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MINING AND ENVIRONMENTAL PROTECTION

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MINING AND ENVIRONMENTAL PROTECTION

PROCEEDINGS

Editor
Prof. dr Ivica Ristović

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FOREWORD

After the consultations with business entities in the field of mining and environmental protection, faculties and scientific institutes, an initiative for organizing a scientific meeting on mining and environmental protection was taken in 1996. The Faculty of Mining and Geology in Belgrade, CENTER FOR ENVIRONMENTAL ENGINEERING, have organized the First Yugoslav Conference with International participants held from 25th to 27th April 1996 in Belgrade, Serbia. 2nd International Symposium was held in Belgrade from 25th to 27th 1998. 3th Symposium was held in Vrdnik from 21st to 23rd May 2001, 4th International Symposium was held in Vrdnik from 23rd to 25th June 2003, 5th International Symposium was held in Vrdnik from 10 to 13 June 2015, 6th International Symposium was held in Vrdnik from 21st to 24th June 2017, and 7th International Symposium was held in Vrdnik from 25th to 28th September 2019.

Last two International Conferences were held in Sokobanja. Eight conference was held from 22nd to 25th of September 2021. and the ninth one from 24th to 27th of May 2023. In these years there were a lot of successes with international projects from whom conference gathered together a lot of international experience and collaborations.

Due to a range of organizational and external circumstances, the symposium was not held in 2025. On the basis of the conclusions made at the 9th Symposium MEP 2023 and great interest of domestic and foreign scientific and professional public, the Faculty of Mining and Geology in Belgrade, in cooperation with co-organizers (BERG FACULTY TU KOŠICE, SLOVAKIA, UNIVERSITY OF LJUBLJANA, FACULTY OF NATURAL SCIENCES AND ENGINEERING, SLOVENIA, GOCE DELČEV UNIVERSITY IN ŠTIP, NORTH MACEDONIA, GEOLOGICAL SURVEY OF SLOVENIA, LJUBLJANA, SLOVENIA, UNIVERSITY OF BANJA LUKA, FACULTY OF MINING ENGINEERING, PRIJEDOR, REPUBLIC OF SRPSKA, BOSNIA AND HERZEGOVINA, INSTITUTE FOR TECHNOLOGY OF NUCLEAR AND OTHER MINERAL RAW MATERIALS (ITNMS), BELGRADE, SERBIA, ASSOCIATION OF MINING AND GEOLOGY ENGINEERS, BELGRADE, SERBIA), shall organize the 10th International Conference Mining and Environmental Protection – MEP 2026.

Considering the overall work of the conference from 1996 until today, we are proud to celebrate this year the 30 years of work and existence of the International Conference on Mining and Environmental Protection – MEP. For all these years, about 800 scientific and professional papers in this field have been published in the Proceedings of the International MEP Conference, and about 1500 participants from the country and abroad have attended the conferences.

The previous Conferences were very successful and scientist and companies from many countries gathered to exchange information and research results. The objective of this Conference is to bring together engineers, scientists and managers working in mining industry, research organizations and government organizations, on development and application of best practice in mining industry in the respect of environment protection.

The Proceedings of the 10th International Conference on Mining and Environmental Protection contain 39 papers. Almost half of the papers are from abroad or have authors from different countries. At least a large number of authors and co-authors took part in the preparation of these papers. The papers were reviewed by Reviewers and Scientific Committee. Only high-quality papers were selected, from two side, one from the scientific basis and the second from point of view of applicability in resolving problems at the development of mining.

We are very grateful to the authors of the papers, who contributed to a great extent to the success of this meeting by having sent enough number of high-quality papers, and thereby made the work of the reviewers a pleasant one in respect of selecting the best quality papers. Also, we would like to thank all of the participants in the Conference, as well as the sponsors who helped and enabled us to hold such a great meeting.

Editor

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MITIGATING ENVIRONMENTAL RISKS AT THE PROBISTIP TAILING STORAGE FACILITY, NORTH MACEDONIA

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Abstract: *Historical mining activities and the application of techniques that caused significant environmental impacts have emphasized the need to pay special attention to these environmental hotspots. Tailings storage facilities are among the most common hotspots, and this paper analyzes the Probistip tailings storage facility as one of the oldest and most significant hotspots in North Macedonia. The study determines the current condition of the area where the old Probistip tailings storage facility is located and assesses its impact on different environmental media. Based on the obtained results, appropriate techniques for mitigating the negative environmental impacts are considered.*

Keywords: *mining, tailings dam, photovoltaic, geoclay, aeolian erosion.*

1. INTRODUCTION

Historical mining practices across the Western Balkan region have left a legacy of significant environmental degradation, increasing the need for effective management, assessment, and remediation of abandoned and active industrial hotspots. Among the most critical environmental liabilities are tailings storage facilities (TSFs), which may pose long-term risks to surrounding ecosystems and human health due to the presence of potentially toxic materials, metal leaching, windblown dust dispersion, and structural instability [1]. Mine tailings may remain persistent sources of acid mine drainage and heavy-metal contamination long after the cessation of mining activities, emphasizing the need for integrated approaches that combine environmental risk reduction, remediation, and resource recovery [2].

North Macedonia is relatively rich in mineral resources, including metallic mineral ores, with lead–zinc and copper ores being among the most important. The exploitation and processing of these resources have resulted in numerous mining and metallurgical sites with different levels of environmental impact. Depending on the mining method and processing technology, different types of environmental hotspots may arise. In surface mining operations, both mine waste and flotation tailings can represent major sources of environmental contamination, whereas in underground mining, the environmental impact of flotation tailings may be more pronounced. In the past, when environmental regulations and criteria for controlling mining-related impacts were less stringent, mine-water discharges and process water from flotation plants also represented significant sources of environmental pressure [3].

Industrial areas characterized by significant contamination resulting from industrial waste and activities, and which pose a substantial potential risk to human health and the environment, are commonly referred to as environmental hotspots. Such sites require comprehensive environmental assessment, timely risk-reduction measures, and, where necessary, environmental remediation and long-term management strategies. Based on available information and the results of previous environmental investigations, 17 environmental hotspots have been identified in North Macedonia, of which 14 are associated with mining and metallurgical activities, while the remaining three are related to other industrial sectors (Table 1).

Table 1. Hotspots related to mining and metallurgy [3]

Subject	Location	Minerals	Remark
Zletovo Mine	Probistip	Zn, Pb	Operating
Sasa Mine	M. Kamenica	Zn, Pb	Operating
MHK Zletovo Smelter	Veles	Zn, Pb	Closed
Bucim Mine	Radovis	Cu	Operating
Lojane Mine	Kumanovo	Cr, As, Sb	—
Silmak Ferrosilicon Plant (former HEK Jugohrom)	Jegunovce	Ferrosilicon	Closed
Toranica Mine	Kriva Palanka	Zn, Pb	Operating
Makstil, Steel Plant	Skopje	Fe	Operating
Krstov Dol Mine	Kriva Palanka	Sb	Closed
Suvodol Mine	Novaci	Lignite	Operating
Brod-Gneotino Mine	Novaci	Lignite	Operating
Oslomej Mine	Kicevo	Lignite	Closed
Feni Industries Smelter	Kavadarci	Ferronickel	Preparing for restart
Rzanovo Mine	Kavadarci	Ferronickel	Closed

Among these sites, the old Probistip tailings storage facilities associated with the Zletovo Mine represent one of the most prominent mining-related environmental hotspots in the country. The site is a legacy of several decades of mining and mineral-processing activities carried out under environmental standards that were considerably less stringent than those applied today. The proximity of the tailings facilities to the urban area of Probistip further increases their environmental significance and potential implications for the local population. Despite the cessation of activities at the old facilities, the site may continue to pose risks through windblown dispersion of fine tailings material, surface erosion, structural degradation, and the leaching and migration of potentially toxic elements into surrounding soils and water systems. Consequently, a comprehensive assessment of the current environmental condition of the site is essential for identifying the major environmental pressures and defining appropriate risk-reduction and remediation measures.

Approximately a decade ago, interest was expressed by foreign companies in recovering valuable metals from the Probistip hydro-tailings, which had accumulated as a by-product of historically used and technologically outdated mineral-processing practices. In parallel, an initiative was proposed to cultivate oilseed rape on the site, with the intention of subsequently using the biomass for experimental biofuel production [4]. Although these initiatives were not implemented as long-term solutions, they demonstrate the potential for considering the former tailings area not only as an environmental liability but also as a site with potential for resource recovery and alternative post-mining land use. In 2022, the idea of a photovoltaic park was also unsuccessful [8].

In this context, the repurposing of degraded mining land for renewable energy generation represents a promising complementary strategy. Former mining areas and tailings sites can offer an opportunity for the deployment of photovoltaic (PV) systems while reducing competition for agricultural land and avoiding the conversion of undisturbed natural areas. Recent research has demonstrated the technical potential of deploying photovoltaic systems on former mining areas as part of a broader strategy for post-mining land revitalization and the clean-energy transition [5]. A specific case study conducted at the abandoned Sangdong Mine in Korea also demonstrated the technical and economic feasibility of installing a photovoltaic system directly on a tailings dam, illustrating the potential for combining rehabilitation of degraded mining land with renewable electricity generation.

This study evaluates the current environmental condition of the area surrounding the old Probistip TSF and its potential environmental impact. The assessment aims to identify the main environmental pressures associated with the legacy tailings and to provide a basis for evaluating appropriate remediation and risk-reduction measures.

2. CURRENT CONDITION AND ENVIRONMENTAL IMPACTS OF THE PROBISTIP TAILINGS STORAGE FACILITIES

The Probistip tailings storage facilities (TSFs) are located between the Štip–Probistip regional road and the Kiseliца River, in the immediate vicinity of Probistip. The tailings ponds were formed by a series of downstream tailings dams and one lateral dam constructed parallel to the Kiseliца River. Probistip TSFs 6 and 7 represent the two most downstream facilities within the cascade system of Probistip tailings storage facilities. At present, both facilities are out of operation.

The surface of the most downstream facility, Probistip TSF 7, contains a water pond formed by precipitation within its catchment area, as well as by leakage from a malfunctioning process-water return pipeline and stormwater originating from the elevated terrain east of the regional road. In the area of TSF 5, these stormwaters pass beneath the road through a culvert and enter the tailings area. They are subsequently conveyed southward through a surface concrete drainage channel running alongside the road (Figure 1), eventually discharging into the settling pond of TSF 6.

The downstream slope of the lateral dam associated with TSFs 5, 6, and 7 has been affected by surface erosion caused by runoff during intense rainfall events and lacks adequate protective measures to prevent the release and dispersion of contaminated dust into the atmosphere (Figure 2). This condition may increase the potential for wind-driven particulate emissions, particularly during dry periods.
A pulp pipeline supplying the newly constructed active tailings facility runs along the area between settling pond 7 and the regional road. The pipeline drainage channel turns along the crest of Dam 5, while the process-water return pipeline descends along the slope of the lateral dam to its toe. Consequently, no pulp or process-water infrastructure associated with the new active tailings facility is installed within the settling ponds of TSFs 6 and 7 [6].

Figure 1. *Concrete stormwater channel from Probištip, within the TSFs 5 area*

Figure 2. *Downstream slope of the side tailings dam constructed of cycloned sand for TSF5,TSF6 and TSF7*

Approximately 12 million tonnes of tailings, corresponding to an estimated volume of approximately 6 million m³, are deposited within the old Probistip tailings storage facilities. The site is not adequately fenced or secured, allowing uncontrolled access by people and domestic animals. The downstream slopes of the tailings dams exhibit visible erosion gullies and localized slope failures, which have developed as a result of several decades of exposure to precipitation and surface runoff.

The environmental risk is particularly pronounced during periods of strong winds, when fine tailings material and dust can become airborne and be transported toward the city of Probistip and nearby settlements located south of the site. This represents a potential pathway for the dispersion of contaminated particulate matter and consequently increases the risk of exposure for the surrounding population. Recent investigations have also reported heavy-metal contamination in soils surrounding Probistip, particularly in areas in the vicinity of the old tailings disposal site.

The site has also been affected by a major historical tailings dam failure. In 1976, a failure of the tailings dam resulted in the release of approximately 150,000 m³ of tailings material, which was transported downstream along the Kiselička and Zletovska Rivers [7]. This historical event demonstrates the potential consequences associated with the structural and environmental management of legacy tailings facilities and further emphasizes the need for their systematic assessment, stabilization, and long-term remediation.

As part of the Study on the Development of Capacities for the Management of Mining-Related Contaminated Soils in the Republic of Macedonia [3], an extensive environmental investigation was initiated in March 2008. The program included sampling and analysis of tailings materials, background and surface soils, sediments, surface and groundwater, river and well water, and crops. In addition, drilling activities were conducted to collect samples of tailings material and deeper soil layers.

Surface soil investigations focused on characterizing the spatial distribution of potentially toxic elements, assessing heavy-metal contamination and contaminant transport, and providing a basis for environmental standards. Sampling was performed using systematic grids with progressively refined intervals, as well as approaches based on geological characteristics and land use.

Laboratory analyses included total elemental concentrations and leachability tests. Ten elements were selected for analysis: As, Cd, Co, Cr, Cu, Hg, Ni, Pb, Zn, and Mn.

Elevated levels of several potentially toxic elements were identified, with numerous samples exceeding established threshold concentrations. The spatial distribution of these elements is presented in the figure 3, highlighting areas of concern and potential contamination sources. The results of the total concentration analyses of 679 soil samples are presented in Table 2.

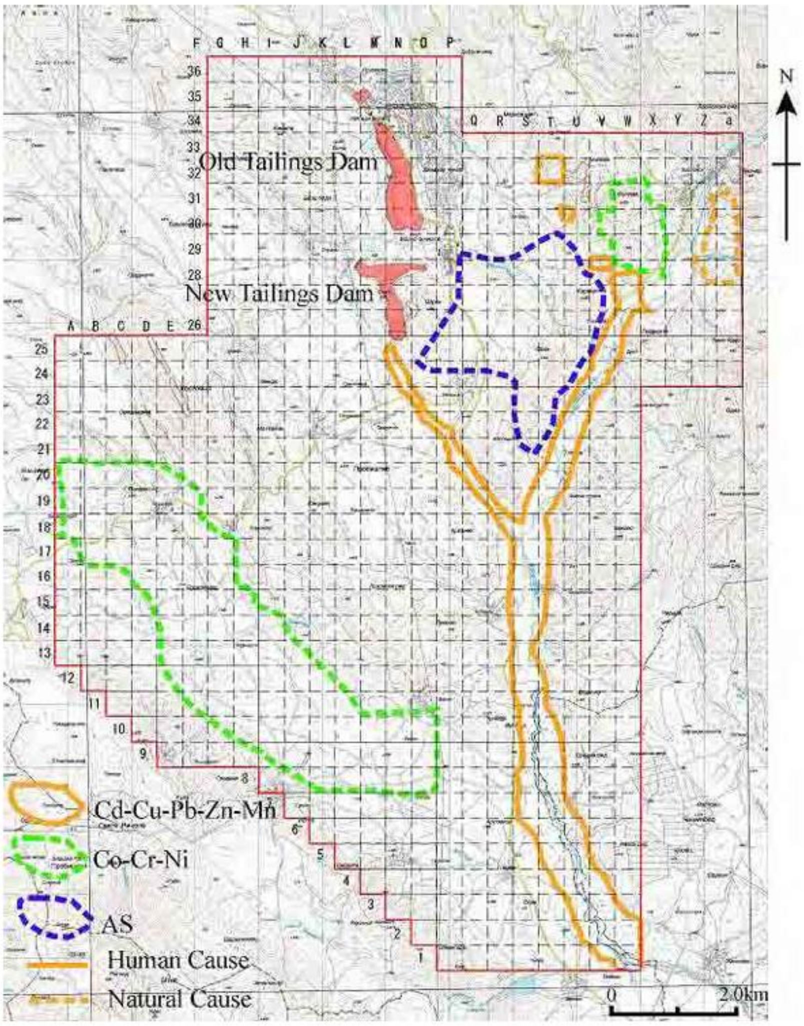


Figure 3. *Elevated Heavy Metal Concentrations and Their Potential Sources [3]*

Table 2. Statistical Characteristics of Samples from the 400 m Grid [1]

Element / Description	As mg/kg	Cd mg/kg	Co mg/kg	Cr mg/kg	Cu mg/kg	Hg mg/kg	Ni mg/kg	Pb mg/kg	Zn mg/kg	Mn mg/kg
Max	740	46	36	420	670	0.23	280	21000	10000	58000
Min	<1	<0.1	6.0	1.3	6.0	<0.1	<1	16	12	220
Mean	16	0.22	19	32	31	0.05	19	82	130	1300
Threshold concentration	209	14,8	29	166	112	-	128	286	276	2290
Number of samples exceeding the threshold concentration	18	7	7	6	33	-	21	79	88	60

3. SITE REHABILITATION AND RECLAMATION

In order to reduce the impact of the tailings storage facilities on all environmental media, it is necessary to undertake rehabilitation and reclamation of the site, after which a decision can be made regarding the future use of the area. This includes shaping by drying, protection from external high waters, ensuring stability from the weight of the objects and devices of the photovoltaic power plant, reclamation of the downstream slope of the side dam and its protection from surface erosion and air pollution, and preparation of the terrain for the installation of the objects and devices of the photovoltaic power plant [4].

Site development and rehabilitation may be implemented in accordance with the following concept (Figure 4):

1. The stormwater drainage channel should be extended by means of a concrete channel along the contact zone between the downstream slope of Dam 5 and Lake 6, extending to the side embankment. The water should then be conveyed to the Kiselička River via high-velocity chute No. 1 along the side embankment slope, followed by a stilling basin or cascade.
2. The surface of Lake 6 should be graded to provide a slope towards a concrete collection basin located at the lowest point of the lake. The collected water should then be conveyed to the Kiselička River via high-velocity chute No. 2 along the side embankment slope and a stilling basin.
3. The surface of Lake 7 should be graded to provide a slope towards a concrete collection basin located at the lowest point of the lake. The collected water should then be conveyed to the Kiselička River via high-velocity chute No. 3 along the side embankment slope and a stilling basin.
4. Material excavated from the crown area of the side tailings embankment should be used to fill the depressions within Lakes 6 and 7.
5. For flood protection of Lakes 6 and 7, which receive runoff from the higher-lying terrain to the east of the regional road, a design flood criterion corresponding to a 100-year return period (T = 100 years) should be adopted.
6. Flood protection should be achieved by grading and routing the ground surface to direct surface runoff generated by intense precipitation towards the collection basins of Lakes 6 and 7, with subsequent discharge to the Kiselička River through the slope of the side embankment.
7. Once the site has been protected against flooding and the stability of the geotechnical mass, following modification of its geometry, has been confirmed under its self-weight and the concentrated loads imposed by the structures and equipment of the photovoltaic power plant, reclamation should be undertaken to control air pollution and surface erosion of the side embankment slope.

The main objectives of the reclamation of Tailings Ponds 6 and 7 are:

- to ensure the geotechnical and geomorphological stability of the site;
- to achieve visual integration of the reclaimed area into the surrounding natural landscape;
- to ensure effective surface-water management that prevents infiltration into the tailings storage facility body and
- minimizes the potential for erosion.

The selected reclamation method should be aligned with regulatory requirements, site-specific conditions, and industry best practices, and should ensure the following:

- protection of public health and well-being;
- achievement of the agreed post-closure land-use objectives;
- geotechnical stability of the tailings storage facility;
- enhancement of the visual landscape by minimizing sediment transport, erosion, and potential adverse impacts on the environment;
- protection of water quantity and quality; and
- protection of air quality.

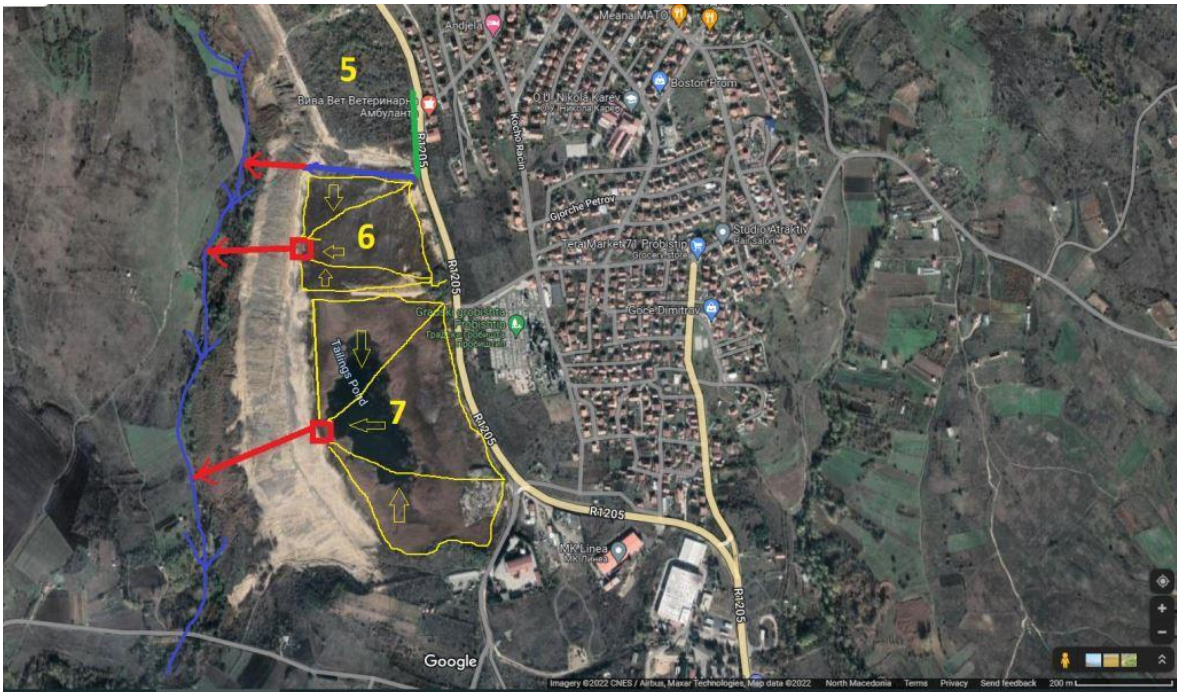


Figure 4. *Layout of Probištip Tailings Ponds 6 and 7 and the Side Tailings Embankment Parallel to the Kiselička River [6]*

An appropriate reclamation strategy can only be developed through a comprehensive assessment of the available options. The assessment should be conducted against predefined criteria applicable to this type of facility, including reliability, reclamation effectiveness, feasibility, acceptability, long-term sustainability, and implementation cost.

The basis or framework of the risk management approach is risk minimization, i.e. identifying a feasible reclamation strategy that is effective in reducing pollution and disturbance to the local population while simultaneously presenting the lowest possible level of risk. Each reclamation strategy should be evaluated against the baseline scenario, i.e. the condition of the disposal site prior to reclamation. The results of this risk analysis may be used to assess hypothetical scenarios. Experimental methods may provide additional information to support the development and evaluation of hypothetical scenarios.

The strategy identified as presenting the lowest level of risk should be evaluated in terms of five key criteria: reliability, remediation effect, feasibility, compliance with legal regulations, acceptability, long-term sustainability and of course the associated costs. In this way, the assessment addresses the overall reclamation strategy rather than merely its individual steps. This assessment can support the justification for selecting the final strategy and help identify potential challenges associated with its implementation.

Taking into account the specific site conditions, and particularly the site history, contaminants of concern, quantities and characteristics of the tailings, geological setting, potential risks, and contaminant migration pathways, the acceptable reclamation methods for mineral-waste facilities are limited to those involving the immobilization and/or isolation of contaminants, thereby preventing their further migration and eliminating their bioavailability. Consequently, all waste-treatment technologies involving any form of processing intended to destroy contaminants, as well as waste relocation, are excluded.

The selected reclamation method should meet the fundamental criteria for the reclamation process established in the BREF Reference Document on Best Available Techniques for the Management of Waste from Extractive Industries, in accordance with Directive 2006/21/EC.

Furthermore, taking into consideration, in particular, indirect factors such as the lack of sufficiently reliable data, limited financing conditions, the availability of technologies at the local level, and, above all, the need for urgent reduction of potential risks, the range of applicable reclamation methods included in the final multi-criteria analysis was limited to the following technologies:

- Leaching;
- In situ leaching;
- Solidification / stabilization;
- Phytoremediation;
- Covering;
- Beneficial reuse for another purpose (recovering valuable metals from the tailings storage facilities as secondary ore deposit by exploitation).

Based on the available reclamation technologies, a multi-criteria analysis was performed in which all technologies were individually rated (1 – excellent, 2 – very good, 3 – good, 4 – acceptable, 5 – unacceptable) for each of the seven criteria: reliability, remediation effect, feasibility, compliance with legal regulations, acceptability, long-term sustainability and associated costs.
The results of this analysis are summarized in the table below.

Table 3. Multi-criteria analysis of alternative reclamation methods

Criteria	Method					
	Covering	**Phytoreme-diation**	**Beneficial reuse for another purpose**	**In situ leaching**	**Leaching**	**Solidifica-tion**
Reliability	2	3	2	4	4	3
Remediation effect	1	2	4	3	2	1
Feasibility	1	2	1	5	5	2
Compliance with legal regulations	1	3	1	3	3	2
Acceptability	1	2	4	4	4	2
Long-term sustainability	2	4	2	3	3	1
Associated costs	2	2	3	3	4	3
Total results	**10**	18	17	25	25	14

Based on the overall results, the most favourable and acceptable reclamation method is covering, which can rapidly and effectively prevent the migration of contaminants, either in the form of fugitive dust or as sediments transported by surface runoff and/or groundwater. A significant advantage of this method is that it does not generate additional waste requiring further treatment or disposal. Taking all of these considerations into account, covering of the tailings storage facilities has been selected as the most appropriate reclamation method for TSF6 and TSF7.

A detailed description of the layers proposed for covering the settling ponds of TSF6 and TSF7 is provided below:

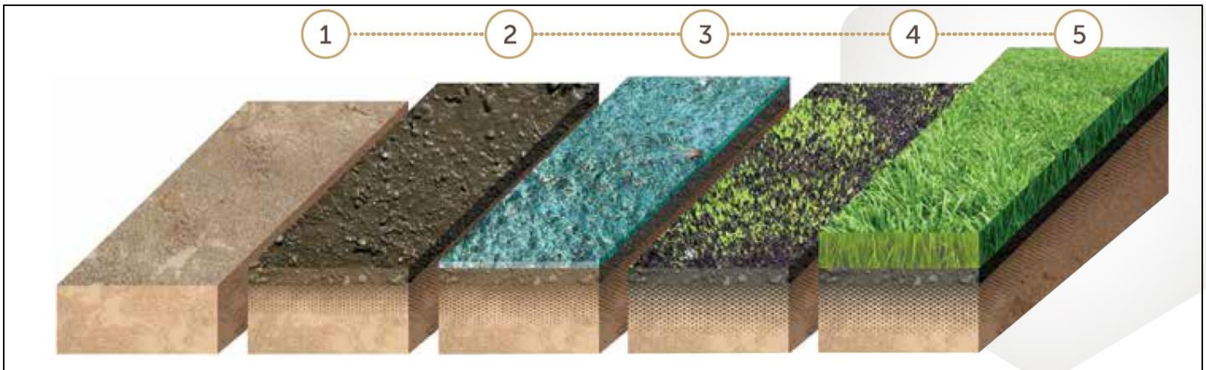
- a geosynthetic clay liner (GCL) layer for lining the settling ponds of TSF6 and TSF7;
- placement of a 30 cm thick granular bedding layer consisting of gravel with a particle size range of 0–64 mm over the surface of the settling ponds, serving as a base for vehicle access and photovoltaic system foundations.

For the reclamation of the tailings embankment slope, and particularly to ensure its rapid and comprehensive protection against erosion, the following measures are proposed:

- installation of a geosynthetic clay liner (GCL) layer along the tailings embankment slope;
- placement of a 10 cm thick bedding layer consisting of gravel with a particle size range of 0–64 mm;
- placement of a 20 cm thick topsoil layer;
- direct establishment of a low-growing vegetation cover consisting of grass species by means of hydroseeding.

The surface of Settling Ponds 6 and 7 and the slope extending to the downstream shear is to be lined with a geosynthetic clay liner, with appropriate anchorage points provided at the downstream shear and along the crest of the tailings embankment, as well as around the perimeter of the settling ponds. The geosynthetic clay liner shall be secured within anchor trenches to ensure adequate anchorage. The anchor trenches at the crest and shear of the tailings embankment shall have a trapezoidal cross-section, with a width of ba = 1.0 m, a depth of da = 0.50 m, and side slopes of 1:1. Along the tailings embankment slope, at an approximate horizontal spacing of 42.5 m, corresponding to a slope distance of 45.0 m, a 1.0 m-wide berm shall be constructed, incorporating a rectangular trench with dimensions br/hr = 0.7/0.7 m for the appropriate anchorage of the geosynthetic clay liner panels, each 45.0 m in length. On the surface of the settling ponds, the panels shall be joined with a 30 cm overlap. Along the perimeter of the settling ponds, an additional trapezoidal anchor trench shall be constructed, with a width of ba = 1.0 m, a depth of da = 0.50 m, and side slopes of 1:1 [6].

In general, hydroseeding involves the application of specially formulated mixtures of seeds, nutrients, stabilizers, and binding agents by direct spraying onto the surfaces where a vegetative cover is to be established. This layer is intended to stabilize the previously applied layers, namely the bedding and topsoil layers, and to promote the development of a vegetative cover. The mixture used to establish the vegetative cover typically consists of water, selected seeds, plant fibres that retain moisture and provide nutrients, and binding agents that facilitate adhesion of the materials to the slope until the vegetative cover becomes established (Figure 5).



1. Slope without cover	2. Application of a 20 cm-thick topsoil layer	3. Application of a vegetative cover establishment mixture	4. Seed germination approximately three weeks after application	5. Development of a vegetative cover approximately six weeks after application

Figure 5. *Process of formation of vegetation cover on the slope of the tailings dam*

4. CONCLUSION

The analysis of the available remediation and reclamation alternatives indicates that the selected approach should primarily focus on source control and containment, rather than on the relocation or extensive treatment of the tailings material. In this context, the application of a covering system represents the most appropriate reclamation option for Tailings Storage Facilities 6 and 7. Such an approach can provide simultaneous control of several exposure and transport pathways by reducing wind erosion and fugitive dust emissions, limiting infiltration and contaminant migration, and protecting the tailings surface from water-induced erosion. The proposed use of a geosynthetic clay liner (GCL), combined with an appropriate granular protective layer and, where applicable, a vegetative cover on the embankment slopes, provides a technically suitable framework for long-term stabilization of the site.

The proposed grading of the tailings surfaces, construction of collection basins and controlled drainage structures, and protection against external floodwaters are intended to minimize uncontrolled runoff and prevent water infiltration into the tailings body. These measures are particularly important for maintaining the long-term geotechnical and environmental performance of the reclaimed facility.

The study further demonstrates that reclamation should be regarded as a prerequisite for any future redevelopment of the site. The proposed rehabilitation concept therefore provides an opportunity to integrate environmental remediation, geotechnical stabilization, and post-mining land reuse within a single management framework.

REFERENCES

1. Hudson-Edwards, K. A., Kemp, D., Torres-Cruz, L. A., Macklin, M. G., Brewer, P. A., Owen, J. R., Franks, D. M., Marquis, E., & Thomas, C. J. (2024). Tailings storage facilities, failures and disaster risk. *Nature Reviews Earth & Environment, 5*, 612–630. https://doi.org/10.1038/s43017-024-00576-4
2. Xu, D.-M., Zhan, C., Liu, H., & Lin, H. (2019). A critical review on environmental implications, recycling strategies, and ecological remediation for mine tailings. *Environmental Science and Pollution Research, 26*, 35657–35669.
3. *Study on the development of capacities for the management of mining-related contaminated soils in the Republic of Macedonia*. Mitsubishi Materials Corporation – Japan Metals & Mining Development Corporation. (2008, March).
4. Ristovski, T. (2023, February 18). *The Probishtip tailings site will become a photovoltaic park*. Sitel Television. https://sitel.com.mk/
5. Wang, K., Zhou, J., Yang, R., Xu, S., Hu, Z., & Xiao, W. (2025). Deploying photovoltaic systems in global open-pit mines for a clean energy transition. *Nature Sustainability, 8*, 1037–1047. https://doi.org/10.1038/s41893-025-01594-w
6. *Project for the development of the area above the Probishtip 6 and 7 hydro-tailings facilities for the installation of a photovoltaic power plant*. Goce Delcev University – Stip. Investor: Municipality of Probishtip, Republic of North Macedonia.
7. Blazhevski, B. (2023, June 30). *Residents of Probishtip have been living with heavy toxic metals in front of their homes for decades [Gallery]*. Meta.mk. https://meta.mk/zhitelite-na-probishtip-so-decenii-zhiveat-so-teshki-otrovni-metali-pred-nivnite-domovi-galerija/
8. Istok Press. (2022, May 20). *The environmental hotspot in Probishtip and Macedonia is becoming a photovoltaic park, but…* Istok Press. https://istokpress.mk/