that the socioeconomic, household, and environmental factors for the region are below the national average, which is to be expected for a region that has been affected by decades of mining. However, the infrastructure is a significant advantage for this region, as it can be utilized to facilitate the post-mining transition process.

10.1.4 Multi-risk calculation

Ultimately, all three factors were transformed into a raster and homogenized to a uniform spatial resolution. For the 10,000,000 individual cells within the 1000 km^2 AOI, the multi-risk was then calculated from the three factors in accordance with the multi-risk equation. This results in a scale from 0 to a theoretical maximum of 729 (MHI = 9, EAR = 9, VI = 9) for each cell. **Figure *12*** depicts the final spatial visualization for both multi-hazard scenarios. The values have been reclassified from numeral values to four classes: No color shows areas with no risk, the expert user can define the limits for the risk classes “low risk”, “medium risk” and “high risk” individually. These classes lead the user directly to different choices, e.g., monitoring, risk mitigation or land planning.

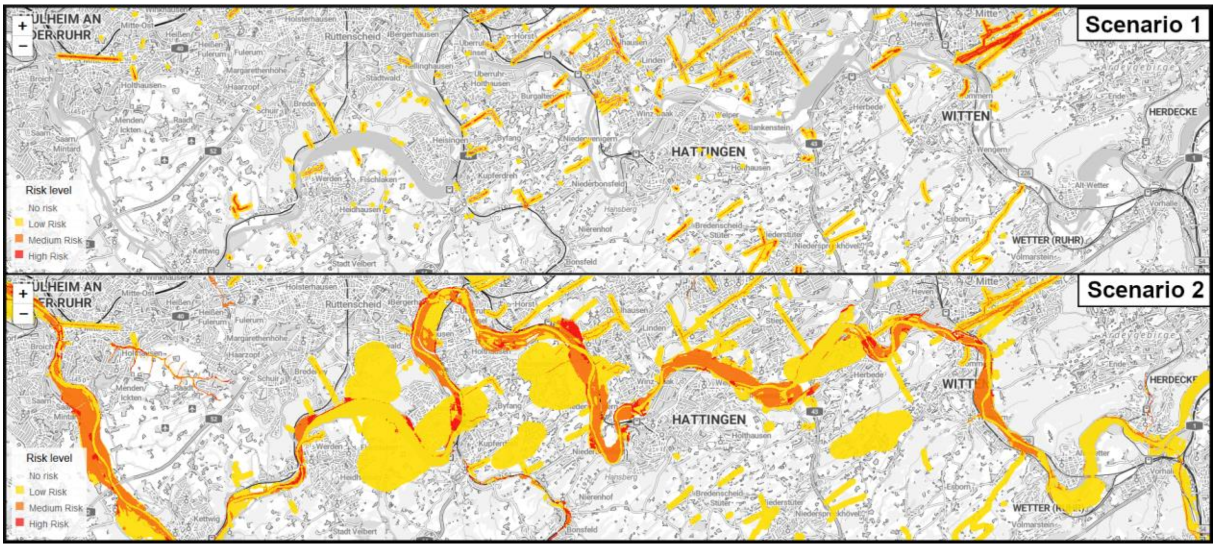

Figure 12: The spatial multi-risk calculation for both scenarios. Limit values for low risk: 150, medium risk: 250, high risk: 350.

The two maps illustrate the impact of disparate choices during the analytical process on the resulting outcome, particularly the utilization of disparate hazards and their potential interactions. A comparison of the outcome with the other factors, EAR and VI, reveals that they also exert a significant influence on the transition from multi-hazard to multi-risk levels, contingent on the elements at risk and their vulnerability.

Usage of the sDSS methodology and the programmed server and GUI will be tested and validated using other mining sites from France, Greece and Poland in WP4 and WP5.

10.2 Test case – Sosnowiec

In addition to the first test case in the southern Ruhr area, the sDSS is currently being verified by the GIG project partners in a second study case in the Polish city of Sosnowiec. This is described in deliverable D4.4.

10.3 First test results

- Functional Testing:
  - All modules returned accurate and consistent results across test scenarios.
  - Minor bugs were identified and resolved in the data upload process.
- Performance Testing:
  - The system maintained stable performance with datasets exceeding several Gigabyte of data.
  - Response time for generating maps was optimized to under 5 seconds.
- User Feedback:
  - Positive feedback on the interactive map design and module structure.
  - Suggestions for additional export formats were noted for future development.

10.4 Extensive user testing

A Sensibility analysis calculates the final integrated risk assessment values for a set of fictive cases of land cover with different values of MHI and VI. Extensive testing is performed to establish stochastic distribution of multi-risk values. These values are proposed to stakeholders in regard to monetarized sustainability objectives and acceptable remediation and mitigation costs.

11 Conclusion and Recommendations

The utilization of GIS-supported evaluation of multi-hazard and multi-risk scenarios demonstrates considerable potential for post-mining areas. The server-based approach allows for low-threshold access via the respective web browser through the use of a simple graphical user interface (GUI). No additional software is necessary for the analysis. Scalability and replicability are key strengths of this approach, as its framework can be adapted to diverse regions by integrating region-specific datasets and addressing local challenges.

Expert knowledge regarding the specific topographic, geological, geotechnical and hydrological information of the region, the assessment of post-mining hazards, as well as the socio-economic and other factors on site, which can be sourced from open data, when combined with automated calculation of spatial risk levels enables rapid results for various stakeholders to manage potential risks. This allows for the preparation of decisions on monitoring measures, risk mitigation, or land planning for a variety of scenarios, which can then be analyzed in an iterative process. The capacity of the sDSS enables the users alter diverse values and weights in an iterative manner and to evaluate alternative scenarios, which makes the sDSS a highly flexible and robust instrument for addressing post-mining challenges.

All results (and intermediate steps) of the sDSS programmed from free software can be downloaded and used in other software applications such as different GIS or CAD programs, land planning or engineering software. Strict data protection guidelines, the separation but also shared use of data strings and silos, and the possibility of anonymization by reducing the resolution also enable the evaluations to be made publicly available.

The DSS has proven to be a powerful tool for assessing and managing multi-hazard risks in post-mining regions. By integrating hazard assessment, exposure analysis, and vulnerability evaluation, the system supports informed decision-making for stakeholders.

The modular architecture of the system ensures flexibility and scalability, thereby enabling adaptation to various regions and hazard types. Initial testing has demonstrated the system's robustness and accuracy in the first two test cases. This further highlights the system's practical application, showcasing its value in supporting land-use planning, monitoring and risk mitigation strategies.

In order to enhance the system's capabilities, a number of key recommendations have been identified:

- Firstly, the integration of data should be expanded to encompass additional formats, such as GeoJSON and NetCDF, thus facilitating more comprehensive data usage.
- Secondly, advanced analytics should be developed, incorporating predictive modelling capabilities to facilitate long-term hazard forecasting, including AI-assisted methodologies.
- Thirdly, user training modules should be designed to help stakeholders fully leverage the tool's potential.
- Finally, an ongoing feedback loop should be established to collect user suggestions and support continuous, iterative improvements to the system.

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13 Annexes

List of annexes:

- Annex A: Spreadsheet for the calculation of the Vulnerability Index (VI)
- Annex B: User manual for the sDSS API
- Annex C: Administrator guidelines for the sDSS API
- Annex D: Sustainable socioeconomic post-mining planning

Annex A

	Area	City 1	City 2	City 3	EU	Germany	World
Socioeconomic status	Unemployment Rate [%]	8,9	13,5	9,7	6	5,7	5,8
	Factor	7	9	8	5	4	4
	GDP per capita [€]	37 650	33 754	35 665	37 620	48 750	11 634
	Factor	4	4	4	4	3	8
	Socioeconomic factor	5,5	6,5	6	4,5	3,5	6
Household composition	Population < 15 y.o. / > 64 y.o.	37,8	39,6	40,4	35	35	35
	Factor	5	5	6	4	4	4
	Population density [People / km²]	2502	2469	60	112	232	62
	Factor	9	9	1	2	3	1
	Household factor	7	7	3,5	3	3,5	2,5
Environment	Settlement area [%]	56,1	57,2	4,4	4	9,5	2
	Factor	9	9	2	2	3	2
	Agricultural areas [%]	10	8	25	40	50	38
	Factor	1	1	1	3	5	3
	Environmental factor	5	5	1,5	2,5	4	2,5
Infrastructure	Building age	50	50	50	60	50	40
	Factor	5	5	5	6	5	5
	Building material	Brick masonry, reinforced concrete	Brick masonry, reinforced concrete	Brick masonry, reinforced concrete, timber framing in older districts	Mixed	Mixed (mostly concrete and brick construction)	Mixed
	Factor	2	2	2,7	3	2,5	4,5
	Geometry	Multi-story rectangular buildings	Multi-story rectangular buildings	Multi-story rectangular buildings	Mixed	Mixed	Mixed
	Factor	3	3	3	4,5	4,5	4,5
	Traffic area [%]	11,7	11,4	1,5	2	2,9	3
	Factor	4	4	2	2	2	2
	Infrastructure factor	3,5	3,5	3,175	3,875	3,5	4
	Vulnerability Index	**5,65**	**5,95**	**3,985**	3,575	3,55	3,85

Vulnerability Index (VI) = Socioeconomic factor x 0.3 + Household factor x 0.4 + Environmental factor x 0.1 + Infrastructure factor x 0.2

	Area									
	Unemployment Rate [%]	< 3	3 - 4	4 - 5	5 - 6	6 - 7	7 - 8	8 - 9	9 - 10	> 10
	Factor	1	2	3	4	5	6	7	8	9
	GDP per capita [€]	> 60.000	50.001 -60.000	40.001 - 50.000	30.001 - 40.000	25.001 - 30.000	20.001 - 25.000	15.001 - 20.000	10.001 - 15.000	< 10.000
	Factor	1	2	3	4	5	6	7	8	9
	Socioeconomic factor									
	Population < 15 y.o. / > 64 y.o.	<= 20	21 - 25	26 - 30	31 - 35	36 - 40	41 - 45	45 - 50	51 - 55	> 55
	Factor	1	2	3	4	5	6	7	8	9
	Population density [People / km^2]	<= 100	101 - 200	201 - 250	251 - 300	301 - 500	501 - 1.000	1.001 - 1.500	1.501 - 2.000	> 2.000
	Factor	1	2	3	4	5	6	7	8	9
	Household factor									
	Settlement area [%]	< 1	1 - 5	6 - 10	11 - 15	16 - 20	21 - 25	26 - 30	31 - 35	> 35
	Factor	1	2	3	4	5	6	7	8	9
	Agricultural areas [%]	<= 30	31 - 35	36 - 40	41 - 45	46 -50	51 - 55	56 - 60	61 - 65	> 65
	Factor	1	2	3	4	5	6	7	8	9
	Environmental factor									
Normalization 1 to 9	**Building age**	<= 5	6 - 10	11 - 20	21 - 30	31 - 50	51 - 70	71 - 90	91 - 110	> 110
	Factor	1	2	3	4	5	6	7	8	9
	Building material	Reinforced Concrete, Steel Structures	Prestressed Concrete, High-Performance Concrete	Modern Brick and Block Construction	Timber Frame Construction	Traditional Masonry, Older Concrete Structures	Untreated Wood, Simple Stone Constructions	Mud, Adobe	Temporary Materials (e.g., Corrugated Metal, Unprotected Plywood)	Substandard Materials, Recycled Materials without Quality Control
	Factor	1	2	3	4	5	6	7	8	9
	Geometry	Simple Rectangular Structures	Single-Story Buildings with Basic Roofs	Multi-Story Rectangular Buildings	Buildings with Simple Extensions (L-shaped or T-shaped Plans)	Buildings with Minor Cantilevers or Overhangs	Irregularly Shaped Buildings	Buildings with Complex Roof Structures (Domes, Vaults, Shells)	High-Rise Buildings with Complex Facades and Forms	Iconic or Unconventional Structures with Advanced Geometry
	Factor	1	2	3	4	5	6	7	8	9
	Traffic area [%]	< 1	1 - 5	6 - 10	11 - 15	16 - 20	21 - 25	26 - 30	31 - 35	> 35
	Factor	1	2	3	4	5	6	7	8	9
	Infrastructure factor									
	Vulnerability Index									

Annex B

Technische Hochschule Georg Agricola

PoMHaz

USER MANUAL

for the sDSS API

Annex B to POMHAZ deliverable D3.3

https://dss.fzn.thga.de/

Table of contents

Introduction

Welcome to the **Spatial Decision Support System (sDSS) API** User Manual. This API has been developed as part of the **POMHAZ Project** (Post-Mining Multi-Hazards evaluation for land-planning).

POMHAZ focuses on improving hazard assessment and risk management strategies in abandoned coalmines. The project aims to enhance the methodological framework for conducting multi-hazard analyses at the scale of mining basins, correlating with the primary post-mining hazards.

The sDSS API provides an intuitive platform to evaluate risk in post-mining areas by incorporating expert knowledge, hazard interaction, and vulnerability analysis. It allows users to assess various scenarios and visualize results through interactive maps. This user manual details the steps for using the API effectively.

The sDSS API is part of the POMHAZ Project funded by the **Research Fund for Coal and Steel (Grant Agreement No 101057326)**. It aims to bridge the gap between theoretical methodologies and practical applications in post-mining hazard assessment and risk management.

Note: This document is intended for expert users of the sDSS system.

Administrators have a separate manual with additional details on system management and data handling (Annex C).

Main API

Initial API Launch

1. Open the SDSS API application via https://dss.fzn.thga.de/[1]
2. Click "Go to sDSS API" in the field "Explore the sDSS API"
3. A login window will appear (see Figure 1). Enter your credentials (username and password) to access the system. If you do not have credentials yet, contact Vinicius.Inojosa@thga.de or Benjamin.Haske@thga.de

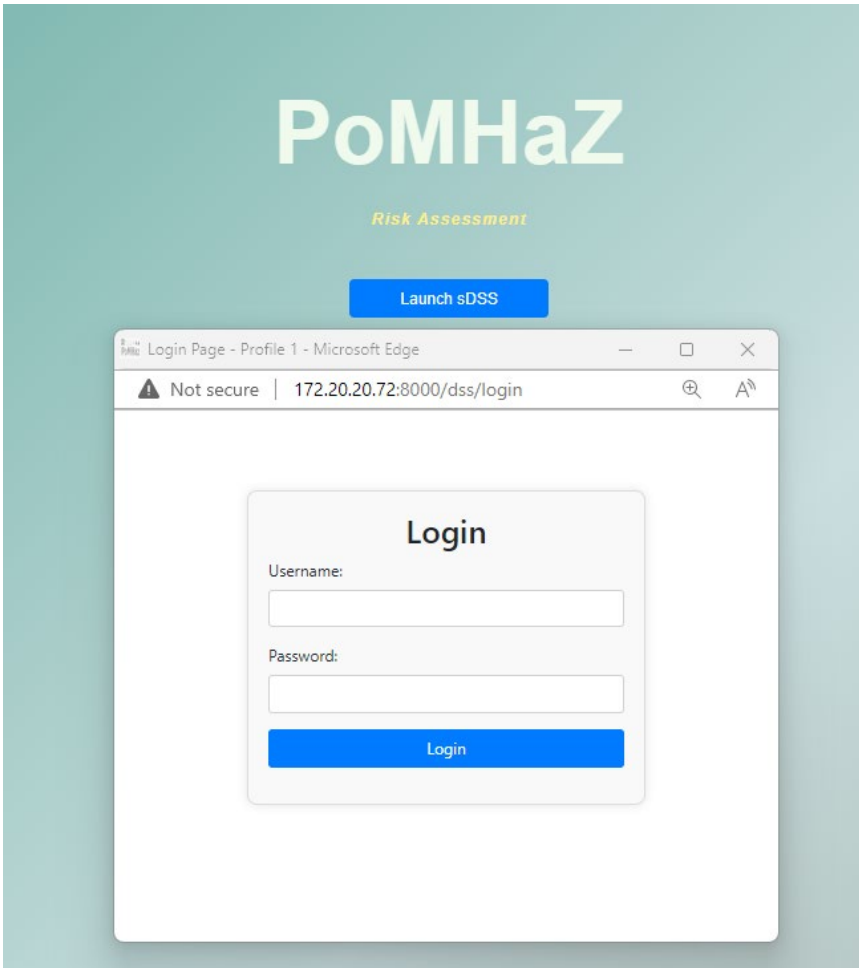

Figure 1: Login window to input credentials

[1] Please note that the sDSS relies on external resources for various API functionalities. Click 'Accept' to proceed.

Defining Initial Options

After logging in, you will see two primary options (see Figure 2):

1. **Work with Study Cases** → This option allows you to work with prepared study cases from project POMHAZ
2. **Start New Risk Management Process** → This option allows you to create a new study case

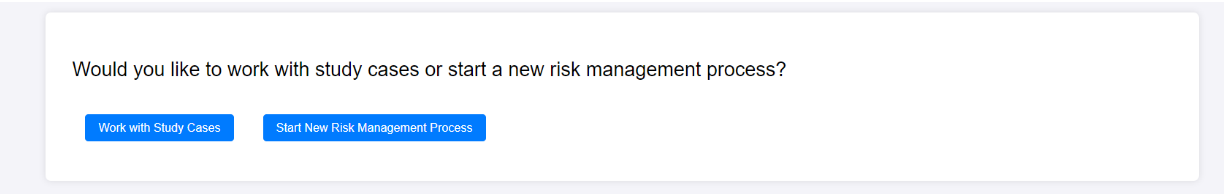

Figure 2: Selection stage for defining the modules of the sDSS API

Work with Study Cases

This option allows users to explore the data available for multi-risk management cases for specific post-mining locations presented in the POMHAZ project:

- **Southern Ruhr area, Germany**
- **Western Macedonia Lignite Centre and Megalopolis Lignite Centre, Greece**
- **Wałbrzych and Piekary Śląskie, Poland**
- **Peypin, France**

Upon selecting this option, a map with highlighted countries will appear (see Figure 3). Click on a location to proceed with the modules.

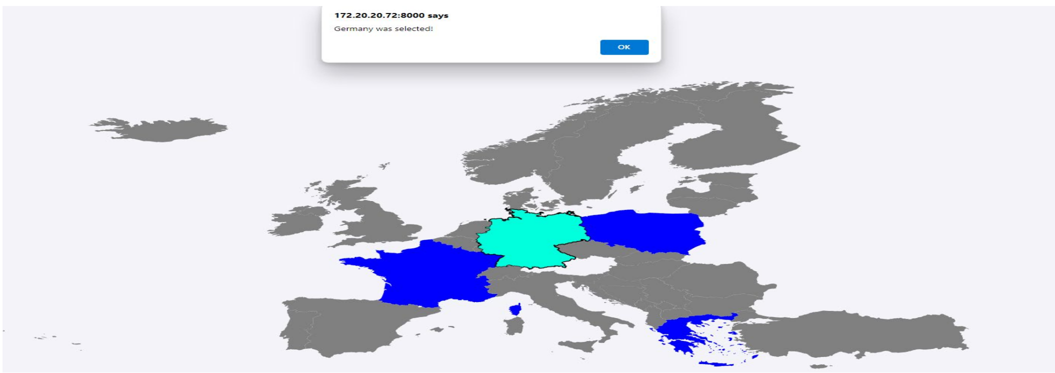

Figure 3: Site selection for loading the study cases

Data Preparation

Users can contribute additional data to the sDSS by contacting the admin assigned to their site. To ensure the data is correctly structured and compatible with the system, users should follow these steps:

1. Hazard Data

To perform multi-hazard assessments, hazard data must be structured according to the sDSS database requirements:

- **File Identification:** Each hazard file must follow the naming convention ID_Site, where Site corresponds to one of the predefined locations:
  - **Germany**: Refers to the Ruhr area.
  - **Poland**: Refers to Sosnowiec or other mine locations in Poland.
  - **Greece**: Refers to Western Macedonia Lignite Centre and Megalopolis Lignite Centre mines.
  - **France**: Refers to Peypin and other mine locations in France.

  The *ID* refers to the type of hazard (see Table 1 for valid IDs corresponding to post-mining hazard events in coal and lignite mining areas).

Table 1: Post-mining hazards with corresponding ID for uploading in sDSS

N°	Hazard	ID
1	Subsidence	subsidence
2	Settlement	settlement
3	Slope movement (slope stability) –Generalized scale	slope_general
4	Slope movement (slope stability) –	slope_local
5	Rock falls	rockfalls
6	Induced seismicity	induced_seismicity
7	Sinkhole	sinkhole
8	Crevice	crevice
9	Environmental water pollution	water_pollution
10	Environmental pollution from spoils	pollution_spoils

11	Environmental pollution from tailings dams	pollution_tailings
12	Hydrological disturbances, mining induced floods	floods_surface
13	Hydrological disturbances, mining induced floods	floods_underground
14	Hydrological disturbances, mining induced floods	floods_pitlake
15	Ionizing radiation emissions	radiation
16	Gas emissions linked to mining	gas
17	Combustion and overheating of mine waste	combustion

- **Hazard Polygon Creation:** Use Shapefiles or GeoJSON to create hazard polygons with intensity levels ranging from 1 (no hazard) to 5 (high intensity). Examples include:
  - Flood hazards, where intensity increases with occurrence intervals.
  - Sinkholes near old shafts, where intensity increases with proximity to the shaft.
- **Export and Submission:** Export the hazard polygons and send them to the admin user of the site.
- **Metadata:** Ensure all data includes proper metadata, such as CRS (Coordinate Reference System).
- **Validation Support:** Provide original datasets (e.g., maps, shaft coordinates) to validate the hazard data and contribute to the Knowledge Database (Knowledge DB).
- **Rasterization and Analysis:** Rasterization, weighting, and analysis will be handled by the sDSS.

2. Exposed Element at Risk data

The sDSS uses open-source Sentinel-2 Land Use/Land Cover (LU/LC) data from ESA imagery at a 10m resolution. The LU/LC data is categorized according to the predefined classes in Table 2.

- **Data Submission Guidelines:** Users may submit additional LU/LC data, but submissions must:
  - Follow the naming convention: LULC_site.
  - Contain raster files with pixels labeled according to the predefined ID values stated in Table 2

- Ensure compatibility with the DSS for reclassification and analysis. The system will only accept the files that are proper structure with the LULC nomenclature

Table 2: Classes defined for the LU/LC layer in the sDSS

ID	Class	Description
1	Water	Areas where water was predominantly present throughout the year; may not cover areas with sporadic or ephemeral water; contains little to no sparse vegetation, no rock outcrop nor built up features like docks; examples: rivers, ponds, lakes, oceans, flooded salt plains.
2	Trees	Any significant clustering of tall (~15 feet or higher) dense vegetation, typically with a closed or dense canopy; examples: wooded vegetation, clusters of dense tall vegetation within savannas, plantations, swamp or mangroves (dense/tall vegetation with ephemeral water or canopy too thick to detect water underneath).
4	Flooded vegetation	Areas of any type of vegetation with obvious intermixing of water throughout a majority of the year; seasonally flooded area that is a mix of grass/shrub/trees/bare ground; examples: flooded mangroves, emergent vegetation, rice paddies and other heavily irrigated and inundated agriculture.
5	Crops	Human planted/plotted cereals, grasses, and crops not at tree height; examples: corn, wheat, soy, fallow plots of structured land.
7	Built Area	Human made structures; major road and rail networks; large homogenous impervious surfaces including parking structures, office buildings and residential housing; examples: houses, dense villages / towns / cities, paved roads, asphalt.
8	Bare ground	Areas of rock or soil with very sparse to no vegetation for the entire year; large areas of sand and deserts with no to little vegetation; examples: exposed rock or soil, desert and sand dunes, dry salt flats/pans, dried lake beds, mines.
9	Snow/Ice	Large homogenous areas of permanent snow or ice, typically only in mountain areas or highest latitudes; examples: glaciers, permanent snowpack, snow fields.
11	Rangeland	Open areas covered in homogenous grasses with little to no taller vegetation; wild cereals and grasses with no obvious human plotting (i.e., not a plotted field); examples: natural meadows and fields with sparse to no tree cover, open savanna with few to no trees, parks/golf courses/lawns, pastures. Mix of small clusters of plants or single plants dispersed on a landscape that shows exposed soil or rock; scrub-filled clearings within dense forests that are clearly not taller than trees; examples: moderate to sparse cover of bushes, shrubs and tufts of grass, savannas with very sparse grasses, trees or other plants.

3. Vulnerability Indicators

The vulnerability index is calculated as described in the vulnerability module and requires data from cities within the study site.

- **Index Structure:** The sDSS calculates the vulnerability index using four weighted categories, divided into 10 subclasses. Each subclass is normalized on a scale from 1 to 9. The categories include:
  - **Socioeconomic Status:** Indicators like unemployment rate and GDP per capita.
  - **Household Composition:** Factors such as the percentage of the population under 15 or over 64 years old, and population density.
  - **Environment:** Metrics like settlement area and agricultural land.
  - **Infrastructure:** Attributes such as building age, material, geometry, and traffic areas.
- **File Format and Submission:** Data for each city must be uploaded in a .zip file containing a Shapefile with the vulnerability categories for the cities in the study site:
  - Naming Convention: vulnerability_site.
  - Shapefile Columns:
    - **Socioeconomic Status:** socioeconomic.
    - **Household Composition:** household.
    - **Environment:** environmental.
    - **Infrastructure:** infrastructure.
- **Metadata Requirements:** As with hazard data, ensure proper metadata accompanies the Shapefile.

Modules Overview

The SDSS API establishes four interactive modules that correspond with the calculation of the risk assessment of each area.

Module I: Multi-Hazard Assessment

This module enables users to evaluate the risk of selected hazards and analyze their interactions. The polygons for the hazards have to be prepared according to the methodology shown in D3.3 and uploaded by the admin user (see Annex C). Expert users can create between 1 to 5 scenarios for assessment and select the hazards relevant to each site.

The interaction between different post-mining, technical or natural hazards is defined by assigning interaction levels (Low = 1, Medium = 2, High = 3) and positioning hazard boxes to represent these interactions. Once the configuration is complete, a map with the normalized Multi-Hazard Index (values from 1 to 9) is generated, indicating the level of risk in the area.

Export Options: After completing the Multi-Hazard Assessment, users can export the generated hazard map as a .TIF file using the "Download" button.

Step-by-step procedure (see Figure 4).

1. **Select Scenarios**:
   - Choose between 1 to 5 scenarios you want to assess in the sDSS.
   - Based on the different scenarios, choose the hazards to evaluate.
2. **Hazard Interaction**:
   - For each hazard, indicate its interaction with others by assigning interaction levels:
     - 1 (Low)
     - 2 (Medium)
     - 3 (High)
   - Drag and position hazard boxes to define the chain of interactions (from left to right).
3. **Submit**:
   - Once hazards and interactions are defined, submit the configuration.

- A map with the normalized Multi-Hazard Index (values from 1 to 9) will be generated, indicating the level of risk in the area (see Figure 5).

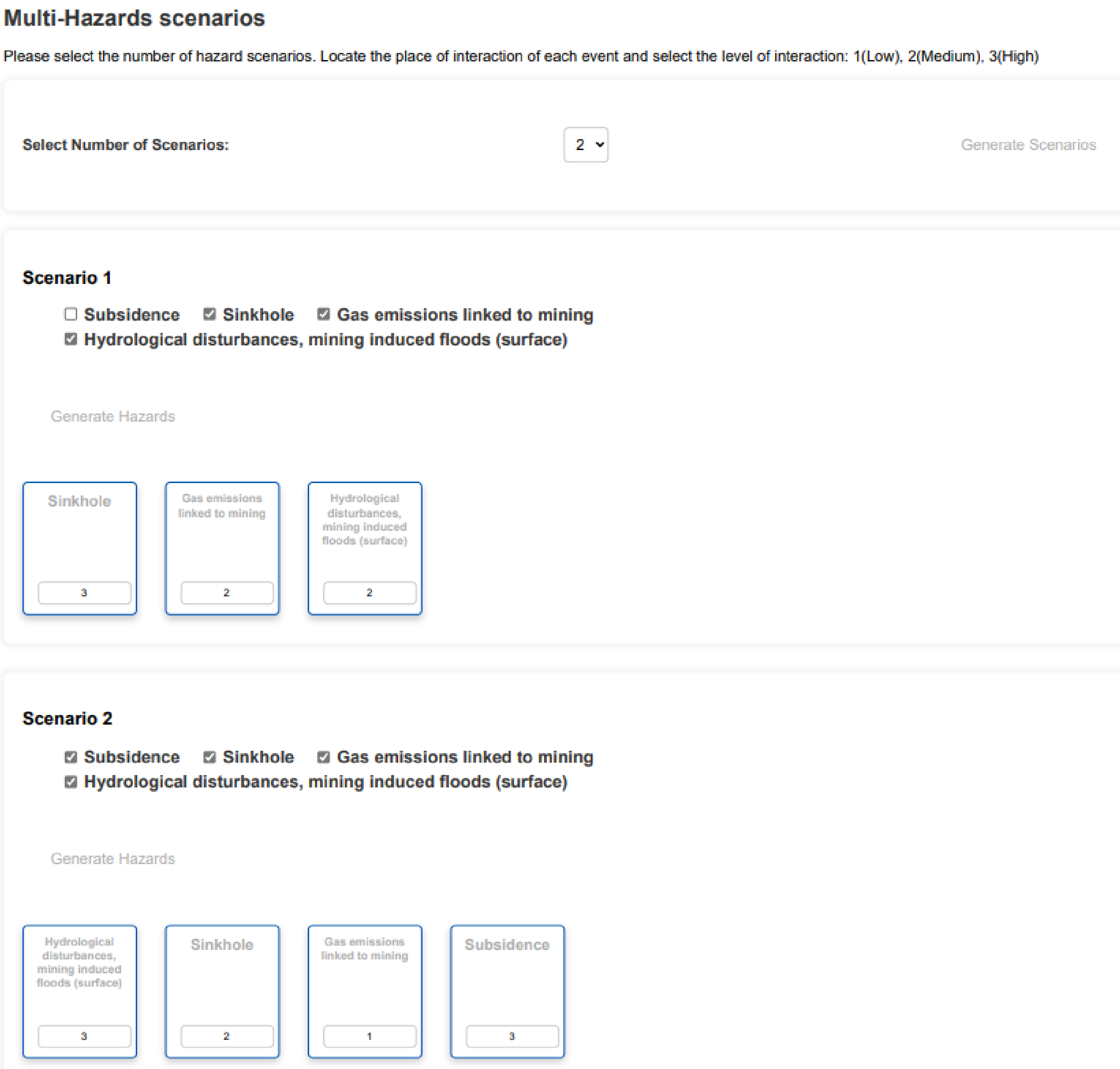

Figure 4: Example of generation of hazard scenarios with Ruhr study case

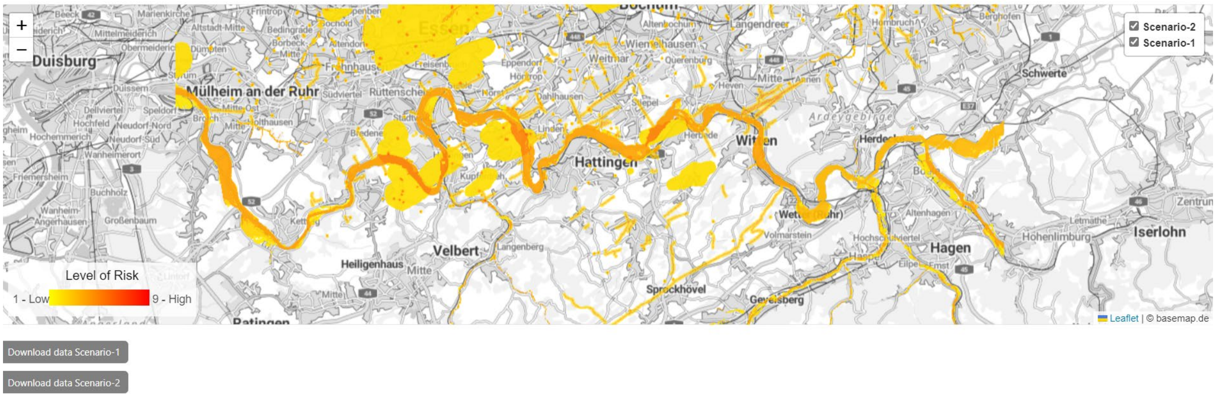

Figure 5: Visual representation of the selected hazards on the case study map

Module II: Exposure Assessment

This module assesses the elements at risk within the selected area base on different classes of the Land Use/Land Cover (LU/LC) 10x10m map derived from Esri's global map ESA Sentinel-2 imagery.

The expert user can assign significance levels to each class, ranging from low to very significant (1 to 9), and submit these weights to reclassify the LU/LC map. The system then generates a risk map indicating the level of exposure from very low to very high.

Export Options: The reclassified land use/land cover risk map can be exported as a .TIF or .SHP file by clicking the "Download" button provided in the module.

Step-by-step procedure (see Figure 6).

1. **Generate Matrix**:
   - View available classes of the Land Use/Land Cover (LU/LC) 10x10m map developed by derived from an Esri global map ESA Sentinel-2 imagery. This data is uploaded by an admin user (see Annex C).
2. **Weight Classes**:
   - Assign a significance level to each class (1 = Low significance, 9 = Very significant).
3. **Submit**:
   - Submit the weights to reclassify the land use/land cover map.
   - The system generates a map displaying the level of risk (1 = Very low risk, 9 = Very high risk, see Figure 7.

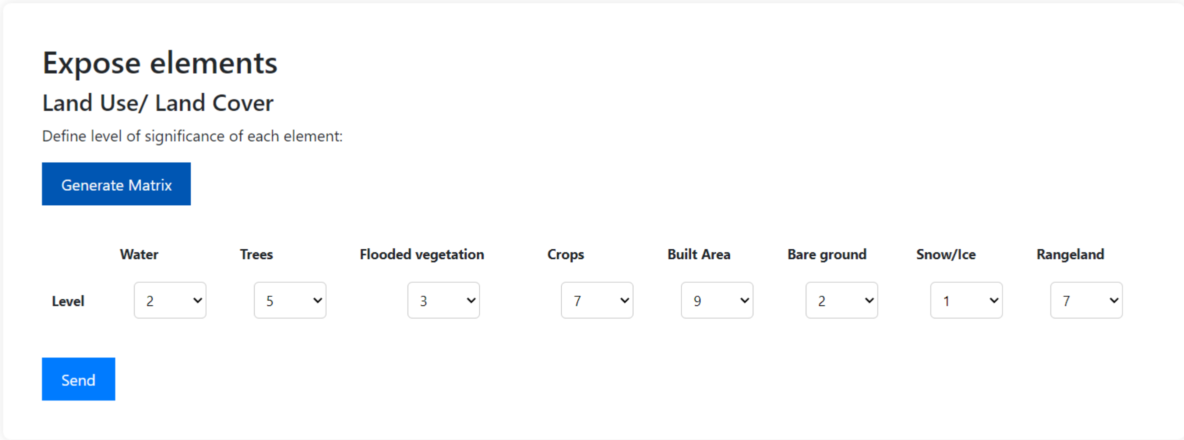

Figure 6: Example of reclassification of LU/LC classes to assess expose element at risk

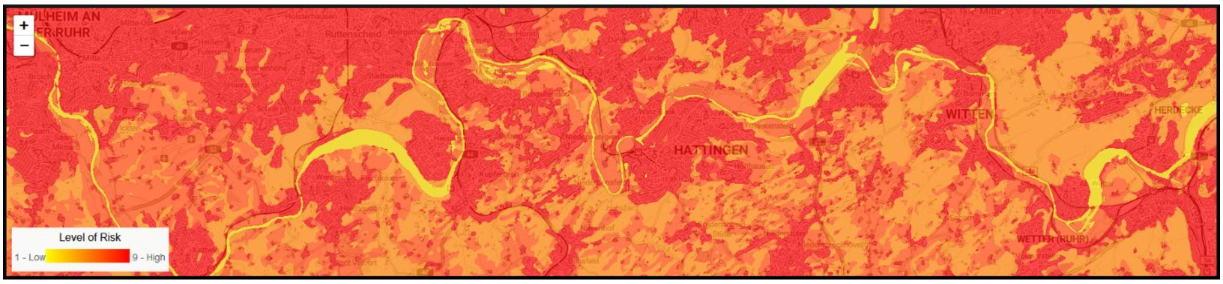

Figure 7: Example of Exposed Elements at Risk (EAR) in the Southern Ruhr area case, screenshot without scale

Module III: Vulnerability Evaluation

Module III focuses on assessing the vulnerability within the study area. Because of the scale of the data available for the socio-economic datasets (Socioeconomic status ,Household composition, Environment) in the Vulnerability Index (VI) calculation (see Annex A), this is done on city-level. The data is prepared by the expert user in the excel spreadsheet (Annex A) and uploaded by the admin user (Annex C).

Users define weight factors by assigning importance levels to each vulnerability indicator (0.1 = Low importance, 1 = High importance). After defining these weights, users can calculate the Vulnerability Index (VI), which is then displayed on an interactive map for easy visualization of vulnerable areas.

Export Options: The calculated Vulnerability Index map can be exported in .TIF or .SHP format by using the "Download" button located within the module.

Step-by-step procedure (see Figure 8).

1. **Define Vulnerability Factors**:
   - Click on "Weight VI Factor" to generate a matrix to assign the importance levels (0.1 = Low importance, 1 = High importance) of each vulnerability indicator.
2. **Calculate Vulnerability Index**:
   - Click "Calculate" to compute the Vulnerability Index for cities in the study area.
   - Results are displayed on an interactive map, see Figure 9.

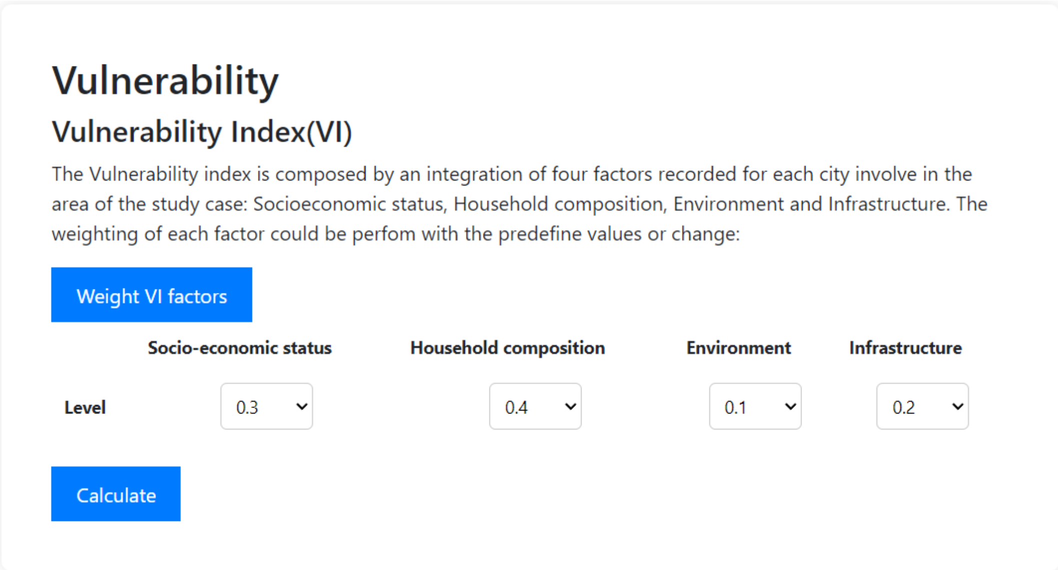

Figure 8: Weighting vulnerability indicators

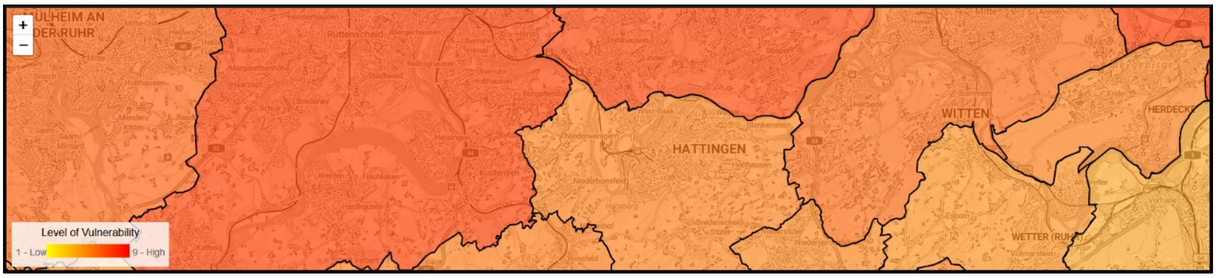

Figure 9: Example of Vulnerability Index in the Southern Ruhr area case, screenshot without scale

Module IV: Integrated Risk Assessment

This module (IV) integrates the outcomes of the previous modules to calculate the overall risk of the selected study case. Users can view the maps corresponding to each multi-hazard scenario, adjust risk levels using sliders (Low, Medium, High), and generate final results. The system then produces downloadable .TIFF files for each scenario with the overall risk results, allowing for further analysis.

Export Options: The spatial risk assessment results for each scenario can be exported as .TIFF files for further analysis by using the "Download" button available in the module.

Additional pages with suggestions for risk evaluation strategies are provided for each risk level. For low-risk areas, monitoring techniques are recommended. Medium-risk areas are addressed with risk mitigation strategies, while for high-risk areas, a guide for land planning approaches is given.

Step-by-step procedure (see Figure 10).

1. **Select Scenarios**:
   - View maps corresponding to each multi-hazard scenario defined in Module 1.
2. **Adjust Risk Levels**:
   - Use three sliders (Low Risk, Medium Risk, High Risk) to adjust risk levels for the area depending on expertise of the area.
3. **Generate Results**:
   - Based on the adjustments, the system generates a downloadable .TIFF files for each scenario with the risk result for further analysis.
   - Additional pages with suggestions for risk evaluation strategies are provided for each risk level. For low-risk areas, monitoring techniques are recommended. Medium-risk areas are addressed with risk mitigation strategies, while for high-risk areas, a guide for land planning approaches is given.

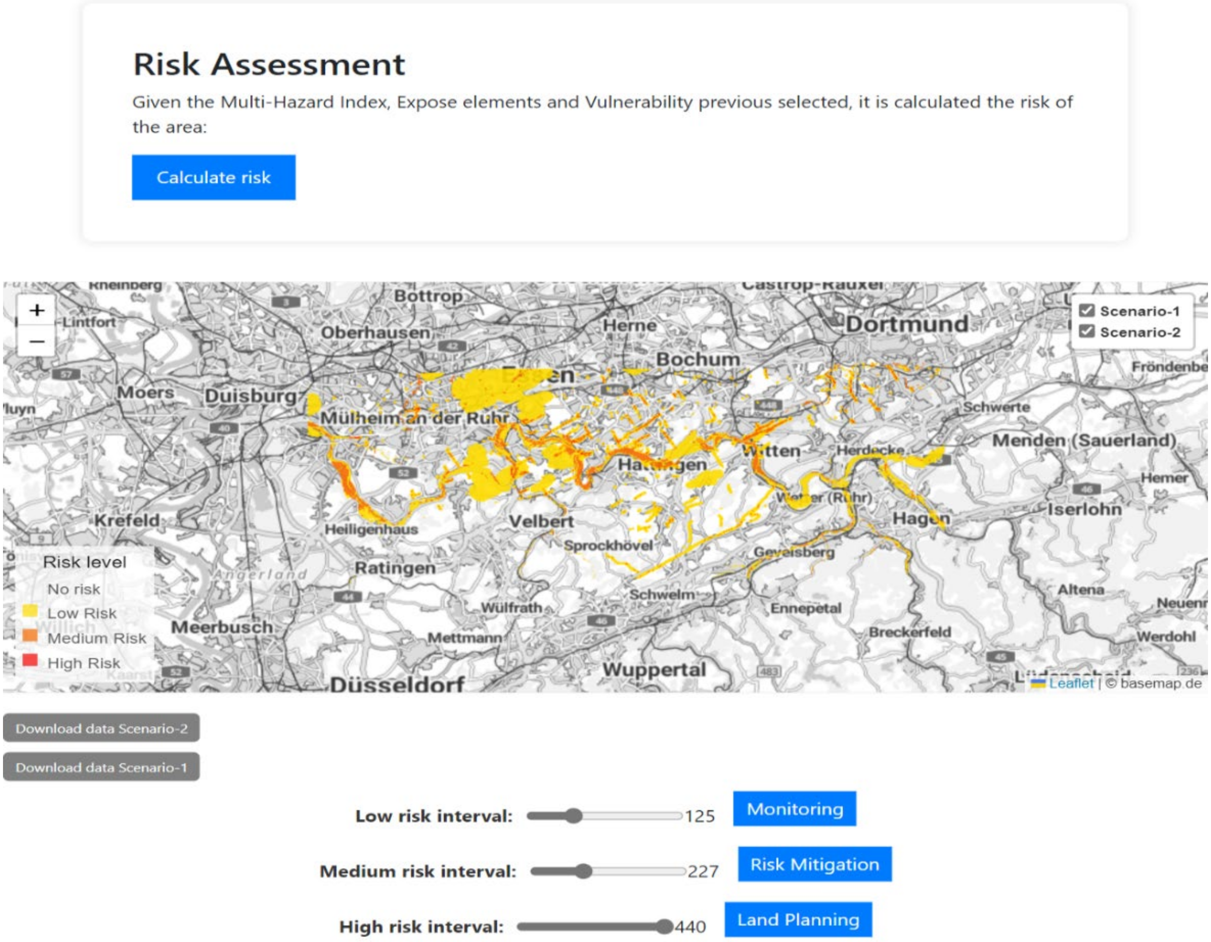

Figure 10: Risk Assessment module with example of Ruhr case

Start New Risk Management Process

This option allows users to initiate a custom risk management analysis with the possibility to upload data for the current studies location of the available study cases or upload a new area of interest to work in a different region (currently in development during the testing phase in WP5).

Additional Features

Reload Server

- Provides users with the ability to restart the API. This option is located at the end of the API

Interactive Maps

- Visualize results dynamically across all modules.
- Adjust parameters and immediately see the impact on risk assessment for each one of the scenarios

Download Options

- Export maps and raster results of each module in forma .TIF or .SHP using the download buttons

FAQ

This chapter aims to assist users in solving common problems and challenges encountered while using the SDSS API. Below are some frequently encountered issues and their solutions:

1. **Login Problems**
   - **Solution**: Ensure your credentials are correct. If the issue persists, contact the system administrator.
2. **Module Not Loading**
   - **Solution**: Verify your internet connection and try reloading the server using the "Reload Server" button.
3. **Exporting Maps or Results**
   - **Solution**: If export options do not work, ensure that all required inputs are correctly defined in the module.
4. **Risk Assessment module not being performed**
   - **Solution:** The Risk Assessment module is only executed if all preceding risk factor modules are completed successfully. This is because the final risk assessment integrates information from all these modules to generate comprehensive results. Ensure that each module is processed correctly before proceeding to the Risk Assessment module.

Annex C

ADMINISTRATOR

GUIDELINES for the sDSS API

Annex C to POMHAZ deliverable D3.3

https://dss.fzn.thga.de/

Table of Contents

Introduction

The Spatial Decision Support System API, developed under the POMHAZ Project, serves as a decision support system to evaluate multi-hazard risks in post-mining areas. This guideline is dedicated to general administrators managing sDSS instances at various sites. It provides instructions for maintaining the system, loading new study case data, and troubleshooting common issues.

As an administrator, your role is critical in ensuring the platform's smooth functioning, data improvement, and accessibility for end-users to each study cases. This manual focuses on non-development tasks and offers a clear roadmap for handling administrative duties.

This manual covers key administrative tasks, such as system maintenance, data integration, troubleshooting common issues, and ensuring seamless platform accessibility for end-users. By following these guidelines, administrators can effectively manage the system and support advanced risk assessments.

The sDSS API is part of the POMHAZ Project funded by the **Research Fund for Coal and Steel (Grant Agreement No 101057326)**. It aims to bridge the gap between theoretical methodologies and practical applications in post-mining hazard assessment and risk management.

Note: This document is intended for Administrators of the sDSS system. End-Users have a separate guideline (Annex B).

System overview

The sDSS API is designed to facilitate comprehensive risk assessment and management in post-mining areas. The system is modular, intuitive, and structured around key components that align with the risk assessment workflow.

Core Concept

The Multi-Risk scenarios are calculated it for different locations by the integration of different factors, as described in POMHAZ deliverable D3.3:

$$Risk = \sum Hazard^{*} \times Exposed\ element\ at\ risk \times Vulnerability \quad (1)$$

* Hazard corresponds to adjusted hazards identified on a mining site.

This approach ensures a holistic evaluation by integrating all critical risk factors and the possibility of risk calculation in the pixel level.

System General Structure

1. **Front-end Modules** The frontend is organized into four modules, reflecting the sequence of the risk assessment process:

    - **Multi Hazards scenarios**: Focuses on identifying and assessing the intensity and interactions of various post-mining hazards adjusting its significance with a multi-criteria decision method based on the adjusted principles.
    - **Exposure Elements at Risk**: Classify elelemts such as infrastructure, populations, or natural resources that are susceptible to identified hazards based on Land Use/Land Cover layers derived from the Sentinel-2 data. Here the expert has the possibility of re-weighting each factor.
    - **Vulnerability**: Evaluates the capacity of exposed elements to resist or recover from hazard impacts based on the calculation of Vulnerability Index by weighting the vulnerability indicators
    - **Risk Management**: Combines data from the first three modules to calculate and visualize overall risk, providing actionable insights for mitigation strategies.

- **Backend** The backend is powered by Flask, enabling the interaction between the user interface and the database. It processes inputs, executes calculations, and serves geospatial data.

2. **Database** PostgreSQL with PostGIS extensions is employed for spatial data management and processing. The database stores all essential datasets, including hazard layers, LU/LC layers and vulnerability indices for each area
3. **Visualization** Interactive maps and visual aids allow users to dynamically explore hazard interactions, vulnerability factors, and risk assessments. These maps are key components of the frontend modules.
4. **Risk Management Focus** The system not only aids in identifying and evaluating risks but also supports decision-making through its risk management module. This module gives the capacity for the expert to re-assess the risk defining the intervals and decide which risk methodology needs to be follow.

Main API

Initial API Launch

1. Open the sDSS API application[1] via https://dss.fzn.thga.de/
2. Click "Go to sDSS API" in the field "Explore the sDSS API"
3. With "Launch sDSS", a login window will appear (see Figure 1). Enter your credentials (username and password) to access the API with Admin features. If you do not have credentials yet, contact Vinicius.Inojosa@thga.de or Benjamin.Haske@thga.de

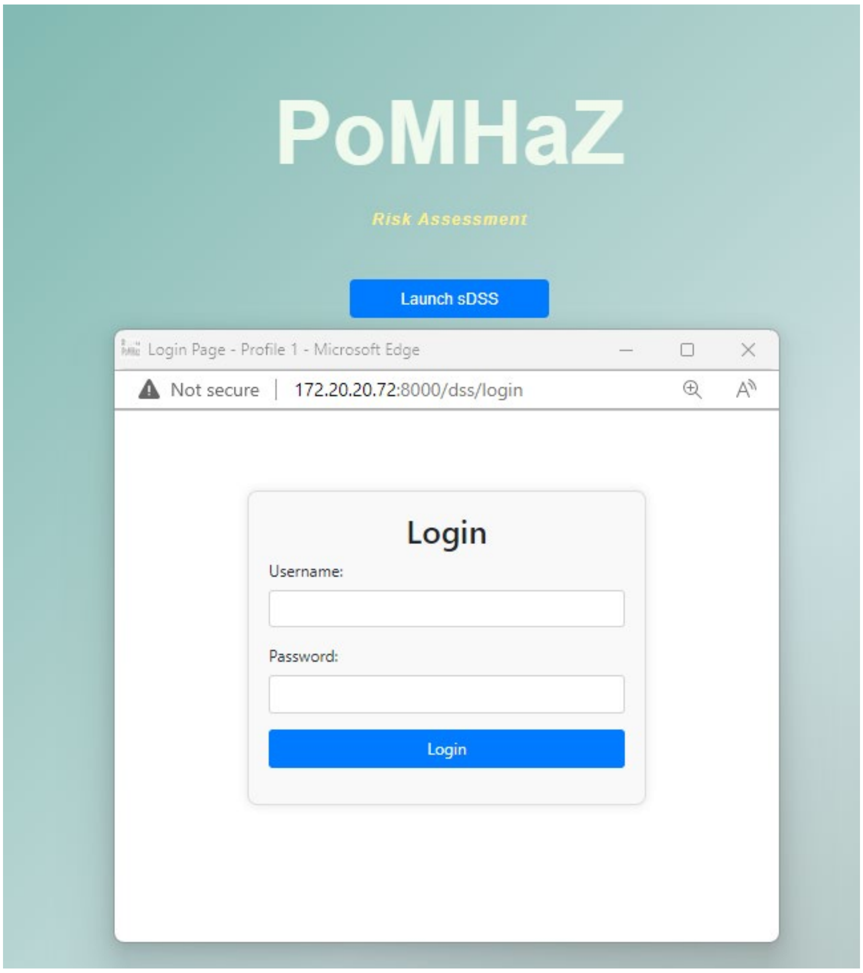

Figure 1: Login window for register the credentials

[1] Please note that the sDSS relies on external resources for various API functionalities. Click 'Accept' to proceed.

Adding feature for Admin users

Admin users assigned to each mining site have the capability to add new data for assessing multi-hazard scenarios, exposed elements at risk, and vulnerability factors (see Figure 2). This functionality allows for the updating of predefined study case data or the incorporation of newly available information. Users can upload data individually for each module and, once ready, click the "Proceed" button to initiate the assessment for their site. If no new data is added, the "Proceed" button can still be selected to perform the assessment using the predefined data stored in the database.

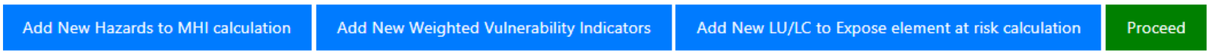

Figure 2: Admin feature to upload data to sDSS modules

New data for multi-hazard assessment module (optional)

After successfully logging in as an admin user, you can choose between adding new data or proceeding without making changes to the site information.

The sDSS accepts .zip files containing hazard intensity information. The data must include a column named hazard_int, with values ranging from 1 to 5, where:

- **1** represents "No hazard information"
- **5** represents "Very high-risk areas."

The uploaded .zip file must contain the following files in Shapefile format (Note: These files must be included whenever a Shapefile is added):

- **.shp**: Geometry of the hazard (Mandatory)
- **.shx**: Index file linking the geometry in the .shp file (Mandatory)
- **.dbf**: dBase file storing the attribute data for features (Mandatory)
- **.prj**: Projection and coordinate system of the shapefile (Recommended)
- **.sbn / .sbx**: Spatial index files for optimizing spatial queries (Recommended)

The .zip file name must follow the format ID_Site, where:

- **ID** refers to the type of hazard (see Table 1 for valid IDs corresponding to post-mining hazard events in coal and lignite mining areas).
- **Site** indicates the location of the site.

Currently, the sDSS supports hazard data for the following sites:

- **Germany**: Refers to the Ruhr area
- **Poland**: Refers to Sosnowiec or other mine locations in Poland
- **Greece**: Refers to Western Macedonia Lignite Centre and Megalopolis Lignite Centre mines
- **France**: Refers to Peypin and other mine locations in France.

For example, if an Admin user wants to upload data for **Sinkhole hazards** in the Ruhr area, the .zip file should be named **sinkhole_germany.zip**.

Table 1: Post-mining hazards with corresponding ID for uploading in sDSS

Hazard	ID
Subsidence	subsidence
Settlement	settlement
Slope movement (slope stability) – Generalized scale	slope_general
Slope movement (slope stability) –	slope_local
Rock falls	rockfalls
Induced seismicity	induced_seismicity
Sinkhole	sinkhole
Crevice	crevice
Environmental water pollution	water_pollution
Environmental pollution from spoils	pollution_spoils
Environmental pollution from tailings dams	pollution_tailings
Hydrological disturbances, mining induced floods	floods_surface
Hydrological disturbances, mining induced floods	floods_underground
Hydrological disturbances, mining induced floods	floods_pitlake
Ionizing radiation emissions	radiation
Gas emissions linked to mining	gas
Combustion and overheating of mine waste	combustion

The data will be uploaded in the MHI module, where it can be incorporated into the calculation of the risk index. If it is successful, a greed label with “Data added” will appear in the corner of the module. Note that if the uploaded hazard data corresponds to pre-existing information in the database, the hazard name will automatically include the suffix "(2)" at the end (see example in Figure 3).

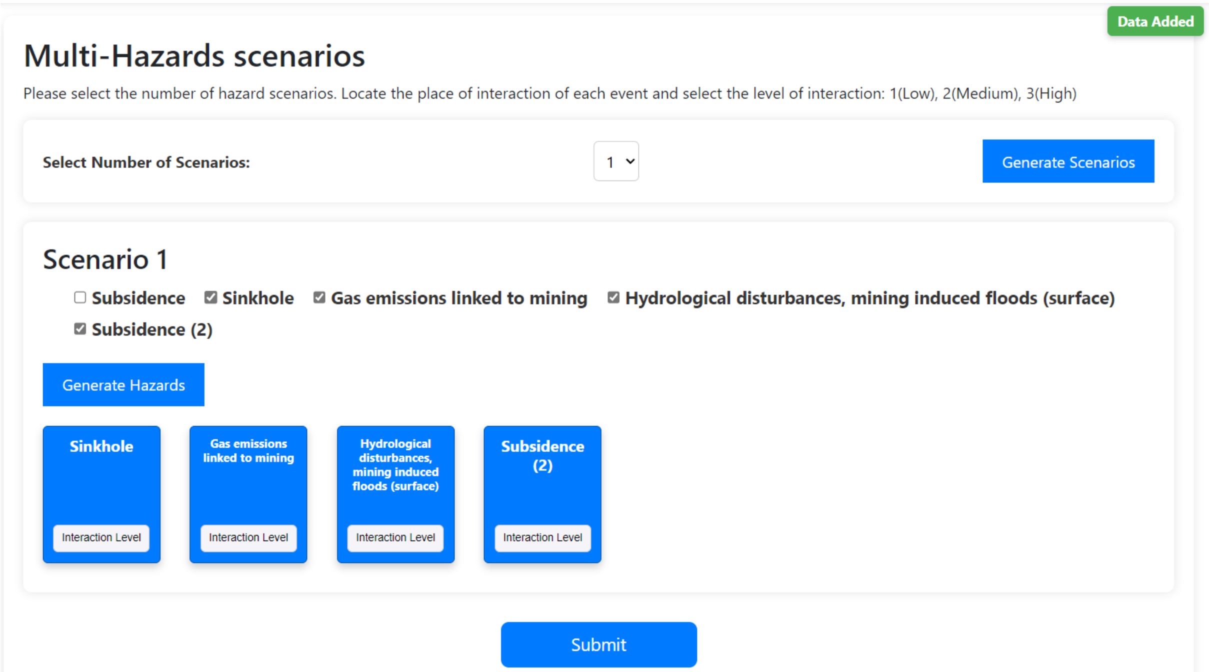

Figure 3: MHI module with new data added.

New data for Expose element at risk module (optional)

The sDSS operates with LU/LC layers containing predefined classes, as outlined in Table 2 .Each class follows a specific nomenclature that enables the backend to process user inputs from the GUI for re-weight the element at risk based on their significance in the assessment.

Table 2. Classes defined for the LU/LC layer in the sDSS

ID Value	Class	Description
1	Water	Areas where water was predominantly present throughout the year; may not cover areas with sporadic or ephemeral water; contains little to no sparse vegetation, no rock outcrop nor built up features like docks; examples: rivers, ponds, lakes, oceans, flooded salt plains.
2	Trees	Any significant clustering of tall (~15 feet or higher) dense vegetation, typically with a closed or dense canopy; examples: wooded vegetation, clusters of dense tall vegetation within savannas, plantations, swamp or mangroves (dense/tall vegetation with ephemeral water or canopy too thick to detect water underneath).

4	Flooded vegetation	Areas of any type of vegetation with obvious intermixing of water throughout a majority of the year; seasonally flooded area that is a mix of grass/shrub/trees/bare ground; examples: flooded mangroves, emergent vegetation, rice paddies and other heavily irrigated and inundated agriculture.
5	Crops	Human planted/plotted cereals, grasses, and crops not at tree height; examples: corn, wheat, soy, fallow plots of structured land.
7	Built Area	Human made structures; major road and rail networks; large homogenous impervious surfaces including parking structures, office buildings and residential housing; examples: houses, dense villages / towns / cities, paved roads, asphalt.
8	Bare ground	Areas of rock or soil with very sparse to no vegetation for the entire year; large areas of sand and deserts with no to little vegetation; examples: exposed rock or soil, desert and sand dunes, dry salt flats/pans, dried lake beds, mines.
9	Snow/Ice	Large homogenous areas of permanent snow or ice, typically only in mountain areas or highest latitudes; examples: glaciers, permanent snowpack, snow fields.
11	Rangeland	Open areas covered in homogenous grasses with little to no taller vegetation; wild cereals and grasses with no obvious human plotting (i.e., not a plotted field); examples: natural meadows and fields with sparse to no tree cover, open savanna with few to no trees, parks/golf courses/lawns, pastures. Mix of small clusters of plants or single plants dispersed on a landscape that shows exposed soil or rock; scrub-filled clearings within dense forests that are clearly not taller than trees; examples: moderate to sparse cover of bushes, shrubs and tufts of grass, savannas with very sparse grasses, trees or other plants.

Admin can upload new LU/LC layers in *.tif* format, following the naming convention "LULC_site". This process is analogous to uploading new data for the MHI module, with the user's assigned site corresponding to the country of the admin's assignment.

For example, if an Admin assigned to Germany wants to upload an updated LU/LC layer for the Ruhr study site, the *.tif* file must contain a raster where each pixel is assigned a predefined class with its corresponding ID value. The file should be named *"LULC_germany.tif"*. The backend will verify that the *.tif* file adheres to this format by checking that each pixel is properly classified with the ID values of Table 2. Upon successful upload, the GUI in the Exposed element at risk module will confirm that the updated LU/LC layer is now in use for further analysis with a green label of "data added"

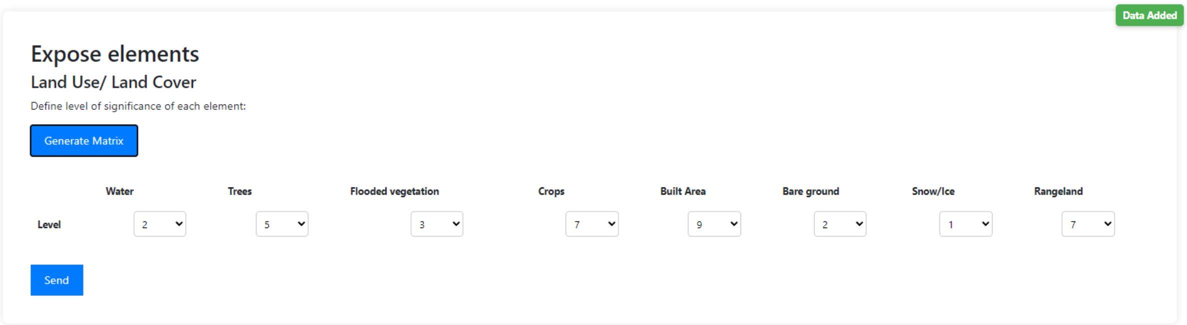

Figure 4: Exposure Assessment module with new data added.

New data for Vulnerability module (optional)

Admin users have the ability to update vulnerability indicator assessments for the cities within their study site, in addition to the uploading capabilities of the previous modules. POMHAZ calculates the vulnerability index using four weighted categories, divided into 10 subclasses, with each subclass normalized on a scale from 1 to 9 with information of the cities that are within the study site. The categories include:

- Socioeconomic Status: Indicators such as unemployment rate and GDP per capita.
- Household Composition: Factors including the percentage of the population under 15 or over 64 years old and population density.
- Environment: Metrics like settlement area and agricultural land.
- Infrastructure: Attributes such as building age, material, geometry, and traffic areas.

The final weight of each category is calculated as the arithmetic mean of the normalized values of its subclasses. If admin users wish to perform a risk assessment with updated information for any subclass, they must adhere to these criteria, keeping in mind that the normalization is done based on each one of the subclasses. The information for each city must be uploaded in a *.zip* file containing a Shapefile that includes the vulnerability categories for the cities within the study site. The *.zip* file should be named as *vulnerability_site* and must include a Shapefile with the final weighted values for the four categories.

The column names in the Shapefile should follow these conventions:

- Socioeconomic Status: *socioeconomic*
- Household Composition: *household*
- Environment: *environmental*
- Infrastructure: *infrastructure*

For example, if new vulnerability data is being added for the Ruhr area, a *.zip* file named *vulnerability_germany.zip* should be uploaded. This file must contain a Shapefile with four columns—socioeconomic, household, environmental, and infrastructure—each normalized with weights. Ensure that the file contents adhere to the format and structure outlined in the MHI module.

Modules overview

The *admin user* generally has the same options for using the data evaluation modules of the sDSS as the *expert user*:

- Module I: Multi-Hazard Assessment
- Module II: Exposure Assessment
- Module III: Vulnerability Evaluation
- Module IV: Integrated Risk Assessment

However, in order to keep the separation of roles stringent (see main document, chapter 4), the evaluations should only be carried out by the expert user. The instructions from Annex B on the use of the modules are therefore not repeated here.

Additional Features

Reload Server

1. After first.
2. Click on the ‘Reload’ option in the system settings menu.
3. Confirm the action to apply recent changes.
4. Wait for the system to restart. Verify the updates by checking the data or configuration changes in the corresponding modules.

- Provides users with the ability to restart the API seamlessly.

Interactive Maps

- Visualize results dynamically across all modules.
- Adjust parameters and immediately see the impact on risk assessment for each one of the scenarios established

Download Options

- Export Formats: Users can export maps and results from each module in the following formats:
  - .TIF: Raster file format ideal for spatial data analysis.
  - .SHP: Shapefile format for vector data compatible with GIS applications.
  - GeoJSON: Lightweight format for representing geographical features and their attributes.

FAQ

This chapter aims to assist users in solving common problems and challenges encountered while using the SDSS API. Below are some frequently encountered issues and their solutions:

1. **Login Problems**
   - **Solution**: Ensure your credentials are correct. If the issue persists, contact Benjamin.haske@thga.de or Vinicius.Inojosa@thga.de
2. **Module Not Loading**
   - **Solution**: Verify your internet connection and try reloading the server using the "Reload Server" button.
3. **What should I do before proceeding to the Risk Assessment module?**
   - **Solution**: Ensure that all required items in each module (Hazard Scenarios, Exposed Elements at Risk, and Vulnerability Factors) are completed before proceeding to the Risk Assessment module. This step is necessary to calculate the risk map accurately.
4. **Why is my data not being accepted during the loading stage?**
   - **Solution**: Please review the steps outlined in the Adding Data feature for Admin users. Ensure that your files and their content adhere to the preestablished nomenclature and format requirements. This includes file naming conventions, structure, and the correct data formats as specified for each module.

Annex D

Annex D: Sustainable socioeconomic post-mining planning

Content

Acronyms

AHP	Analytical Hierarchy Process
CAPEX	Capital expenditure
CBA	Cost Benefit Analysis
CICES	Common International Classification of Ecosystem Services
CLC	Corine Land Cover
DSS	Decision Support System
ELECTRE	ELimination Et Choix Traduisant la REalité
ES	Environmental Services
LP	Linear Programming
MCDA	Multi-Criteria Decision Analysis
MCDM	Multi-Criteria Decision Method
MP	Market Price
NGO	Non-Governmental Organisation
NPV	Net Present Value
OPEX	Operation expenditure
PROMETHEE	Preference Ranking Organization Method for Enrichment of Evaluations
P/V	Photo Voltaic
PV	Present Value
RFCS	Research Fund for Coal and Steel
SEEA EA	System of Economics-Environmental Accounting Ecosystem Accounting
TBL	Triple Bottom Line
TEEB	The Economics of Ecosystems and Biodiversity
TOPSIS	Technique for Order of Preference by Similarity of Ideal Solutions

Executive Summary

This annex is the part of the Task 3.3 for the development of a DSS, devoted to sustainable socioeconomic post-mining planning. Defining DSS objectives in this Task will include clarifying the usage of the DSS; the type of decision outcome(s); and the decision-making level the DSS will support.

PoMHaz starts with WP 2 on Multi Hazard and therefore multi risk management (remediation).

The last objective of the PoMHaz project is: “to provide consistent documents for future land “management” and a special planning and tool to better anticipate interactions and prepare the mine transition”. Its final goal is to plan the future use of the mine’s basin (rehabilitation). Therefore, sustainable socioeconomic post-mining planning must consider the final uses, that is repurposing.

Furthermore, according to the WP 5.1 objectives, the requirements formulated by the end users/administrators of the selected test sites will be included in the DSS. The developed DSS will provide an essential platform for complete sustainability appraisal.

Numerous research papers present multi actors and multicriteria methods for post coal mining land uses selection. We propose in this report a comprehensive and versatile method based on different steps.

The first step of the process is to gather stakeholders, define land use needs at different scales, from local to international, and to perform stock taking of all the necessary data. During this step, stakeholders and decision makers are identified and the sustainability objectives are to be shared with these stakeholders.

The second step maps the area to be repurposed according to the feasibility of setting up the different land uses identified during the first step. It takes into account the multi-hazards (WP 2), risks acceptance associated with vulnerability of each land use, land criteria, monitoring and mitigation and costs (tasks 3.1 (Development of post-mining risk assessment) and 3.2 (Application on specific post-mining risk assessment)), compared to market price.

The third step assesses the impacts of land use on environment, and in social and economic terms. It compares the initial state to future land uses. It includes a Cost/Benefit Analysis for provisioning and non-provisioning services.

In the last step, conflicts of uses are described, and a multi-criteria decision analysis (MCDA) based on Analytical Hierarchy Process (AHP) will allow to offset the different land needs claimed in step one, in order to optimize the sustainability criteria. A financial assessment of the project is first performed on provisioning services, then on non-provisioning services. We suggest that non-provisioning services could be used to mobilize funds for community benefit.

Several databases and tools are identified and will need to be implemented in the DSS framework for transparency, providing relevant information for the stakeholders.

The next task following the present DSS specification will be extensive user testing of the DSS, not only upon completion but also during the development process, including the outcomes of the tasks 2.2 (Critical analyses of existing tools and methodologies), 3.1 and 3.2.

1 Background

1.1 Description of the WP3 Post-mining risks assessment methodology and Decision Support System (DSS)

WP3 is dedicated to post-mining risk assessment and the development of the decision support systems (DSS) for **the management and land planning of the territories** and coal region impacted by the multi-hazards and multi-risks associated to the abandoned open pit and underground lignite and coalmines in Europe.

WP3 will provide a tool and methodology for assessing post-mining risks and the tools for decision-makers and coal communities facing multi-hazards and multi-risks.

The main objectives of the WP3 are:

- To provide methodological and practical input for each step of post-mining risk assessment.
- To define and develop the DSS specifications for technical and socio-economical hazards in mining regions.
- To support planning and decision-making processes by providing relevant and scientifically sound information to a broad range of stakeholders.
- To define risk specifications as input for WP4

1.2 Description of the Task 3.3. Development of a DSS for Risk management

The DSS will allow to implement risk assessment methods developed in Task 3.1 and tested in Task 3.2 with the aim to be a tool for risk management and decision. The modelling of environmental decision problems using multi criteria decision analysis (MCDA) methods is very useful, both as a method for engineers and scientists to test theories to better understand the way systems function, and as a predictive or forecasting tool for better and quicker assessment of complex environmental systems. However, MCDA solutions only model one site at one time; hence decision support systems (DSS) can/should be developed to encapsulate the MCDA decision models by codifying scientific and technical knowledge; expert judgement and policy requirements into stored process with the aim of providing concise representation of the optimum decision.

The first stage of the DSS development process involves identifying the DSS specifications. The partners (**Ineris** and TU BAF) under the lead of DMT-THGA will compile and analyse the DSS objectives, functional and non-functional requirements, and the restraints on the DSS development, use and evolution. Defining DSS objectives in this Task will include clarifying the usage of the DSS; the type of decision outcome(s); and the decision-making level the DSS will support. The uses envisaged for post-mining multi hazard management DSS will include: (i) identifying the realistic management choices; (ii) integrating information into a coherent framework for analysis and decision-making discerning key information and impacts decision-making from more basic information; and (iii) providing **a framework for transparency** (i.e. all parameters, assumption, and data used to reach the decision are clearly demonstrated). Functional requirements will be defined for the DSS operational functionalities. They will depend on the role of DSS in meeting the decision objective(s) and on technical objective(s) of the DSS. These will be elicited from all project partners, in relation to their geographic areas through their knowledge of the decision situation and the decision-making process, and by evaluating existing similar case-studies (e.g. outputs of Task 2.2 and Task 2.3). Non-functional requirements will be considered to describe the behaviour of the DSS in its operational environment and will cover issues as broad as reliability of the DSS in providing accurate and timely support when needed, performance of the DSS, safety and security especially in cases of sensitive data.

CERTH and **Ineris** will oversee the functional specifications of the DSS for mining application, to be adequately integrated in the risk assessment application in post-mining areas.

DMT-THGA additionally will then develop the DSS tool based on the methodology of the **AHP** (analytical hierarchy process) approach. The AHP methodology has been successfully applied to other complex engineering problems (e.g. water management, building systems, etc.). In this approach a suitable objective function will be considered to aggregate the different facets of a decision problem where the main goal is to select the decision alternative that has the greatest value of the objective function. AHP uses pairwise comparisons of criteria where all individual criteria are paired with all other criteria and the end results compiled into a decision matrix, details of which can be found in various literature.

The DSS tool will have a strong emphasis on **socio-economic aspects**, including **sustainability**. **Ineris** will focus mainly on the **social and economic development of the DSS** (see Figure 2). The socio-economic and sustainability aspects of the tool will be developed based on the Elkington's **Triple Bottom Line** (TBL) framework which recommends commitment not only to economic factors but also to social and environmental concerns. Sustainability has so far been somewhat under explored in management of mining areas after termination of mining activities and as such it has not been incorporated in computer-based management systems. The developed DSS will provide an essential platform for **complete sustainability appraisal** in decision makings to address post-mining hazards. In total the system will have five main components (see Fig. 1.1) including: i) site characterisation for site assessment, reconnaissance and investigation; ii) a risk assessment component that is fed in line with outputs of WP2 and Tasks 2.1 and 2.2 ; iii) mitigation methodology component for selection and comparison of remediation technics; iv) cost benefit analysis component (based on socio-economic criteria such as cost of risk mitigation measures, and benefits measured as avoided damages to human health, the environment and to the built and economic environment, including major indirect economic consequences of damages to infrastructures) developed in Task 3.1); and v) a sustainability appraisal component to collate all findings of the other components and recommend a decision based on the set if sustainability criteria. It is important to address **ease-of-use** factors, something that should be carried out by different people to those involved in developing the DSS. For this reason, **Ineris** will carry out extensive user testing of the DSS, not only on completion but also during the development process, reporting preliminary results back to DMT-THGA.

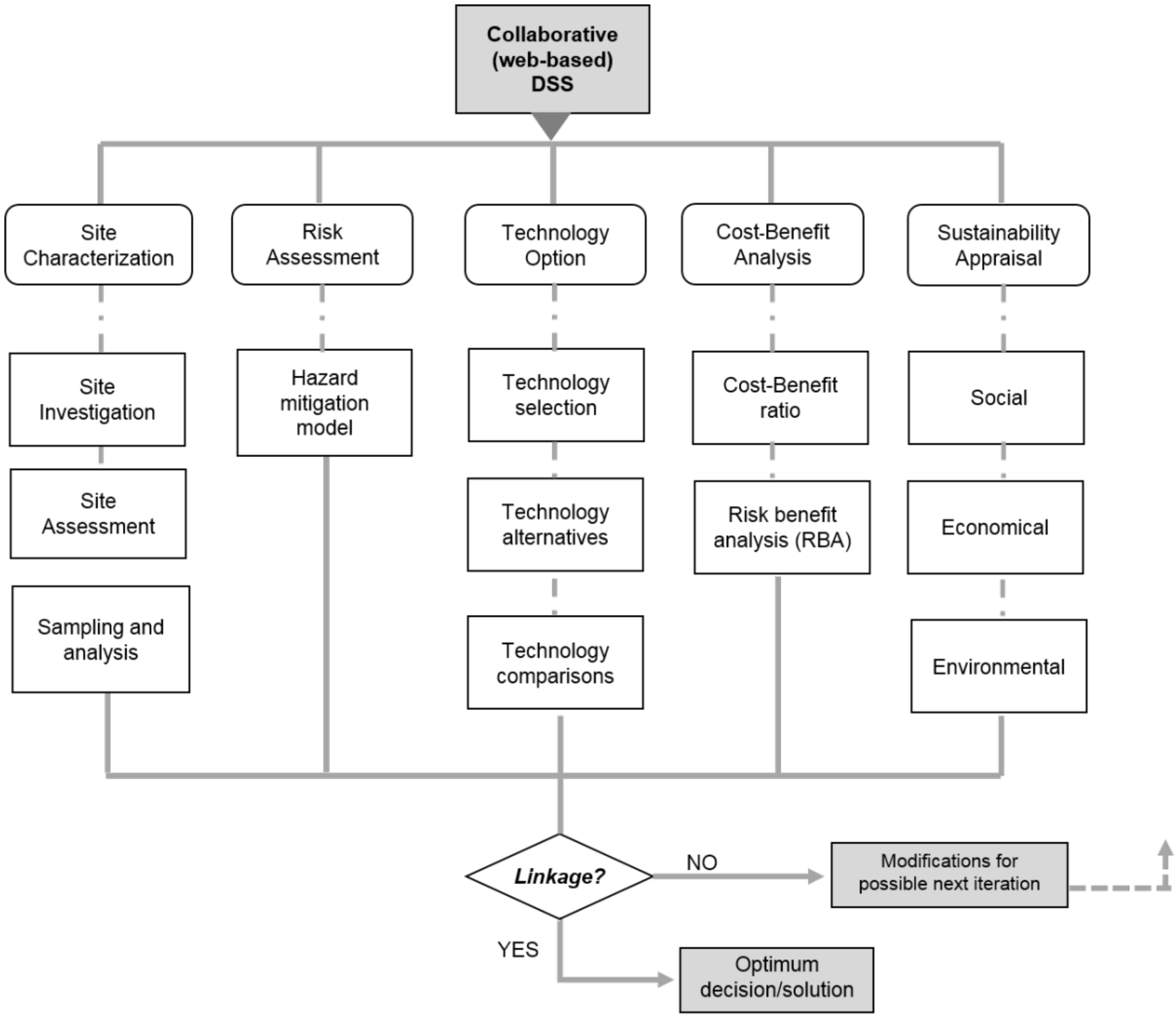

Fig. 1.1. Components of the decision support system

2 Introduction

Management of decommissioned mines comprises different tiers: remediation, reclamation, restoration, rehabilitation. Remediation is the first stage and consists of managing risks prior any settlement of other activities. Restoration means restoring the preexisting ecosystem. Reclamation means replacing the ecosystem, but it does not deal with socioeconomic aspects. Rehabilitation means prioritisation of provisioning or non-provisioning services. Repurposing means planning final uses of the landscape, and it may be the best approach to deal with surface mining legacies (Lima et al. 2016). PoMHaz first focuses on Multi Hazard and therefore multi risk management (remediation). Its final goal is to plan the use of the mine's basin (rehabilitation). Therefore, sustainable socioeconomic post-mining planning must consider the final uses, that is repurposing.

According to the task 3.3 description "development of a DSS for Risk management", the sustainability appraisal component of the DSS will collate all findings of the other components and recommend a decision based on the set of criteria. The intent is to set up a user-friendly system for all the stakeholders. The decision outcome is defined by planned land repurposing for elementary parcels of the mine area, based on maximization of sustainability criteria. Furthermore, the proposed plans should be technically and economically feasible. A spatialized tool is therefore supporting these goals. The DSS will support a versatile decision-making level, for which the roles of all the stakeholders can be parametrizable.

The last objective of the PoMHaz project is: *"to provide consistent documents for future land "management" and a special planning and tool to better anticipate interactions and prepare the mine transition"*. According to PoMHaz proposal description: "*a strong emphasis is on data analysis and decision-making techniques and not modelling per se*". "*The EU legislation must be followed in the post-mining management*". "*The DSS will provide an essential platform for complete sustainability appraisal in decision makings*".

In this annex, we propose a multicriteria decision analysis and methodology for land planning post-mining repurposing, in multi-hazard context and in accordance with the triple bottom line approach.

3 Multicriteria decision analysis and methods for land repurposing planning

3.1 The Triple Bottom Line approach for large areas of repurposing

The levels of complexity associated with the closure of mining operations is the result of historical factors, the geophysical characteristics of the territory, market dynamics, together with socio-economic and political issues (Arratia-Solar et al. 2023). Former coal mines potentially represent very large areas, on a local and even regional scale. In North-Rhine Westphalian area in Germany, overall 600km² are impacted by former mines activity. In Greece, open mine pits are about 5 to 20 km width and length. They present risks generated by mining, to which are added natural risks amplified by climate change. They offer yet degraded and anthropized areas. Compared to natural, agricultural, or lightly anthropized areas, settlement of human activities will have a lower ecologic impact. They offer space and opportunities to the settlement of activities that have also an impact on the environment. They also offer opportunities to host biodiversity and other environmental functions. Access to land presents a key capital opportunity available to people living in these territories. These possible uses must be chosen in competition with land uses of all kinds at the local, regional, or even European community scale. These uses are sensitive to hazards (intensity and predisposition of events) linked to the nature of the terrain. The sensitivity is specific to each use. The repurposing involves proposing a multi-criteria method for selecting uses for post-mining developments considering the surface needs for activities defined at different spatial scales, adapted to the nature of the risks associated with these lands. This multi-criteria analysis method will, in agreement with the description action, take into account the economic, social and environmental requirements theorized in the Triple Bottom Line (TBL) approach (Elkington, J. (2018). The TBL accounting expands the traditional reporting framework to take into account social and environmental performance in addition to financial performance (see Henriques and Richardson, 2004, see Wikipedia). The people, social equity, or human capital bottom line pertains to fair and beneficial business practices toward labour and the community and region in which a corporation conducts its business. A TBL company conceives a reciprocal social structure in which the well-being of corporate, labour and other stakeholders' interests are interdependent. The planet, environmental bottom line, or natural capital bottom line refers to sustainable environmental practices. A TBL company endeavours to benefit the natural order as much as possible or at the least do no harm and minimize environmental impact. A TBL endeavour reduces its ecological footprint by, among other things, carefully managing its consumption of energy and non-renewables and reducing manufacturing waste as well as rendering waste less toxic before disposing of it in a safe and legal manner. The profit or economic bottom line deals with the economic value created by the organization after deducting the cost of all inputs, including the cost of the capital tied up.

The environmental, social and economic approaches are also fostered at the European level. The Commission Communication of 22 September 2006 entitled 'Thematic Strategy for Soil Protection' and the Roadmap to a Resource-Efficient Europe underline the importance of the sustainable use of soil and the need to address the unsustainable increase of settlement areas over time ('land take'). Furthermore, the final document of the United Nations Conference on Sustainable Development held in Rio de Janeiro on 20-22 June 2012 recognises the economic and social significance of good land management, including soil, and the need for urgent action to reverse land degradation. Public and private projects should therefore consider and limit their impact on land, particularly as regards land take, and on soil, including as regards organic matter, erosion, compaction and sealing;

appropriate land use plans and policies at national, regional and local level are also relevant in this regard.

3.2 Post mining repurposing guidance

Any source of information about repurposing should be considered, to avoid lacks in the methodology, and to share opinions between stakeholders.

According to the Integrated Mine Closure: Good Practice Guide (2nd edition): "*integrated closure planning and implementation needs to capture and balance the views, concerns, aspirations, efforts, knowledge and capacity of relevant internal and external stakeholders. The goal is to achieve sustainable outcomes that are beneficial to the mining company and its employees, the environment and host communities*". It gives emphasis to the mining companies concerns, such as mining life cycle management, closure costs, reduction of liabilities, social transition, lasting benefits.

The EU Coal Regions in Transition (CRiT 2020) Initiative provides guidance for repurposing. The Toolkit Guidance on the governance of environmental rehabilitation and repurposing in coal regions in transition presents roles and responsibilities of governance, and sources of information for best practice.

3.3 Repurposing flowcharts and decision methods

Since 2008, about 4 articles each year present methods for integrating risk management and multicriteria analysis, including sustainability, for post-coal-mining land usage selection (Ronyastra et al. 2023). Pavloudakis et al. (2009) developed a methodology in order to match the land characteristics and repurposing scenarios based on broader land criteria. Pavloudakis et al. (2020) propose an algorithm of optimisation, considering Political, Economic, Social and Technological factors that affect decisions regarding post-mining land use. An application case considers four land uses for repurposing (agriculture, farming, forests, P/V parks), rating them according to four criteria (revenues, investment, conservation of nature and equity), and with threshold value for each criterion. With combination steps each of 10% of available land, they calculate an optimum of each land use to achieve a more balanced development. This method was applied using the opinions of 10 experts involved in mine land reclamation project, but not of all the stakeholders. The proposed method is driven by the goal of long-term prosperity of the society, whatsoever the investments costs. Amaro et al. (2022) use a participatory process in the last step of a Multi-Criteria Decision Making (MCDM) method to lead to a spatial distribution of different alternatives. One of the most comprehensive flowcharts, in five stages, is proposed by Arratia-Solar et al. (2022). The stage 1 establishes generic land-use classification and land repurposing criteria lists. The stage 2 performs a Multi-Dimensional Analysis that filters the land-use types based on specific conditions of the study area, with the implication of stakeholders. The stage 3 collects stakeholders' preferences in order to determine a ranking of both Post Mining Land Use attributes and alternatives. The stage 4 applies a Multi-Criteria Decision Method, chosen from a review of the MCDM used in mine basin repurposing, including AHP, ELECTRE, PROMETHEE, LP, TOPSIS. The outcome is a ranked set of land repurposing alternatives that are suitable for the area and for stakeholders, and its implementation is caried out in stage 5.

Spanidis et al. (2022) propose a comprehensive project risks assessment methodology, based on expert judgment. It integrates a strategic planning, where inputs come from geophysical constraints, policies, plans, mining companies' duties. Communities act as controls through public consultations. Risks are ranked at each stage of the repurposing planning process. On 20 identified risks, the relative weight of technical, schedule, cost and quality risk factors were calculated using Analytical Hierarchical Process (AHP). After consideration of impacts of each risk, a mitigation strategy of the repurposing project risks can be established. The RECOVERY project assesses the provisioning (tangible) and non-provisioning incomes of land uses environmental services of different scenarios. According to the theory of the proposed method, the scenario with the total highest value should be preferred, but the authors chose a trade-off in favour of the non-provisioning ecosystem services value. Stakeholders were not involved in this choice.

According to the recommendations of the Joint Research Centre (Munda, G., 2017), the application of a MCDA framework involves the following main steps:
i. Description of the relevant social actors. For example, institutional analysis may be performed on historical, legislative and administrative documents to provide a map of the relevant social actors.
ii. Definition of social actors' values, desires and preferences. In a MCDA framework, the pitfalls of the technocratic approach can be overcome by applying different methods of sociological research.
iii. Generation of policy options and selection of evaluation criteria as a process of co-creation resulting from a dialogue between analysts and social actors. In this way, evaluation criteria become a technical translation of social actors' needs, preferences and desires.
iv. Construction of the multi-criteria impact matrix synthesising the scores of all criteria for all policy alternatives, i.e. the performance of each option according to each criterion.
v. Construction of an equity impact matrix, including all the distributional consequences of each single option on the various social actors.
vi. Application of a mathematical procedure in order to aggregate criterion scores and obtain a final ranking of the available alternatives.
vii. Finally, sensitivity and robustness analysis look at the sensitivity of results to the exclusion/inclusion of different criteria, criterion weights and dimensions.

3.4 Proposed methodology and flowchart to achieve the PoMHaz objectives

To encompass the most comprehensive socio-economic and sustainability aspects, the PoMHaz methodology is developed based on the Triple Bottom Line (TBL) framework, pertaining to economic, environmental, and social factors. Outcomes from European funded projects (MERIDA, TRIM4Post-mining, RECOVERY, TRACER) will be extensively used to build the core elements of the methodology. One specificity of PoMHaz lays in the land feasibility maps construction, taking into account the outcomes of the Work packages 2 and 3 on multi-hazards and multi-risks. According to the WP 5.1 objectives, the requirements formulated by the end users/administrators of the selected test sites will be included in the DSS. Different specialized agencies and experts need to collaborate through using the DSS (PoMHaz proposal description). The proposed method is intended to be smart, to be suitable for any land repurposing cases, and any type of governance. For example, the role of each stakeholder could be set, e.g. for weighting criteria. Another specificity is to perform a Cost Benefit Analysis (CBA) for provisioning services and a global CBA for provisioning and non-provisioning services to assess the Net Present Values (NPV). A global positive NPV with a negative NPV for provisioning services can justify public subsidiaries.

To implement the spatialized DSS, a flow chart is proposed (figure 3.1). Chapters 4 to 7 depict each step of the flowchart, with detailed flowcharts. Finally, the chapter 8 depicts the possible interactions between the databases needed to implement a land planning repurposing.

The first step of the process under the following proposed MCDA methodology is to gather stakeholders and define land use needs and objectives.

The second step will map the area to be repurposed according to the feasibility of setting up the different land uses identified during the first step. It takes into account the multi-hazards assessment (WP 2), risks acceptance associated with vulnerability of each land use, land features, physical events monitoring, risks mitigation efficiency and the associated sunk costs e.g. polluted land removing (WP 3), compared to market price.

The third step assesses the impacts of land use on environment, social and economic aspects. It compares the initial state to future land uses. It includes a Cost/Benefit Analysis from WP 3.1. and a CBA for non-provisioning services.

In the last step, conflicts of land uses are described, and a multi-criteria decision analysis (MCDA) will allow to trade-off the different land use needs claimed in step one, combining risk mitigation and sustainability criteria and costs. To implement MCDA, a multi-criteria decision method based on AHP is applied, with the most transparent fashion.

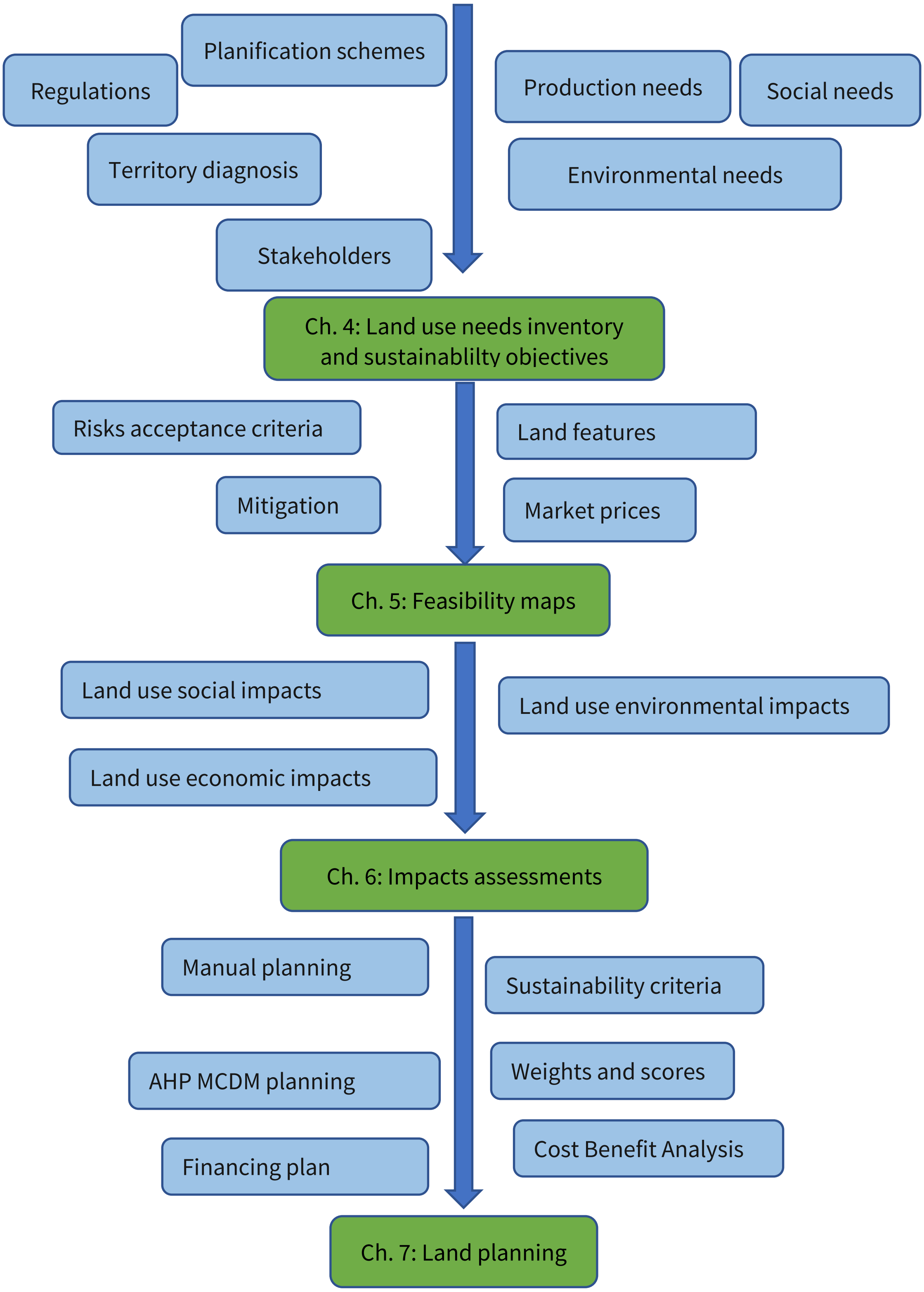

Figure 1 : General flow chart of land planning and references to chapters of the report

4 Land use needs inventory and sustainability objectives

This first step of the process under the following proposed MCDA methodology is to gather stakeholders and define land use needs and objectives.

4.1 Stakeholders

The selection of group decision-making participants, the level of involvement of participants in the process must receive attention (Dean 2022). Authors acknowledge the need for wider regional planning approaches in which repurposing considers regional and local planning strategies, the surrounding landscape and community views (Worden et al. 2024). The TRIM4Post-Mining project elaborated a guide for the choice of engagement strategies of stakeholders divided in four categories according to their potential influence and impact (Benndorf et al. 2022). Siontorou (2023) proposed two groups of stakeholders, the project contributors' group, and the affected/impacted group.

We propose four groups of participants (stakeholders), with possible overlapping. Stakeholders can be organizations or their representatives, or the public through consultations or panels.

- The first group gathers stakeholders in charge of decisions on future land use. It includes landowners, administrative authorities, elective assemblies, financing bodies, projects repurposing leaders.

- The second group includes organizations whose interests will be affected as a result of the repurposing project's completion. Stakeholders can be identified through the consideration of the impact on people (leisure activities, employment, welfare, public health, safe environment, housing) and considering organizations (companies, trade unions, cultural and cult associations).

- Stakeholders in the third group are those having interest in taking action and defending wider actions or policies, and they include NGO officially recognized in a field concerned by the project, such as nature preservation, cultural or religious heritage, and agencies in charge of environmental plans (water, wastes, biodiversity). Their differ from the group 2 as they have general action at a national level with no local direct interest.

- Stakeholders who are involved in the project, but without direct interest form the fourth group. It includes experts, political groups, media, relevant regional or national environmental authorities solicited for advisory opinion prior administrative decision.

Stakeholders will be involved in different actions: Information via general communication media, interviews, public meeting, periodic engagement, expectations interest survey, fostering opportunities for partnerships, specific working groups, involvement in planning process, participation in monitoring activities, participation or actions in multicriteria analysis. For each particular stakeholder, these actions must be defined and implemented in the DSS, in accordance with the policy of the project.

A database for stakeholders' inventory and their roles in the land repurposing process at the different steps should be established.

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4.2 Territory diagnosis

Territory is here defined as the area affected by the post-mining land repurposing project. It must be defined at the beginning of the project, on socioeconomics and environmental considerations. It is not limited to the pit mines area and plants but comprises cities where employees of the mine and subcontractors are living, the hydrological basin affected by the mine, among others.

The diagnosis includes a socio-economic profile (population, education and skills, economic activities), the mining activity profile, coal production shut down planning and its socio-economic consequences, the challenges and trends affecting the territory, the current strategies and plans for economic development.

Financing sources for the land repurposing project must be listed in a database: possible compensation funds from projects located outside the area, mining duties funds, grants, investors. The attractiveness of the territory for production investments must be assessed. These data are inputs for the economic assessment.

Examples of such territory diagnosis are given by the European Commission in the initiative for coal regions in transition: ec.europa.eu/coal-regions-in-transition.

The territory will be mapped with geospatial data. CORINE Land Cover (CLC), COPERNICUS and any other source are used. To establish the baseline (i.e., prior land repurposing) of the ecosystem services, the Common International Classification of Ecosystem Services (CICES) is used. For each parcel of homogenous land (i.e. CLC) the CICES class levels are determined. Parcels providing low levels of ES should already be considered for reclamation prior repurposing.

The adequate boundaries of the study area are defined based on spatial connectivity of ecosystems and socio systems, risks, and functional cohesion, and are likely larger than the strict boundaries of the mine land to be repurposed.

4.3 Land use regulations and standards

The regulatory corpus should be wide as to encompass all the land uses. Stakeholders should be informed and have in mind this corpus at each step of the project. A database should be implemented to bind the relevant regulation to corresponding impacted project issues.

4.3.1 Land planning-oriented risk prevention regulations

Vigier et al. (2019) provide a method for analysing the French law on natural hazards and environmental protection for land planning. A diagnosis of the coherence and difficulties related to the implementation of public policies at the local level is presented, as well as an inventory of regulatory texts. Texts can be optional or mandatory. For example, the flood risk regulations include a national strategy for flood risk management, a regional plan for flood risk management, a local strategy for flood risk management, a program for action and flood prevention and local plans for flood risk prevention. Land repurposing will affect potentially water fluxes. The projects must comply to the rules for flood prevention. Similarly, other regulations deal with water as a resource, natural and technological risk managements, terrestrial environment, air, climate and atmosphere, sustainable development in territories, sustainable agriculture, forests. All these regulations should also be inventoried and their potential application to the land repurposing project should be assessed. Some elements are provided in sections hereafter.

4.3.2 Mining and Post-mining regulations

Each country has specific mining regulations (see D7 Deliverable 2.2) that should be inventoried.

4.3.3 Regulations on exposure to pollutants and industrial risks

A complete inventory of regulations must be performed for each risk identified. For example, radon exposure must abide to council directive 2013/59/EURATOM. Regulation on industrial risks also relate to regulations on water quality, waste management, mining and post-regulations, specific regulation for each land use, such as landfill, and finally Seveso directive for industrial plants.

4.3.4 European regulation on impact assessments

Many lands uses in a complex repurposing project are concerned by the European directive 2014/52/UE on impact assessment of projects. In particular, the environmental impact assessment shall identify, describe and assess in an appropriate manner, in the light of each individual case, the direct and indirect significant effects of a project on the following factors:

(a) population and human health;
(b) biodiversity, with particular attention to species and habitats protected under Directive 92/43/EEC and Directive 2009/147/EC;
(c) land, soil, water, air and climate;
(d) material assets, cultural heritage and the landscape;
(e) the interaction between the factors referred to in points (a) to (d).

The effects referred on the factors set out therein shall include the expected effects deriving from the vulnerability of the project to risks of major accidents and/or disasters that are relevant to the project concerned.

This directive depicts other majors' points including public access to the information and consultation (see stakeholders' chapter).

The proposed PomHaz methodology aims to comply to this directive.

4.3.5 Standards

The ISO/TC 82/SC 7 Sustainable mining and mine closure deals with Standardization of environmental, social and governance aspects of mining to:

- minimize the negative impacts from mining through its life cycle and transition to post-mining land use,
- take action to combat climate change and its impacts,
- develop sustainable benefits and opportunities for local and regional communities,
- respect community cultural connections to places,
- adopt a long-term view that ensures inter-generational equity,
- embrace opportunities for innovation by adopting the principles of the circular economy,

- enhance transparency of mining practices.

These requirements, in particular to develop sustainable benefits and opportunities for local and regional communities, to respect community cultural connections to places, and minimizing the impacts of post-mining transitions, are included in the approach proposed here.

4.4 Land use needs inventory

The main categories of land uses are the following (adapted from RECOVERY). Subcategories should be listed in a database to be adapted from Corine Land Cover. CORINE Land Cover is a pan-European land cover inventory with 44 thematic classes.

- Recolonisation of the site by local vegetation, wildlife and nature conservation
- Wetland, marsh, moor
- Commercial forestry plantations
- Secondary forests using local plant species
- Development of agriculture: arable land and pastures
- Leisure and recreational purposes: historic heritage, sport and recreation areas
- Development of artificial water bodies, ponds, lakes, reservoirs, streams
- Renewable energy generation: photovoltaic, wind turbines, biomass for energy
- Industrial areas, and business facilities
- Landfills, warehouses, energy storage, and other storages
- Residential areas

Regulations applicable to land use are to be collected in a database.

The land use capacities to produce services leading to the repurposing objectives should be assessed from literature and be stored in a database.

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Table 4.1 Examples of economic, social and environmental needs from different possible stakeholders

	Carbon sequestration	Natural hazards prevention	Wastes management	Leisure	Economic needs
International UE	European commitments				
National	Compensation for other projects (highways…)	water reservoir for aircrafts fire fighters	Long lasting wastes	High level Sport facilities	Strategic industries, Energy production
Regional	Timber production	water reservoir for flooding or drought prevention		Regional interest park	Food production
District		Water for fire fighting	Urban wastes		Employment
Local		Temperature regulation		Wandering	
Mine industry			Damp heaps		Reuse of materials

4.5 Functional sustainable objectives and attributes of land repurposing

Transition challenges in the context of mining closure are different at the local scale (mainly social), regional (ecologic corridors, landfill) or nationwide (ecologic objectives in respect to international treaties). Land planning documents are sources of information for the inventory of repurposing objectives.

The Common International Classification of Ecosystem Services (CICES) defines ecosystem services as the contributions that ecosystems make to human well-being and are distinct from the goods and benefits that people subsequently derive from them. These contributions are framed in terms of 'what ecosystems do' for people. It has been designed to help measure, account for and assess ecosystem services. It has been used widely in ecosystem services research for designing indicators, mapping and for valuation. We propose to use it for objectives setting.

The requirements and expectations of the stakeholders are collected through questionnaires. The expectations could vary from local characteristics, for example, territories with air pollution, intermittent and abundant rainfall. Different consultation methods and statistical treatment of the responses are possible such as the Smic Prob-expert tool (RECOVERY project) for interactions between the impacts of different objectives toward the others. A database of possible objectives and related indicators is to establish. Objectives can be qualitative (wishes) or quantitative, with min-max values of indicators. Minimum or maximum only are also possible.

Table 4.2: examples of non-provisioning ecosystem services and provisioning services to be established with qualitative or when possible, at his stage, quantitative indicators.

	CICES V5.1 code when applicable	Indicator	Qualitative importance	Stakeholders' remarks
Environmental objectives:				
Biodiversity	3.2.2.1 3.2.2.2	Impact Richness of species		
Water management		Avoided direct run-off m3		
CO2 capture	2.2.6.1	t/ha		
Air purification (dust, aerosols)	2.2.6.1	PM10 absorbed		
Temperature regulation	2.2.6.2			
Risk reduction (flooding, drought, fire, landslide…)	2.2.1.3			
Erosion control	2.2.1.1			
Social objectives				
Housing		Inhabitants		
Employment		Full time eq		
Wages				
Skills				
Natural heritage				
Leisure, sport, fishing, hunting		Inhabitants in distance buffer		
Human health				
Economic objectives (provisioning)				
Energy production (solar, wind, biomass, hydropower)		MWh/y		
Water production		m3		
Food production, farming, livestock (including aquatic)				
Timber and fibre		m3		
Storage (energy, goods, water)				
Permanent storage (wastes)		t		
Industrial production		K€		
Economic feasibility (CAPEX, OPEX, NPV)		qualitative positive, equilibrium, negative		

5 Land use feasibility maps

Land use feasibility assessment is performed for each different and homogenous land types, according to physical characteristics, chemicals composition of the soil, hazards, proximity to other activities. Feasibility means that the land characteristic after mitigation is compatible with the land use objective at reasonable risks level and at reasonable cost. In a multi-hazard approach, the reasonable risk is cumulative of all risks identified in the WP2. Mapping of multi hazards and risks diagnosis is performed according to the methodology set in WP2 and WP 3.1 and 3.2. If necessary, an iterative risk assessment for each specific sensibility of land use is performed. These data should be stored in a database. Figure 5.1 depicts the DSS flow chart of multi-hazards land uses feasibility maps elaboration (according to DMT-THGA). Fig 5.3 illustrates feasibility maps for different land uses.

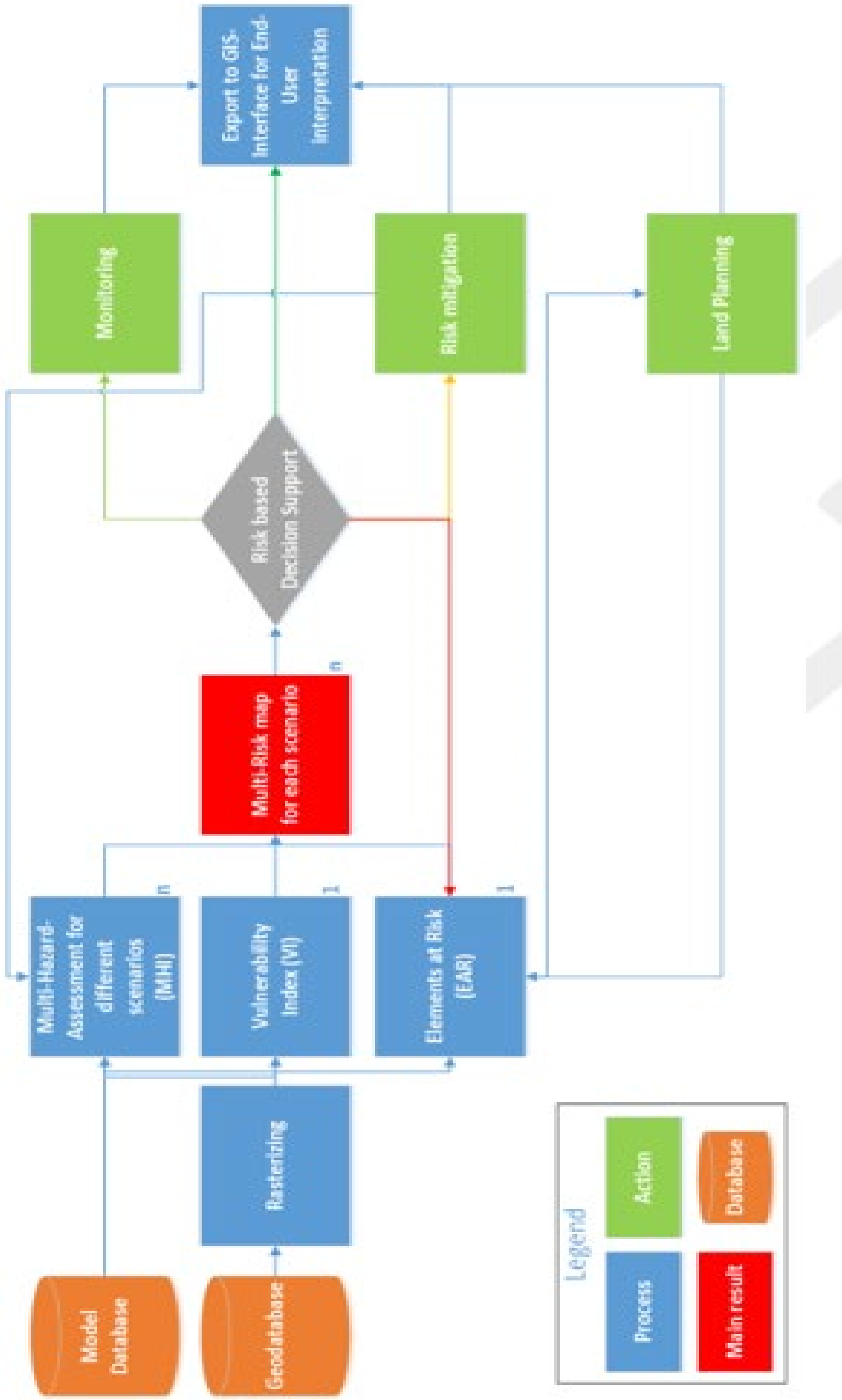


Figure 5.1: land use feasibility maps elaboration flowchart with multi-hazards (according to D 3.3

5.1 Risk rating

5.1.1 Initial land remediation

The risk rating described here is relying on multi-hazard assessment depicted in WP 3.1: “Methodological guidelines about risk management”, and which is the first step of repurposing. It provides a scaling of risks for new projects and alteration of structures or systems elements, with probabilities and consequences and their respective uncertainties.
The step of risk assessment typically rates the multi risks with prevalence rating and an intensity rating matrix. In this first step, the future land use is not necessarily determined. The consequences can be assessed in terms of financial costs for each scenario of land use, by incorporating the exposed elements values of future land use, or of land use in place in no change of land use is a hypothesis. Actions to be undertaken to preserve integrity of the site and of people are generic of all land uses. These rates determine the type, extend and time scale of the risk treatment that should be considered (Figure 5.2).

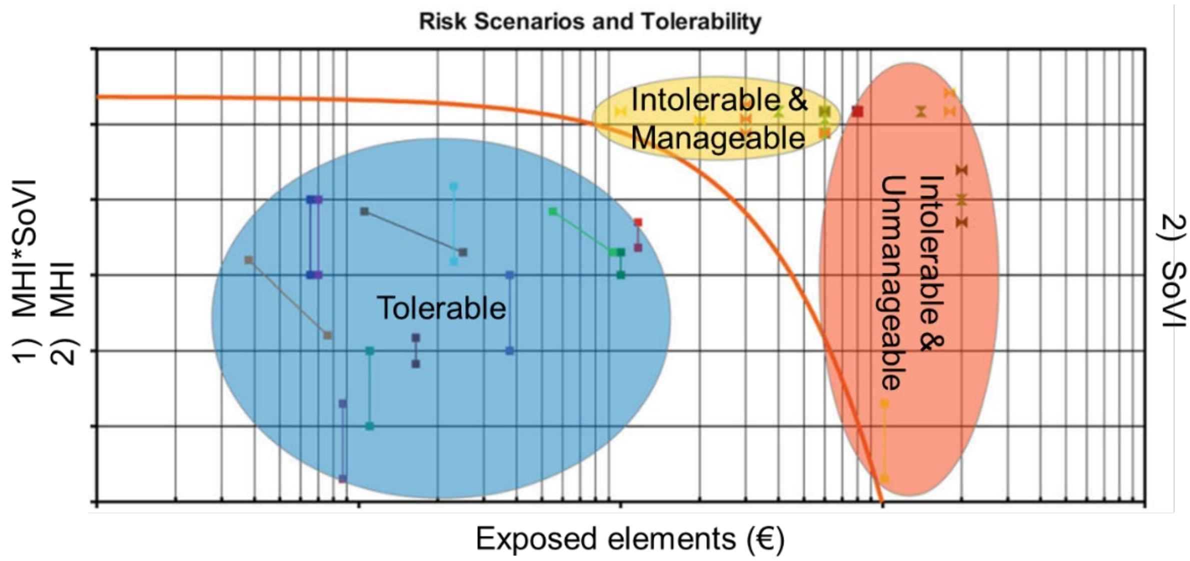


Figure 5.2: Rating of risk management (According to WP 3.2)

5.1.2 Sensitivity of land use to multi-hazards

This rating is applied in a second step specifically for each land use with its specific vulnerability (see D2.2 figure 4). For example, flooding can be acceptable for forest but not for housing. Consequences of events can be mapped on a bow-tie diagram, to include environmental and socio-economic aspects. Risk criteria are to be defined for each land use. Acceptance of damages, if any, will be translated in ranges of costs. Costs can be assessed from a database of structures prices, including loss of functionalities. According to these criteria, land repurposing feasibilities are established. If risks are not acceptable, mitigation measures of land must be elaborated, as far as reasonable.

5.1.3 Risks generated by land use

For example, landfill, Seveso plants, warehouses, can generate new risks. Conversely, land uses can mitigate risks, like forest for erosion and landslide, or water run-off prevention. These services will be considered in the ecosystem's services section. Buffer zones with specific land use could be of great importance. The layout of land uses will be considered in the multi criteria decision analysis (chapter 6).

5.2 Mitigation and monitoring techniques

The objective is to determine proposed risk reduction treatment options that will reduce the residual risk to an acceptable level. Performance of treatments these options should be assessed, and the residual risk is rated (figure 5.2 above). The acceptable risk is defined a priori by stakeholders in the initial phase of the PoMHaz method.

The MERIDA project proposed measures for different types of hazards: ground movement (surface deformation, fractures, cracks, sinkholes), groundwater pollution, surface water pollution, gas emission (methane, radon), including geomechanics adaptation of the ground for each land use, soil amendment for farming, slope reduction, drainage, dams. Monitoring techniques and associated costs are depicted in the deliverable of WP 3.2 "DSS specifications related to post-mining hazard management".

Mitigation and monitoring should be adapted for each land use planning and for each hazard. Note that most data available pertains to buildings.

Specific risk analysis after mitigation must be carried out in a similar fashion than initial risk analysis.

5.3 Land remediation costs

Land remediation costs are calculated for each type of land repurposing and for each type of land present in the territory. The costs include investment costs and periodic costs for maintenance and monitoring. A cost analysis is undertaken in order to evaluate the costs of each specific measure. A sensitivity analysis should be carried out to compare the effect of variation of each parameter (investment costs, operating costs, discount rate) on the net present value (NPV). An uncertainty analysis on the most impacting variables can be performed to obtain a NPV distribution, through Monte Carlo simulation.

These costs are compared with land market price for each specific land use. A specific database for local land market price is needed. If remediation costs are higher than market price, it means that specific fundings should be considered, as grants, mining company funding for liability of post-mining, compensation funding from projects with negative impacts located in another area.

Costs mentioned here are only remediation costs, and the costs of developing novel activities will be considered during the next step (chapter 6.3). Time laps and discount rate used in the remediation CBA should be equal to those used for the repurposing activity (chapter 6.4).

5.4 Land criteria according to land use

Criteria of land characteristics for supporting land uses are defined for geomechanics, environmental and socioeconomics considerations. A database should be set up with specialists for each land use need identified at the previous step. Lamelas et al. (2009) propose a methodology to assess general land capability to agriculture activities in relation with soil types. Lopez et al. (2022) defined physical, environmental and socioeconomic land criteria for landfill site selection, including among others elevation, slope, soil texture, natural areas, proximity to access roads. Palagos et al. (2017) consider slope and fertility of the soil, and proximity to interest zones as land use criteria.

5.5 Land use feasibility maps

The land use feasibility adds risks criteria, economic criteria, and land criteria. For each land use, a map is established with levels of feasibility. We propose a five feasibility levels ranking.

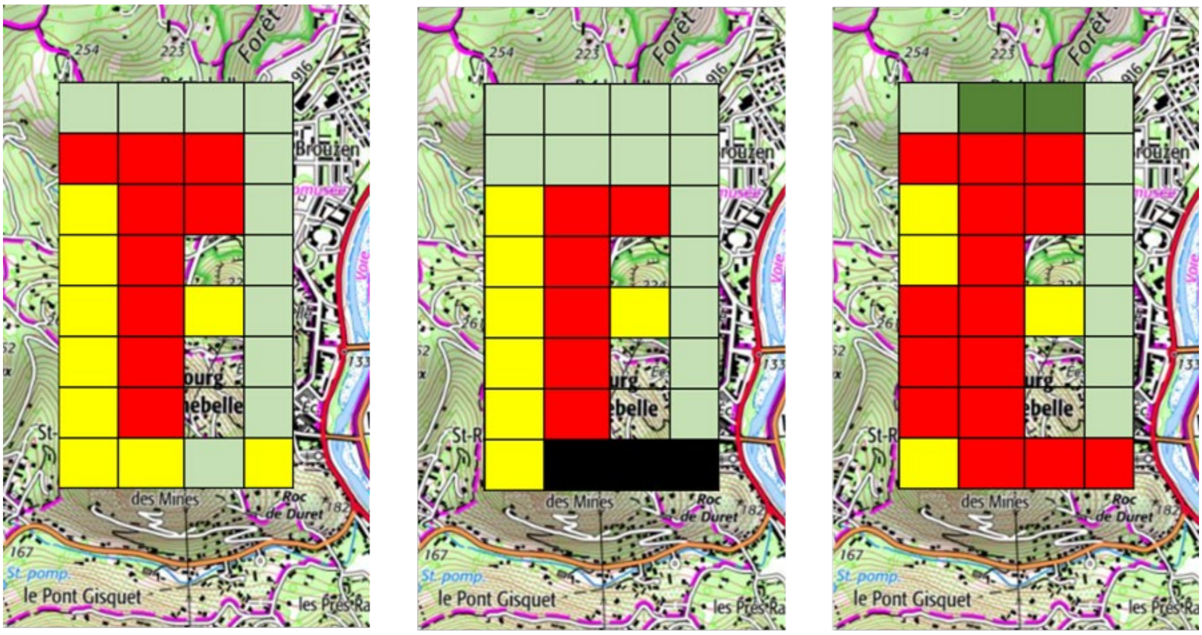
A feasibility level "I" means that the land use is not feasible, even with any treatment measure.

A feasibility level II means that the land use is possible, but with economic costs, including costs of predicted damages in cases of occurrences of hazards, monitoring and mitigation (sunk costs). These costs are in level II higher than market price in similar conditions, local or national. In order to be able to deal with high costs, extending the duration of repurposing projects could be also considered.

The level III means that the land use is feasible, at a cost similar to market price. It means that the land can be sold to a user without economic loss, but no gain either.

The level IV means that the sunk costs are lower than market price, and the level V that there are no sunk costs (costs devoted for remediation).

The owner (often mining company) can forecast financing needs or incomes. Theoretical examples are given in figure 5.3.



Forest | Housing | Agriculture

	Immediate, no cost
	Lower than land market price (MP)
	Close to land MP
	Higher than MP or important delay
	Not feasible

Figure 5.3: Illustration of land feasibility maps for three land uses.

6 Repurposing impacts assessments

To achieve the objectives defined at the beginning of the land planning process (chapter 4, table 4.1), the capacity of each land use to fulfil part of the objectives are assessed with indicators (table 4.2). A database of indicators of land use production is established, for ecologic, social, and economic impacts. Suitable impact indicators should be selected based on relevant scientific studies, and proposals are made in the following sections.

The geographic scale of assessment of non-provisioning services can be larger than the land mine. For example, water bodies used as reservoir for firefighting can be used for forest far from the mine basin, and therefore providing potential benefits on a large area. Air quality improvement can have positive effects on populations dwelling at several km away, according to pollution transfers models.

6.1 Ecological impacts

Ecological impacts are assessed and quantified as non-provisioning environmental services (ES). ES can be quantified for each land use defined with Corine Land Cover (CLC) classes. In the first place, non-provisioning ecosystem services will be quantified using tables of coefficients for each land cover type derived from field experiments with methods assessed by Bagstatd et al. (2013). Ecosystem services quantification and units are derived from literature (table 6.1). A literature review and local empirical data are needed to quantify ES to be included in a database. The local empirical data may differ from literature due to local conditions, such as ground composition, climate. In the absence of empirical data, modelization can be performed.

Table 6.1: Summary of non-provisioning ecosystem service indicators, quantification methods and primary references

Ecosystem service	Indicator	Quantification method	References
Climate regulation (Temperature)	Land surface thermal emissions	Thermal emissivity	Schwarz et al. (2011)
Climate regulation (Humidity)	Evapotranspiration	Evapotranspiration potential	Schwarz et al. (2011)
Water flow regulation	Runoff	Runoff in % of total rainfall	Nunes et al. (2011)
Erosion control	Soil loss	Soil erosion in g/m2 during a monitored period	Nunes et al. (2011)
Air purification	Pollutant capture	Dry deposition of pollutants in t/year	Jones et al. (2017)
Carbon sequestration	Carbon storage	Above-ground carbon storage in t/ha	Strohbach & Haase (2012)
Qualities of species or ecosystems (Biodiversity)	Impact of shrinkage related cover patterns	Degree of suitability	Haase et al. (2014)

Relative impact calculation: the non-provisioning ecosystem service quantification are transformed into a common metric, an index between one and ten, through local scaling. Local scaling sets upper and lower bounds using locally measured performance values (instead of global scales that may cause irrelevance of differences between local measures):

Relative index = (impact value – min value)/(max - min) x 9 + 1

Ecologic impacts proposed in the RECOVERY project are air quality regulation (air pollution absorption), water flow regulation (water run-off), temperature regulation (thermal emissivity), Interactions with natural environment (biotopes values for recreation and contact with nature) and soil. Example for CLC classes ecological impacts for biodiversity are given (table 6.2).

Table 6.2. Biodiversity impact and respective normalised impact index (adapted from Haase et al., 2014).

CLC classes	Biodiversity Impact	Relative Index
Discontinuous urban fabric (112)	0	1
Industry or commercial units (121)	0	1
Mineral extraction sites (131)	1	4
Dump sites (132)	1	4
Pastures (231)	2	7
Broad-leaved forest (311)	3	10
Coniferous forest (312)	2	7
Moors and heathland (322)	2.5	8.5
Transitional woodland/shrub (324)	2.5	8.5

6.2 Social impacts

6.2.1 Employment, training and wages

The objectives in terms of employment and type of jobs should be set up in adequacy with the territory diagnosis. To achieve these objectives, stakeholders must define if it is a priority of land repurposing. Spatial intensity of job differs from nearly zero (free natural area like shrub) to very intensive in manufacturing plants and some services. Furthermore, attempts to re-train unemployed people in coal-intensive regions in transition must consider possible structural unemployment and a lack of jobs in the surrounding labour market, the insufficient engagement with potential employers to identify needed skills (TRACER project).

The qualification and specialization of people for new occupational fields, replacing the lost jobs by ceasing mining activity are dependant to land uses, such as renewable energy, tourism and services, cultural activities, support for teaching and research activities, health and sports activities, farming, or natural evolution in shrub. The territory diagnosis performed in chapter 4 assesses the ability of the region to attract new investments. According to willingness of potential investors, needs for area and nature of land could be determined, and are input for the DSS.

Wages are generally lower in new activities compared to mining. As far as possible, diversity of jobs should be proposed, provided special training programs. Expected wages can be a social indicator. A database of number and qualification of employees to land use could be established.

6.2.2 Health and Wellbeing

Recreational area should be in accordance with the population, and not only for tourism. Workers and household should be set up in favourable environment, good air, and landscape qualities.

6.2.3 Cultural heritage

Coal heritage is a source of pride for many former coal communities, and heritage and history can be used as an asset (TRACER project). Therefore, outstanding cultural heritage should be identified in the SDSS to restraint other land uses.

6.3 Economic impacts

The economic impacts must be evaluated for the entire repurposing plan and must encompass all financial fluxes. A complete "business plan" can be set as far as reasonable, and financing needs and sources from the stakeholders quantified.

As far as possible the economic impact is assessed at the global level, that is on all the mine basin and surroundings affected by the project. The stakeholders need to know the exact costs they will incur (Lessons learned from RECOVERY).

The non-provisioning ecosystem services will be assessed in a separate step for cost-benefit analysis. Monetary values are assessed in euros and euros/ha per year.

6.3.1 Investment costs

Investments costs (CAPEX) represent the total amount to achieve the land use adequation estimated in the feasibility stage prior repurposing (sunk costs, see chapter 4.5), and the new land use investments costs. Note that sunk costs and productive investments could be supported by different stakeholders, e.g. mine company for sunk costs and new investors for productive. The Recovery project (Deliverable 5.2) gives example for fibre production, food production, green urban areas, shrubs, grassland areas for sport and leisure facilities, water bodies, dump sites, photovoltaic farm, industrial or commercial units. Training costs for workers according to skills should be anticipated for assessment of the economic impacts.

6.3.2 Operating costs

Maintenance costs (OPEX) include monitoring costs, insurances (bonded to risks), and prevention and restoration of forecasted degradation. Maintenance costs are in euro/ha per year. The MERIDA project and the RECOVERY project give examples of monitoring and maintenance costs for risk mitigation at the acceptable level.

6.3.3 Incomes from activities

Tangible incomes examples are given in RECOVERY Deliverable 5.1. It includes market public services (landfill), mining services (depositing mining wastes), commercial transactions (sale of real estate, energy production). They are assessed from similar transactions associated with the good to be valued. Income taxes should be considered for public stakeholders.

6.4 Cost-benefit analysis

The cost-benefit analysis (CBA) includes provisioning and non-provisioning monetarized costs and benefits. It is performed for each land use in euro/ha per year. Despite non-provisioning CBA is subject to controversy, it allows to compare land uses to achieve social and environmental objectives beyond economic ones.

6.4.1 Environmental services valuation

The Economics of Ecosystems and Biodiversity (TEEB) provides a basis for the monetary valuation of ecosystems and biodiversity by assessing their total economic value. It is implemented in the System of Economics-Environmental Accounting Ecosystem Accounting (SEEA EA). It has been developed by the United Nations as a framework for measuring the ecosystem services and associated ecosystems and landscapes that underpin them. The goal has been to develop an internationally agreed way to document the changes in ecosystem assets and how these changes link to economic and other human activity. Outcomes of Ecosystem Accounting for each land use are introduced in the Cost/Benefit analysis. Example of using CICES and SEEA EA is given by Bravi et al. (2023). TEEB values are available for several countries in Europe (see Naturkapital-TEEB DE p 54). For example, aggregated monetary value of a variety of forest ecosystem services in Germany, using different valuation methods, are evaluated (in € million per year, year of publication 2014) at 267 for carbon sequestration, 2,200 for biodiversity, and 1,900 for recreational activities. Timber production is to be included in the provisioning services. A database should collect ES values for land repurposing.

The TEEB net values are obtained by comparing the value before and after repurposing, or in case of compensation, before and after completion of the project to be compensated.

6.4.2 Health impacts monetization

Health impacts monetization is a complex problem. We suggest a method dealing with air quality, recognize by Word Health Organisation as the first environmental burden on human health.

Air quality impacts on health can be assessed through the "Impact Pathway Approach" (IPA), which includes:
- an inventory of pollutant emissions linked to the scenario(s) studied,
- assessing the impact of these emissions on the concentration of pollutants in the atmosphere,
- assessing the impact of these changes in concentration on health and the environment,
- monetising the impact on health.

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The Alpha-Risk Pol (ARP) tool quantifies and monetise the exposition of a population to air pollutants $PM_{2.5}$, O_3 and NO_2 (Holland et al. 2013). More comprehensive databases have been published (Schucht et al. 2021)

Note that the benefit of recreational areas is assessed in the ES above.

6.4.3 Net present value

NPV is determined by calculating the costs (negative cash flows) and benefits (positive cash flows) for each period of an investment. After the cash flow for each period is calculated, the present value (PV) of each one is achieved by discounting its future value (see Formula) at a periodic rate of return (the rate of return dictated by the market). NPV is the sum of all the discounted future cash flows (Wikipedia).

$$\mathrm{NPV}(i, N) = \sum_{t=0}^{N} \frac{B_t}{(1+i)^t} - \sum_{t=0}^{N} \frac{C_t}{(1+i)^t}$$

Where:
i is the discount rate
N is the total number of periods (years)
t is the time of the cash flow
B_t are the benefits or cash inflows at time t
C_t are the costs or cash outflows at time t

Typically, at time 0, the Ct is equal to the initial investment.

NPV is an indicator of how much value an investment or project adds to an investor. From a private investor, appropriately risked projects with a positive NPV could be accepted. An investment with a positive NPV is profitable, but one with a negative NPV will not necessarily result in a net loss: it is just that the internal rate of return of the project falls below the required rate of return.

The net present value is determined according to a discount rate and a time laps, including a sensitivity and uncertainty analysis.

We consider the total NPV as the sum of the provisioning NPV and the non-provisioning NPV. Some costs and benefits can be shared by provisioning and non-provisioning services, in particular investment costs, and therefore must be consolidated. In case of compensation measures for projects located outside the repurposing area (such as highways constructions, forest destruction for PVi), the negative Environmental services value (ESV) of the projects on ecosystems to be compensated must be added (negative value).

$NPV_{total} = NPV_{provisioning} + NPV_{non\text{-}provisioning} + ESV_{compensated\ sites}$

6.4.4 Discount rates and lifespan

Emphasis will be put on the choice of discount rate for each case study and for each land use. A variety of discount rates, as low as zero, could be used, as they do not represent real cash flows but timeless values. Negative rates have been proposed, to consider higher future value for environmental services in the future, for example in anticipating higher carbon market prices in coming years or acceleration of general environment degradation, material prosperity increasing willingness to pay for scarce ES. A low discount rates favour ecosystem restoration instead of economic activity because restoration activities imply benefits in the far future. Stakeholders should be aware that discount rates could play a crucial role in economic assessment and cost benefit analysis.

Different discount rates for costs/benefits are used according to land repurposing and to the goods produced by the provisioning services. Non-provisioning services discount rates are generally comprised between 1% and 2%, 2.1% is proposed for recreational services, 1% for permanent welfare (RECOVERY project). For Intensive natural goods production the discount rate propose is 3-3.5% and for industrial goods production around 6-7%.

A lifespan of 70 years is chosen for environmental services. Different choices, decommissioning or new repurposing may occur by the next generations.

A database is required for NPV parameters (N and *i*) for the different land uses.

6.5 Financing needs assesment

In case of negative provisioning NPV, and positive non-provisional NPV, the project will need different sources of financing justified by positive environmental services.

Financing includes private investments for productive assets, grants from public sources for political reasons (social welfare), public grants for public services (fire protection for example), mine company grants in the frame of their post-mining liabilities, and possibly funding for environmental services of land repurposing coming from compensation of negative environmental impacts of projects located outside the mining area.

According to TEEB DE, it makes clear that simply putting a value on ecosystem services is not enough. These values must also be considered in decision-making. We need rules and incentives for a change of perspective that creates new alliances, promotes cross-sectoral thinking and helps to ensure that existing instruments are systematically applied. Remember that compensatory financing implies the withdraw of the corresponding destroyed ES.

7 Land planning

Previous steps of the methodology provide the data needed to perform land planning with a Multicriteria Decision Method.

7.1 Flowchart of land planning

Note the numerous ethical, methodological and practical reserves of monetization of ecosystems. Monetisation of non-provisioning services is a quite difficult and not completely compelling. In particular, if the value is underestimated, we will disqualify virtuous rehabilitation projects compared to projects that are less so. To circumvent these objections, CBA is introduced as a component of MCDA. A careful combination of MCDA and CBA facilitates evaluation of projects involving natural ecosystem services and agriculture changes (Sijtsma et al. 2013). According to Munda (2017), "CBA *and multicriteria evaluation (MCE) can be considered as relevant methods only if all consequences of a policy decision can be correctly transformed into monetary values and efficiency is the only relevant policy objective. In all other cases, CBA can be used as a criterion in an MCE framework. Thus, in general terms, CBA and MCE are complementary in nature.* "

We therefore propose to use a MCDM based on preferences of the stakeholders to attributes (weights) of the alternatives. Non-provisioning services will be used to assess the total costs and benefits of the operations, including costs and benefits for externalities. A negative cost-benefit analysis on provisioning services can be justified for financing with public grants if the total NPV is positive.

The objectives of the land planning are not to choose between different scenarios of repurposing by comparison, but to determine the proportion of different land uses and their layout. It differs from usual MCDA problems/objectives and need adaptation of them. To achieve the components of the DSS depicted in figure 1.1, a detailed flowchart of land planning is proposed (table 7.0).

Table 7.0: Detailed flowchart of land planning

Number	Step	General framework chapter	Land planning §	Table/Figure
1	Manual prioritization from diagnosis	4	7.2	
2	Definition of the area of MCDA	4	7.3	
3	Land uses needs inventory	4		T 4.2
4	Land uses performances to sustainability criteria	4	7.4.1	T 4.1 T 7.1
5	Pairwise comparison of alternatives preferences		7.4.1	T 7.2
6	Scoring of sustainability criteria		7.4.2	T 7.5
7	Scoring of land uses		7.4.3	T 7.7
8	Proposed land uses repartition		7.4.3	T 7.8
9	Assessment of indicators of sustainability		7.4.3	T 7.9
10	Objectives of sustainability	4		T 4.2
11	Sensibility and uncertainty analysis		7.4.8	
12	Land use repartition revision		7.4.3	T7.10
13	Feasibility maps	5	7.4.4	F 7.4
14	Layout of land uses in accordance with feasibility maps		7.4.4	F 7.5
15	NPV calculation for alternatives according to feasibility zone	6	7.4.4	T 7.11
16	Provisioning NPV calculation	6	7.4.5	T 7.12
17	A posteriori control of non-provisioning environmental services value	6	7.4.5	T 7.13
18	Comparison with NPV objectives and financing plans		7.4.6	
19	Revision of repartition and layout using evolutionary algorithms		7.4.7	

7.2 Manual prioritization:

First, imperative land use for essential uses, such as rivers, riverbanks and water run-off are planned on the GIS. Such zones identified with no feasibility of any repurposing land use need should not be considered in the MCDA. Similarly, lands matching obviously with an identified and quantified land need should be devoted for this use. For example, lakes should be maintained if water bodies are needed for instance for flood and drought regulation.

Second, If MCDM failed to attribute land use for highly important objectives and low consuming space activities, it could be first attributed as to not jeopardize land repurposing with large area needs. For example, the DSS should select sufficient intensive job land use to achieve the employment objectives, and then determine the land use for less job intensive. However, in an alternative process, the job objective could be achieved after iterations of land uses planning, with increasing employment weight for ranking activities.

7.3 Multicriteria decision analysis methodology

The MCDA applies to the remaining lands. The first output will be the definition of optimum land use areas ratio to foster sustainability criteria. The second output is the locations and layout of the different land uses in respect of the ratio of optimum.

7.3.1 The AHP methodology

The AHP fundamental scale in assigning the weights comprise 9 levels (Lowest =1, Low = 3, Average = 5, Good = 7, Excellent = 9). The correspondence between performance of alternatives and scale can be determined by a simple mathematical formula (1 for the lowest to 9 for excellent), or by a questionnaire presented to the stakeholders, especially experts (Arratia-Solar et al. 2022) when a strong uncertainty affects the knowledge of the technical capacities. A matrix is filled with inverses (1 to 7 and 1/7 for example). Priorities of each alternative are calculated. The sum of each column is calculated and use to average each pair. The averages are summed for each line to obtain the priority of each alternative for each objective (eigenvector). The total of the priorities equal 1.

The preference scale between objectives criteria to achieve the most sustainable land repurposing is established by stakeholders, in a participative consultation (Arratia-Solar et al. 2022). A preference matrix is given. If there is not a consensus, then it might be best to take two or more sets of weights forward in parallel, for agreement on choice of options can sometimes be agreed even without agreement on weights. Even if this does not lead easily to agreement, explicit awareness of the different weight sets and their consequences can facilitate the further search for acceptable compromise (multi-criteria analysis manual for making government policy, 2009). Alternatively, the Simple Multi-Attribute Rating Technique Extended to Ranking (SMARTER) uses the Rank Order Centroid (ROC) weights to aggregate the answers of the different stakeholders (Amaro et al. 2022).

7.3.2 Optimum land uses area ratio

1) Alternatives of land uses are compared by pairs for their capacity to reach attributes of each sustainability criterion.

This operation is repeated for each objective.

2) The prioritization of objectives is performed by pairs as above, according to the willing of the stakeholders. Priority of each objective is calculated with the eigenvector. The score of each alternative is calculated as the product of the priorities of alternatives and objectives and summed for each alternative.

3) Alternative performance scores

The final score of each alternative is obtained by the sum of the products of criteria priority with alternatives priority. The AHP theory made choose the alternative with the highest score as the unique land use for all the land mining repurposing.

However, a unique land use is not satisfactory in most cases, as diversity is an important consideration considering the different expectations of the stakeholders. Different statistical tools are proposed to consider all the attributes, such as TOPSIS (Soltanmohammadi et al. 2010). An open discussion among stakeholder should be considered at this stage. Therefore, we propose that the scores are used as an ideal proportion of land uses alternative to fulfil the objectives of sustainability.

7.3.3 Layout optimization

The layout of alternatives is set up with minimisation of costs. The alternatives are located according to land cost repurposing for each alternative.

The productions of objectives are calculated as the sum of the production of each alternative.

NPV calculations are performed, considering the specific remediation cost of repurposing for the considered alternative.

Provisioning and non-provisioning NPV are calculated and summed. Economic attributes are not considered in the MCDA method proposed, but as a tool for justification of extra-financing sources. Positive non provisioning NPV can justified public fundings if necessary.

7.4 Fictive example

Let us consider the mine area presented in the following figure. Each square is 2.6 ha. White squares are out of the mine area. For simplification of the example, two squares will be devoted to housing and commercial activities out of the scope of MCDA. It remains 27 squares awaiting for repurposing decision, that is 70.2 ha.

The objectives can be quantified or not. Let assume for the example objectives of sustainability determined by stakeholders as follow:

	Energy	Biodiv	Water reserve	Employment
Production	MWh	Units	m3	Full time eq
Objectives	> 600	> 100	50 à 100 000	20

7.4.1 Alternatives land uses performances

To achieve the goal of sustainable land repurposing, four socioeconomics factors are identified and shared by stakeholders for four sustainability objectives: renewable energy production (Energy, MWh/year), Biodiversity relative index (RI, see chapter 6.1) Water reserve for flooding, drought and fire prevention, drainage and limited water run-off (Water, m^3), Employment (full time equivalent).

We also assume that the contributions of each land use to achieve the objectives indicators have been assessed. They are listed in table 7.1.

Note that financial aspects are not considered as a sustainability criterion but will be taken into account in the decision making in chapter 7.4.5.

Table 7.1: technical capacity of land use alternatives for achievement of repurposing sustainability criteria

	Renewable Energy Production	Biodiversity	Water reserve	Employment
Alternatives	MWh/ha	RI/ha	m3/ha	Full time eq/ha
Forest	3	8	10	0,2
P/V	20	1	0	0,3
Lake	0	3	10000	0,1
Farming	0	4	200	0,4

We assume that based on data in the table 7.1 and stakeholders' views, table 7.2 depicts the pairwise comparison for the Energy criterion. It means that P/V is "good" compared to forest for energy production, and "excellent" compared to lake.

Table 7.2: pairwise comparison of alternative preference for the Energy criterion

Forest	1	P/V	7
Forest	3	Lake	1
Forest	3	Farming	1
P/V	9	Lake	1
P/V	9	Farming	1
Lake	1	Farming	1

These preferences for Energy are reported in reciprocal Table 7.3:

	Forest	P/V	Lake	Farming
Forest	1	1/7	3	3
P/V	7	1	9	9
Lake	1/3	1/9	1	1
Farming	1/3	1/9	1	1
Total	8,667	1,365	14,000	14,000

The comparison matrix is determined, and the eigenvector calculated for the alternatives in Table 7.4:

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	Forest	P/V	Lake	Farming	**Priority**
Forest	0,115	0,105	0,214	0,214	**0,16**
P/V	0,808	0,733	0,643	0,643	**0,71**
Lake	0,038	0,081	0,071	0,071	**0,07**
Farming	0,038	0,081	0,071	0,071	**0,07**
Total					1,00

Priorities are calculated similarly for Biodiversity, Water reserve and Employment (data not shown).

7.4.2 Preference criteria

The prioritization of objectives is performed by pairs as above, according to the willing of the stakeholders (Table 7.5).

Table 7.5: Pairwise comparison of sustainability criteria

	Energy	**Biodiv**	**Water reserve**	**Employment**
Energy	1	2	5	3
Biodiv	1/2	1	1/9	4
Water reserve	1/5	9	1	9
Employment	1/5	1/4	1/9	1
Total	1,900	12,250	6,222	17,000

The comparison matrix is determined, and the eigenvector calculated for criteria in Table 7.6.

Table 7.6: comparison matrix of criteria

	Energy	Biodiv	Water reserve	Employment	priority
Energy	0,526	0,163	0,804	0,176	**0,42**
Biodiv	0,263	0,082	0,018	0,235	**0,15**
Water reserve	0,105	0,735	0,161	0,529	**0,38**
Employment	0,105	0,020	0,018	0,059	**0,05**
Total					1,00

7.4.3 Alternative performance scores and land uses ratio

The final score of each alternative (Table 7.7) is obtained by the sum of the products of criteria priority (table 7.4) with alternatives priority (table 7.6).

Table 7.7: sustainability scores of land uses alternatives

	score
Forest	0,19
PV	0,38
Lake	0,29
Farming	0,14
Total	1

These scores rank the alternatives. The best alternative to achieve the objectives is photovoltaic parks, followed by lake, forest, and farming. It means that PV is the most suitable alternative to fulfil the objectives indicators. A first approach could be to use the final scores (table 7.7) as proportion for different land use, in a first cycle of planning.

If we consider the 70.2 ha to be repurposed, the total indicators for each criterion obtained with land uses proportion obtained in table 7.7 will be the following (Table 7.8)

Table 7.8: Quantification of impacts of land uses on sustainability indicators

	Area	Energy	Biodiv	Water reserve	Employment
Production	ha	MWh	Units	m3	Full time eq
Forest	13,40	40,20	107,19	133,99	2,68
PV	26,39	527,71	26,39	0,00	7,92
Lake	20,69	0,00	62,08	206 931,73	2,07
Farming	9,72	0,00	38,89	1 944,48	3,89
Total	70,20	567,91	234,54	209 010,20	16,55

These productions are compared with the objectives (qualitative or quantitative) of the territory defined by the stakeholders, if these objectives were quantified. We calculate for illustrative purposes, the following quantitative objectives as in table 7.9:

Table 7.9: quantitative objectives of sustainability criteria obtained through the first iteration of land repurposing

	Energy	Biodiv	Water reserve	Employment
Production	MWh	Units	m3	Full time eq
Objectives	> 600	> 100	50 à 100 000	20
Total	567,91	234,54	209 010,20	16,55
Achievement of objectives	insufficient	OK	To be lowered	insufficient

Discussion with stakeholders can be conducted to improve the land planning capacity to achieve the objectives. For example, first the lakes surfaces could be lowered of at least 50%. Since the P/V presents the highest sustainability score, objectives regarding their use could be increased. An example of such results is presented in table 7.10:

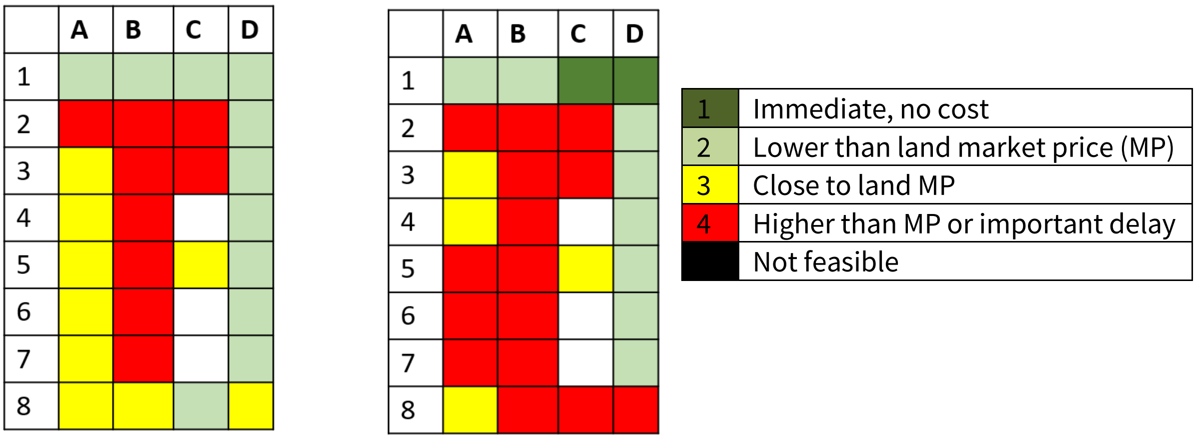
Table 7.10: revised land use proportions after iteration

	Area	Energy	Biodiv	Water reserve	Employment
Production	ha	MWh	Unit	m3	Full time eq
Forest	13,34	40,01	106,70	133,38	2,67
PV	40,01	800,28	40,01	0,00	12,00
Lake	7,02	0,00	21,06	70 200,00	0,70
Farming	9,83	0,00	39,31	1 965,60	3,93
Total	70,20	840,29	207,09	72 298,98	19,31
Objectives		> 600	> 100	50 à 100 000	20
Achievement of objectives		OK	OK	OK	Almost OK

When it is impossible to achieve all objectives, and this is generally the case, discussion on the weights in table 7.5 should take place with the stakeholders, in an iterative process. The gaps between objectives and outcomes should be coherent with the weights of the different objectives (a important gap could be acceptable for a low weight and reciprocally). A sensitivity and uncertainty analysis will be helpful for the discussion about final choices (see below). A strong uncertainty can lead to lower the weight of an objective indicator, and conversely.

7.4.4 Layout

In the next step of the repurposing process, spatial layout of land use is performed according to the feasibility maps established at the previous stage (chapter 5), for four land uses (figure 7.4). In this example, feasibility maps of forest and P/V (Fig. 7.4 A), and Lake and farming (Fig. 7.4 B) are represented. Each square is 2.6 ha. White squares are out of the mine area. Squares D6 and D7 are devoted to housing and commercial activities. It remains 27 squares awaiting for repurposing decision, that is 70.2 ha.



A : Forest and PV B : Lake and farming

Figure 7.4: Land use feasibility maps for four land uses

Let assume the following NPV values for each alternative calculated according to the method described in chapter 5 (feasibility maps).

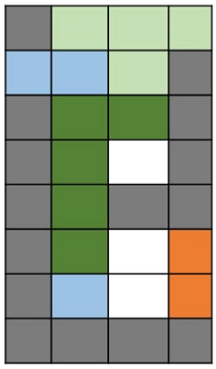
Table 7.11: NPV for alternatives according to the feasibility zone

	NPV zone 1	NPV zone 2	NPV zone 3	NPV zone 4
	K€/ha	K€/ha	K€/ha	K€/ha
Forest	5	2	-5	-20
PV	50	20	0	-5
Lake	-9	-12	-15	-30
Farming	10	5	5	-10
Total				

A specific algorithm (Linear Programming, Pavloudakis et al. 2009) should be developed and used to design the spatial layout of activities that maximizes the NPV. For the sake of illustration only, here we carried out a manual operation, and propose to set up forest in 5 squares in zone 4, lake in 3 squares in zone 4, farming in 2 squares in zone 1 and 1 square in zone 2 and one square in zone 4, PV in 6 squares in zone 2 and 9 squares in zone 3 (figure 5).

	A	B	C	D
1	PV			
2				PV
3	PV	Fo	Fo	PV
4	PV	Fo		PV
5	PV	Fo	PV	PV
6	PV	Fo		H
7	PV			H
8	PV	PV	PV	PV

	A	B	C	D
1		Fa	Fa	Fa
2	L	L	Fa	
3				
4				
5				
6				H
7		L		H
8				



	P/V
	Forest
	Housing
	Farming
	Lake

Figure 7.5: proposed layout of land uses in accordance with land uses ratio and minimized costs according to and uses feasibility.

7.4.5 Cost-Benefit analysis

Cost-benefit analysis is performed according to the sum of the NPV of each land use, taking into account the different land uses costs. First, the provisioning NPV are assessed (table 7.12).

Table 7.12: Provisioning NPV of land uses (illustrative figures)

	Area	squares zone 1	squares zone 2	squares zone 3	squares zone 4	Total NPV
	squares	nb	nb	nb	nb	k€
Forest	5				5	-260
PV	15		6	9		312
Lake	3				3	-234
Farming	4	2	1		1	39
Total	27	2	7	9	9	-143

The total NPV value is compared to the financial objectives of the repurposing project. It indicates funding needs, especially public (grants), private compensations fundings, investors and from the mining company (responsibility of post-mining areas). The proportion of land uses can be revised in case of difficulties of completion of financing plan.

If we consider that no additional costs are specifically affected for non-provisioning services, but are consequences of land uses, we can calculate the Present Values for Ecosystem Services and health services ((table 7.13). In this example, we consider that agriculture has a negative impact on health due to phytosanitary products aerosols.

Table 7.13: Non-provisioning present value of the proposed land repurposing (illustrative figures)

	Area	Area	ES PV	Health PV	Total
	ha	squares	K€/ha	K€/ha	k€
Forest	13,34	5	10	1	146,7
PV	40,01	15	0,05	0	2,0
Lake	7,02	3	1	0	7,0
Farming	9,83	4	1	-1	0,0
Total	70,2	27			155,8

7.4.6 Layout improvement

The layout can be improved by integrating landscape quality and the proximity of different activities of mutual interest (forest and its recreational function with housing) or avoiding proximity of conflicting activities (landfill versus housing or commercial areas). Palagos et al. (2017) propose evolutionary algorithms for this purpose.

7.4.7 Sensitivity and uncertainty analysis

The range of values of parameters should be chosen from literature. Typically, a -10%/+10% input change is used to assess the change in output (MERIDA project). Sensitivity can be assessed for provisioning and non-provisioning NPV.

To face the high number of parameters, Monte Carlo analysis can be performed. The distribution of the variation of the parameters value can be gaussian, or to be more accurate on prices variations, a Wald distribution can be chosen (MERIDA project). The number of Monte Carlo iteration must be set in accordance with the number of parameters.

7.4.8 Financing

In the present illustrative example, provisioning NPV is negative, and non-provisioning positive. The total NPV is positive. That means that it is noteworthy and justified to get financing to get the overall social and environmental benefits of the repurposing project.

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8 Databases relationships

Numerous databases are proposed in this report. They are useful for the implementation of the method for sustainable socioeconomic post-mining planning. These databases can share data. They are listed in the table 8.1. To implement this DSS, a careful description of databases on socioeconomic aspects should be performed.

Table 8.1: list of identified databases in the report

Stakeholders
Objectives
Land uses
CICES codes
CORINE CLC
Applicable rules
Structure prices
Land market prices
Land use criteria
Land use production
Land use Environmental Services production
Land use employement
Discount rate
Environmental Services values
Alpha Risk Pol
Financing sources
Land use sensibility to risks
Preference objectives scale

9 Conclusion

The proposed method is focused on ecologic, social and economic impacts, encompassing most of the repurposing questions to face this very complex problem due to multihazards land risks.

The financial feasibility of the projects is also an important issue. To take into consideration the non-provisioning ecological services, possible grant financing can be justified with a global Net Present Value assessment. It's avoid considering financing as a sustainability criterion, but a political issue.

The proposed method aims to be versatile and comprehensive, and expected to be implementable in a DSS. It uses as far as possible determinist parameters, more than probabilistic. An extensive user testing of the DSS will be performed with data, real as much as possible. The study cases, especially for projects in progress, will allow to assess the pertinence of the method.

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What is PoMHaz?

The goal of PoMHaz is to improve methodological and practical knowledge for the assessment and management of multi-hazards, at the scale of a coal mining basin, through the active and continuous engagement of key stakeholders involved in or affected by post-mining activities.

PoMHaz is a project funded by the Research Fund for Coal and Steel programme.

Further information can be found under https://www.pomhaz-rfcs.eu.

For feedback on the PoMHaz project or the published deliverables, please contact contact@pomhaz-rfcs.eu.

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