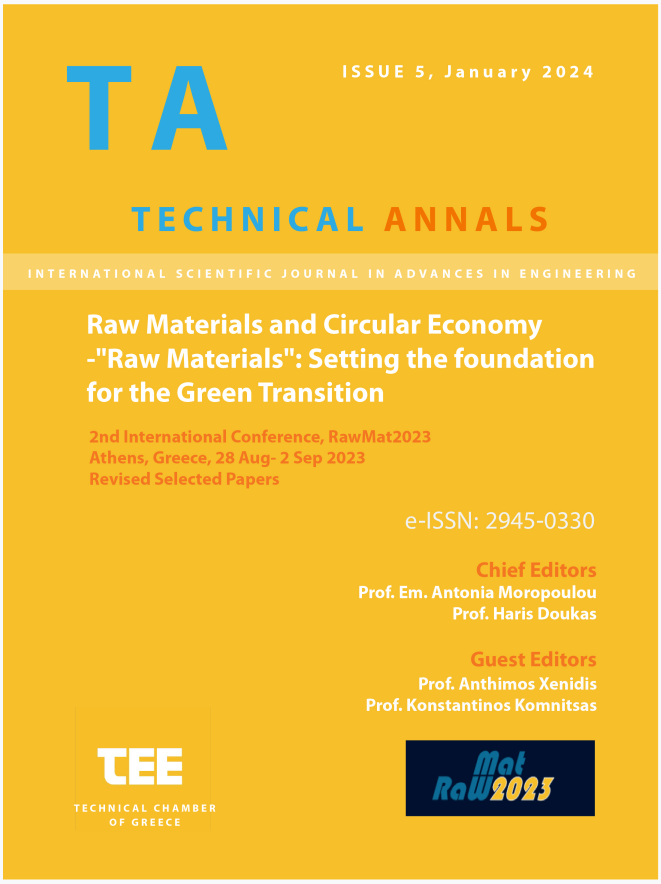
Technical Annals

Vol 1, No 5 (2024)

Technical Annals



Sustainable Use of Extractive Wastes in Continuous Surface Coal Mines: The case of Anyntaion Mine, Greece

Ariadni Sokratidou, Nikolaos Paraskevis, Aikaterini Servou, Francis Pavloudakis, Christos Roumpos

doi: [10.12681/ta.41772](https://doi.org/10.12681/ta.41772)

To cite this article:

Sokratidou, A., Paraskevis, N., Servou, A., Pavloudakis, F., & Roumpos, C. (2024). Sustainable Use of Extractive Wastes in Continuous Surface Coal Mines: The case of Anyntaion Mine, Greece. *Technical Annals*, *1*(5). https://doi.org/10.12681/ta.41772

Sustainable Use of Extractive Wastes in Continuous Surface Coal Mines: The case of Anyntaion Mine, Greece

Ariadni Sokratidou[1], Nikolaos Paraskevis[2][0009-0004-1892-6896], Aikaterini Servou[2][0000-0001-7814-706X], Francis Pavloudakis[3][0000-0002-9492-1032], Christos Roumpos[2][0000-0001-9394-8041]

[1]Environment Department, Public Power Corporation of Greece, 104 32 Athens, Greece
[2]Department of Mining Engineering and Closure Planning, Public Power Corporation of Greece, 104 32 Athens, Greece
[3]Mineral Resources Engineering Department, School of Engineering, University of Western Macedonia, 501 00 Kozani
c.roumpos@ppcgroup.com

Abstract. Continuous surface coal mines are related to large amounts of extracted overburden or interburden waste material. One of the main objectives of the strategic mine planning of such mines is to optimize the coal production, considering the waste-to-ore ratio in combination with the optimal allocation of the waste material to the outside and inside dumping areas. Further to other uses of waste material, the suitable sustainable reclamation of mining land is directly associated with the sustainable use of waste dumping sites for post-mining activities. This study investigates the main issues related to extractive waste management in continuous surface coal mining projects, focusing on a long-term strategic mining planning and scheduling model and the post-mining utilization of waste dumping areas. As a case study, the basic geospatial parameters of the waste dumping areas of the Amyntaion lignite mine in North Greece are examined based on the results of a long-term experimental design of water and soil sampling and monitoring program. The applied methods include a model for validating lignite production and waste extraction and dumping scheduling, and the geotechnical, hydrogeological, and geochemical spatial analysis of the waste material considering the post-mining land uses and the circular economy principles. The findings indicate the geotechnical and geochemical stability of the examined areas and the suitability of mining land to transition to post-mining activities, mainly related to renewable energy systems.

Keywords: Waste Management, Circular Economy, Closure, Reclamation, Post-Mining

1 Introduction

The optimal reclamation and post-mining exploitation of a continuous surface coal mining project is directly related to the long-term strategic mine planning and scheduling and the suitable management of waste mine lands. Considering the phase-out of such projects, the sustainable reclamation planning of the mined-out and waste dumping areas is an indispensable part of mine closure and post-mining activities, incorporating circular economy principles [1].

Extractive waste generation is an unavoidable procedure in the mining industry, so the respective companies try to face the issue in a sustainability context. Coal mining is accompanied by its geological history and the respective rock formations through time, which gives information about the type of rocks and the respective geological environments. This type of information is beneficial for selecting the methods that would be followed for waste management. A percentage of approximately 45% of total extracted material annually is estimated to be waste for each of the leading coal production countries in both open-pit and underground mining (United States, China, India, and Australia) [2]. Among the aggregated industrial sectors, European countries' highest extractive waste generation is observed in the mining and quarrying sector compared with manufacturing, energy supply [3].

Regarding the mining industry, the circular economy model tends to replace the linear economy model of traditional coal production, meaning “take, make, and dispose”. This linear model includes a closed system with constantly increasing entropy [4]. It has been observed that the studies concerning mining waste have an increasing trend, especially those for sustainable management, accounting for approximately 40% of the total [5]. The study for the best possible waste management is fundamental to complete sustainable mine planning. The ideal concept is the implementation of circular economy priorities on post-mining land uses in surface mining operations to achieve the viability and sustainability of mining projects [6]. In particular, the waste materials generated during the operation of mines are investigated, considering specific parameters. For instance, in the hard coal mining region of Ostrava-Karvina of the Czech Republic, mining waste is used as reclamation material [7,8] Other scientific works focus on waste management as a resource and recycling materials [7].

In recent years, the circular economy concept has gained interest, including all the procedures that can ensure a harmonious coexistence of industry, society, and the environment. These procedures are summarized in the 4 R framework of the European Union (EU) Waste Framework Directive, meaning Reduce, Reuse, Recycle, and Recover [8,9]. According to the European Commission, this concept aims to decompress natural resources and enhance new sustainable growth and employment. Particularly, the generated mining residues are reused for filling excavation voids for rehabilitation and construction purposes [10]. In this context, the circular economy deals with waste management of industrial operations. The circular economy concepts are distinguished into three different levels depending on the related actions: the macro (city, country, and more), micro (products, companies, consumers, etc.), and mezzo level (defined as the regional level, e.g., eco-industrial parks) [9]. As it was concluded in [11] the management of extractive waste in coal surface mining projects can be effectively combined with circular economy principles.

The post-mining areas’ release is a complex procedure that is followed by each country’s legislation and affects the economic, social, and environmental sectors. In a sustainable framework, the post-mining areas are designed considering the most economically valuable land uses. For the most efficient mine closure, some fundamental criteria for taking into consideration are the following: physical and chemical stability, hydrogeological and hydrological conditions, geographical and climate conditions, local characteristics, land uses, required resources for the closure, socioeconomic parameters [12]. In this context, several studies are conducted by the coal mining companies, including geotechnical, geochemical, and hydrogeological ones.

The sustainable use of extracted materials from the mining exploitation constitutes one of the basic stages of waste management. Usually, the extracted waste materials are used for filling the mining gaps that are created during the mining exploitation. However, alternative uses could be applied depending on the physicochemical composition of these materials. Some of the sustainable uses of waste materials are considered for the spatial configuration of squares and yards, for the stabilization of excavation and dumping slopes, while they could be used for the road configuration and construction, even in larger construction projects [13]. In addition, desulfurization is one possible use of limestone in wet flue gas desulfurization systems of coal-fired power plants to control sulfur dioxide emissions.

The waste dumping site operation might last for some decades, but the waste materials will remain on the site after the end of the mining operations. In the framework of the mine closure phase, the waste dumps have been reclaimed for several land uses, such as agriculture, forests, and water bodies (lakes), according to the approved environmental terms. However, considering the principles of the Circular Economy, some decisions about land use may be changed. For instance, areas that were proposed for typical land uses for reclaimed surface mining areas, such as forests and agricultural land, will finally be used for the development of activities [14] that add more value in terms of socio-economic development and environmental protection, such as the installation of renewable energy systems [15].

In this study, the main procedures that follow the gradual land release are investigated. More specifically, for the environmental monitoring and decision-making regarding post-mining land use proposals, land properties must be determined. The main parameters of interest are the soil and water properties of the reclaimed mining areas, as well as the atmosphere, noise, vibrations, and slope stability conditions.

The main research questions are:

(a) Is the allocation of the extracted waste material to outside and inside waste dumping areas compatible with the strategic mine planning and post-mining land uses of the Amyntaion mine?
(b) How does the spatial variability of the main hydrogeological, geochemical, and other environmental parameters affect the suitability of mining land to transition to post-mining activities?
(c) How can the concepts of circular economy be incorporated into the transformation of mining areas to new land uses?

The investigation is based on the quantitative analysis of the waste material in the outside and inside dumping areas, and the results of the experimental water and soil sampling and monitoring.

2 Materials and Methods

2.1 The Amyntaion Mine

The waste material and dumping areas of the exhausted Amyntaion lignite mine, North Greece, are investigated. Most part of the mine area is located in the Florina Prefecture, whereas a small part is in the Kozani Prefecture of Western Macedonia region. Being in the southern part of Amyntaion city, the main mining sites are situated among the Filotas, Perdikkas, and Olympias villages (Fig. 1). The elevation values of the area range between 407 m and 1200 m, with mean elevation in the +625 m. Public Power Corporation of Greece (PPC) mines, have elevation values ranging from 400 to 600 m. Three individual fields delineate the Amyntaion lignite mining complex: the main Amyntaion mine, the Anargiri mine, and the Lakkia mine. The total area included in the Environmental Permit Limits of the Amyntaion Lignite Mining complex is 61.83 km^2.

The excavation work began in 1984, whereas the lignite production in 1986. In the main Amyntaion mine, the excavation works began in 1989 while the lignite production began in a limited amount in 1990 and full operational scale in 1991. A large amount of the waste materials that were excavated from the Amyntaion and Anargyri mines were deposited in the outside dumping site, while the remaining in the inside dumping site. In 2013, the excavation works began in the Lakkia mine, which is operating today in the initial excavation mining sites. On the 10th of June 2017, a landslide event occurred in the southwest slopes of Amyntaion mine, and since then the operation works include only configuration and restoration works, which were completed in July of 2020. In 2018, the EIA was modified concerning the remaining small part of the Amyntaion mine, while the exploitation planning for the Lakkia mine was not differentiated.

The complex deposit geometry of the Amyntaion mine, is obvious in the Digital Elevation Maps (Fig. 2) where three different mining phases are presented: the initial surface before the excavation works, the technical mine bottom declaring the excavation areas, and the final surface after the mining operation works.

The final post-mining land use planning of the study area does not follow the initial planning according to the EIA and the Waste Management Plan, because of the new energy planning following the phase-out of electricity generation by lignite.

2.2 Waste Management Framework

Waste management in surface mining projects constitutes one of the early stages of mine planning and exploitation. It could be distinguished into four fundamental pillars: (i) mineral exploration, (ii) mine planning strategy, (iii) immediate utilization of waste materials, and (iv) spatial utilization of waste dumping materials. Mineral exploration constitutes one of the primary stages of the whole mining exploitation. It includes the exploration of the spatial distribution of the lignite deposits and the overburden and interburden materials. More specifically, this stage of waste management includes the mapping of the area hosting the mineral, the assessment of borehole findings, the assessment of the material volumes that will be dumped, as well as their geological composition.

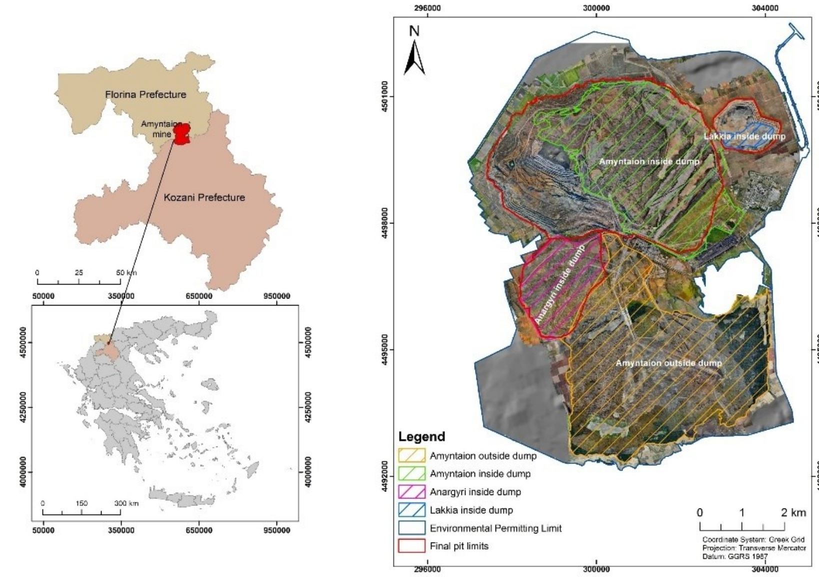


Fig. 1. General overview of the Amyntaion mine and the four investigated dumping sites

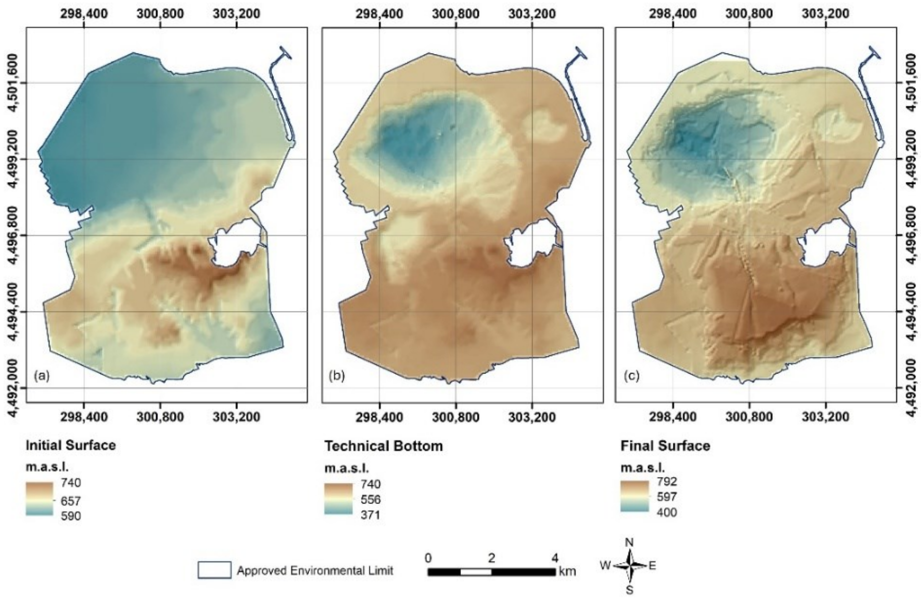


Fig. 2. Digital Elevation Maps of three different phases in Amyntaion mines: (a) initial surface before the excavation works, (b) the technical bottom declaring the excavation areas, and (c) the final post-mining surface

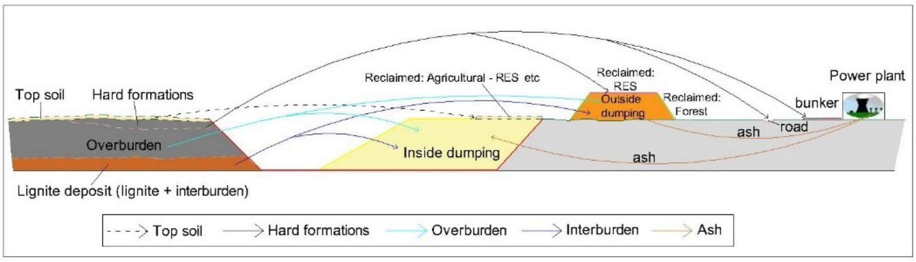


Fig. 3. Spatial representation of waste management in a surface coal mine

At the same time, the mine planning should have already been prepared and focused on the optimal way of the initial excavation and the planning of exploitation progress, aiming to deposit as little extractive waste as possible in the outside dumping areas. An essential part of the mine planning is the spatial definition of the outside dumping limits following the material volume intended to be deposited. It is worth noticing that the definition of the critical start point of the inside dumping is of high importance for achieving the minimum volume of waste materials outside deposition and, as a result, the configuration of a successful and safe mine operation. Inside dumping is the process of dumping waste materials within the void of the mine, while outside dumping refers to the practice of dumping waste materials outside the boundaries of the mine. Figure 3 depicts the whole procedure of waste management.

In the same context of mine planning and scheduling, the necessary configuration of the slopes and dumps is included to ensure geochemical and geotechnical stability. In particular, ash deriving from lignite Power Stations as a by-product is used as a stabilizer material in the outside dumping areas. Furthermore, the type of waste materials and their spatial arrangement are two components that need to be investigated. In this framework, geochemical and geotechnical attributes of the waste materials were investigated to classify the suitability of materials for several land uses. Additionally, the groundwater quality was investigated to clarify if there are any environmental consequences from the extractive procedure. More specifically, a sampling campaign was scheduled, and chemical analyses of soil and water samples were conducted for the determination of some critical parameters (pH, electrical conductivity, $CaCO_3$ content, soil organic substances, nitrates, and ammonium ions, etc.). Electrical conductivity and pH were measured electrometrically using a soil saturated paste based on WCC-103 Publication WREP-125, 2nd Edition. From the geotechnical aspect, slope stability analyses and systematic site monitoring concerning possible land movements were employed. It is worth noticing that the slope stability analyses and the site monitoring are in a continuous process to ensure the required mining safety.

Figure 3 also shows the allocation of waste material and the waste management system from a circular economy perspective. Initially, the upper beds of the soil system, namely the topsoil, are transferred to areas that are intended to be reclaimed for agricultural use, as they carry all the necessary ingredients for agricultural development. In turn, the hard formations are moved to outside dumping or/and are used as material for road construction, slope stability, and the configuration of bunkers, as their mechanical strength permits it. The overburden and interburden materials are moved for outside and inside dumping, as they could be materials of several compositions. These materials are also used for the preparation and suitable spatial configuration of areas that aim to be reclaimed for post-mining land uses (e.g., agricultural, forest land use, industrial areas, recreation parks, and photovoltaic parks). In addition, the lignite processing in the power plants produces ash, which could be used to improve slope dumps and the cohesion of the dumping materials.

2.3 Volume Calculation of Waste Materials

Several methods could employ volume calculation. In the present study, volume calculation to validate the planning of the waste material allocation was employed via the triangulation method. This method is based on Triangulated Irregular Network (TIN) surfaces and calculates the signed volume defined by two TIN surfaces declaring the elevation differences between the two surfaces [16]. This method differs from the grid-based and cross-section volume routines. Compared with the other methods, the triangulation method is considered faster and more accurate because it considers actual TINs. In general, the volume calculations among the TIN surfaces are usually employed through interpolation methods like Inverse Distance to a Power (k=1 and k=2), Point Kriging, Minimum Curvature, Modified Shepard's Method, Natural Neighbor, Nearest Neighbor, Polynomial Regression (simple planar surface), Multiquadratic Radial Basis Function, Triangulation with Linear Interpolation [17]. The type of triangulation that was applied in the framework of this study was the Linear Interpolation.

3 Results and Discussion

In the Amyntaion lignite mining area, three surface lignite mines had been in operation: the Anargyroi Mine (1984-2010), the Amyntaion Mine (1989-2020), and the Lakkia Mine (2013-2021). The mining exploitation completed in 2021, and a total of 232 million tons of lignite has been extracted, with total excavations of 1.817 million m^3 and a mining ratio (waste materials to lignite) of 7:1 m^3/t. Concerning the changes in land uses in the broader area of the Amyntaion mine, Figures 4 and 5 show the land uses in 2000, almost a decade after the opening phase of the main Amyntaion mine field, and in 2018, three years before the closure of the lignite extraction phase.

Considering the validation of lignite production and waste extraction and dumping scheduling, Figure 6 shows a graphical representation model including the excavations rate and the waste dumping allocating into the outside and inside dumping areas as a function of the lignite production, according to a long-term master plan, conducted in 1996 and revised later, and the actual data of total excavations, outside dumping and total waste dumping. On the x-axis of Fig. 6 the accumulated lignite reserves are shown. On the y-axis, the positive volumes represent the excavation site of the mine. The minimum and maximum total excavations (T.E.Min. and T.E.Max.) depend on (a) the required lignite production to meet the needs of the corresponding power plant and (b) the design of the excavation mine sectors according to the pit slope which ensures the stability of excavation site based on the geotechnical investigation). The negative volumes correspond to the dumping site of the mine (D.V.Min. and D.V.Max. are the minimum and the maximum dump volume requirements taking into account the swell factor).

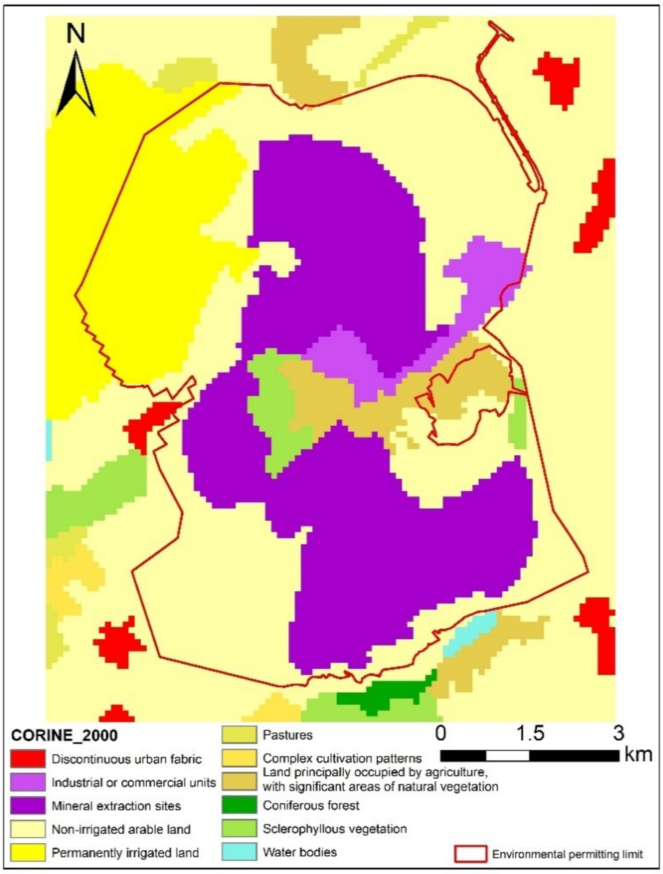


Fig.4. Land uses in the Amyntaion mining area in 2000

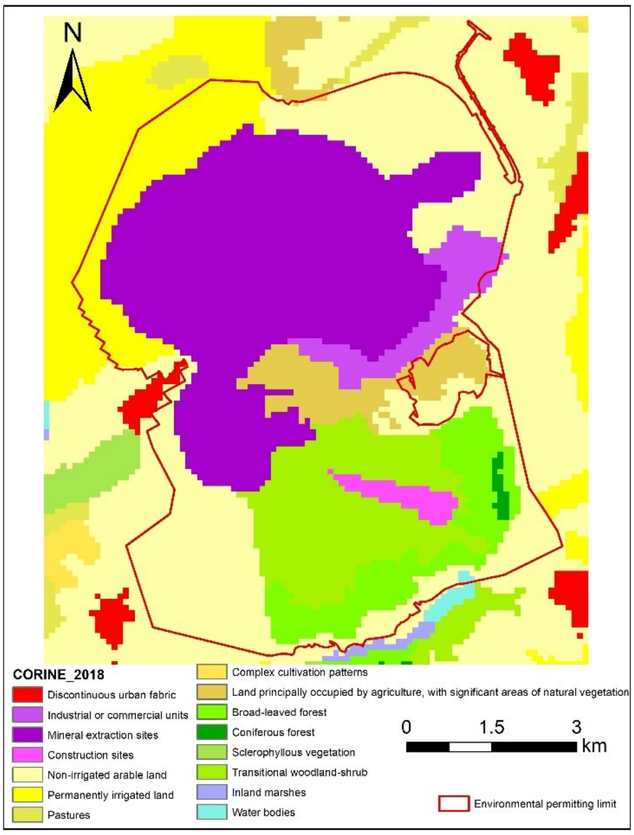


Fig. 5. Land uses in the Amyntaion mining area in 2018

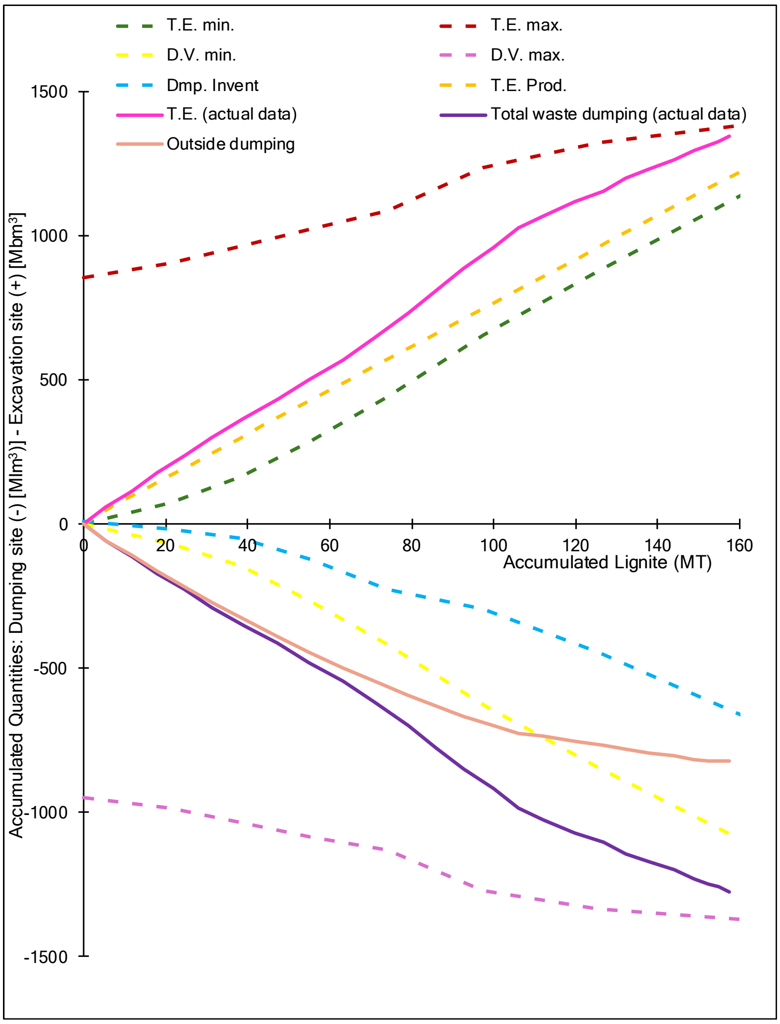


Fig. 6. A graphical representation model for the long term mine planning of the Amyntaion mine to validate the lignite production and waste extraction and dumping scheduling (T.E.Min.: minimum total excavations, T.E.Max.: maximum total excavations, T.E. Prod.: Total scheduled excavations V.Min.: minimum dump volume requirements, Dmp Invent.: dump space inventory on the inside dump, and D.V.Max.: maximum dump volume requirements according to a master plan, and T.E., Total waste dumping and Outside dumping: the actual production data respectively)

The dump volume is further increased by the deposition of ash (and possibly other materials to be dumped in the mine). The dump space inventory on the inside dump (Dmp Invent.) of the mine is determined by deducting the accumulated volume of the inside dump sectors (based on the appropriate design of dumping sectors) from the minimum dump volume requirements (D.V.Min.). The minimum of this graph (Dmp Invent.) is the minimum outside dump volume.

Considering the actual total excavations volumes and the actual outside and total waste dumping volumes shown in Fig. 6, it is concluded that (i) the total actual excavations ranged between the scheduled limits, (ii) the actual excavations pit slopes had less inclination than the initially designed excavation faces, and (iii) the actual outside and total waste dumping volumes were increased compared with the initial calculations. Therefore, the allocation of the extracted waste material to outside and inside waste dumping areas is compatible with the strategic mine planning and post-mining land uses of the Amyntaion mine.

Figure 7 presents the distribution of waste materials in the inside and outside dumping areas, while Figures 8-11 show the excavation and dumping sites of the Amyntaion mine, the spatial distribution of the waste material, and the spatial differences of the initial and final topography in the Amyntaion mining areas. It is observed that in the middle of material dumping, in 2004, the inside dumping began to increase while the outside dumping materials began to decrease significantly. In addition, a normal distribution appears for both materials deposited in outside dumping during 1990-2009 and those deposited in inside dumping during 2004-2019. This indicates a balance of material disposal, which in turn is attributed to a feasible mining design. The primary dumping materials are waster interburdens in the lignite seams, consisting of stiff clays, usually with medium (15-35%) to high (35-50%) carbonate content (marls), while the thinner waste interburdens are present in the lignite blocks.

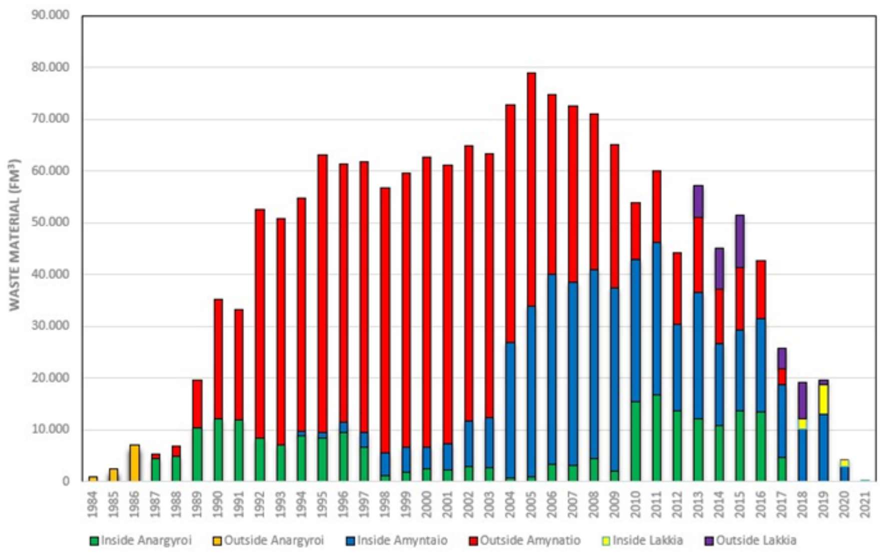


Fig. 7. Waste material distribution in the inside-outside dumping area

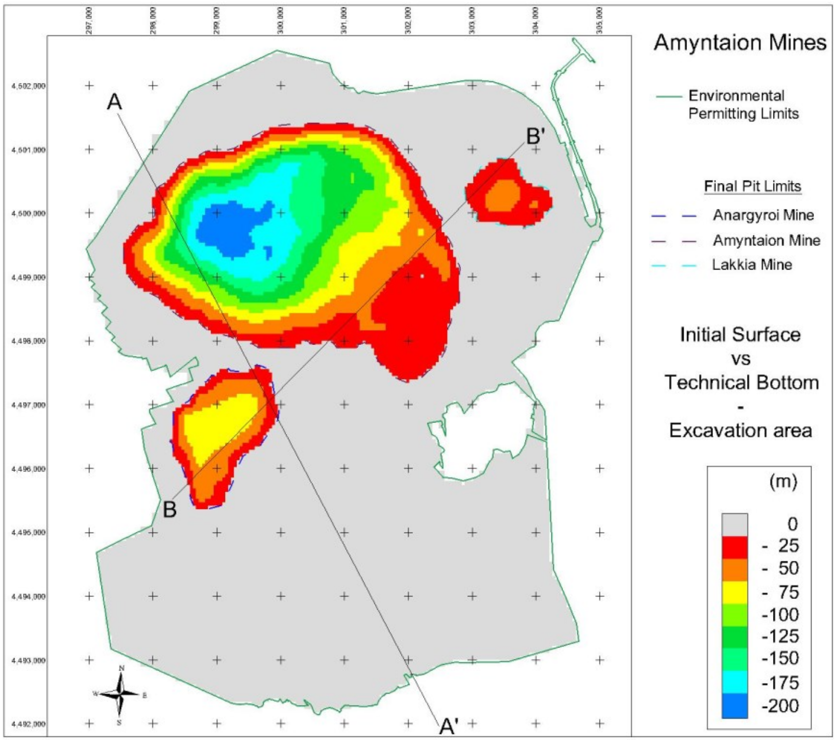


Fig. 8. Excavation sites of the Amyntaion mines

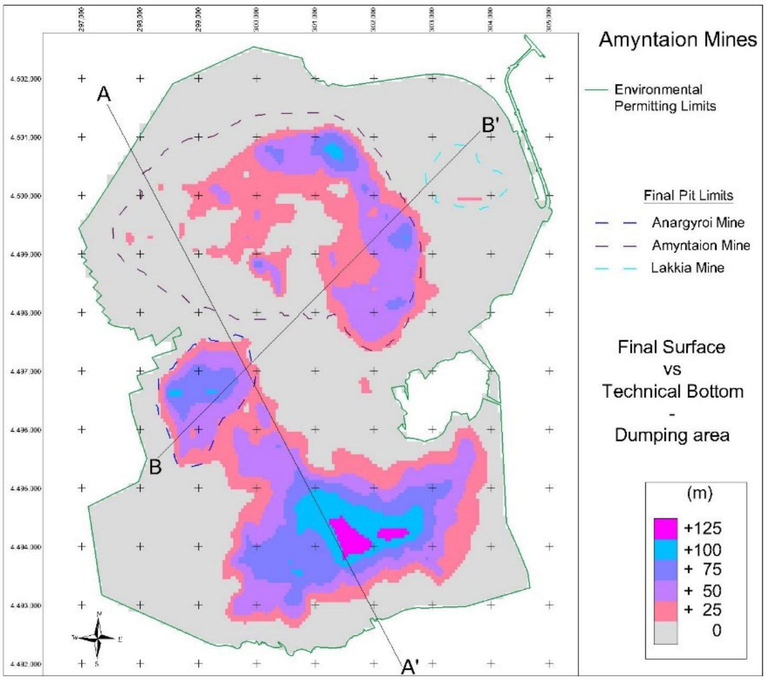


Fig. 9. Waste material distribution in the inside-outside dumping areas

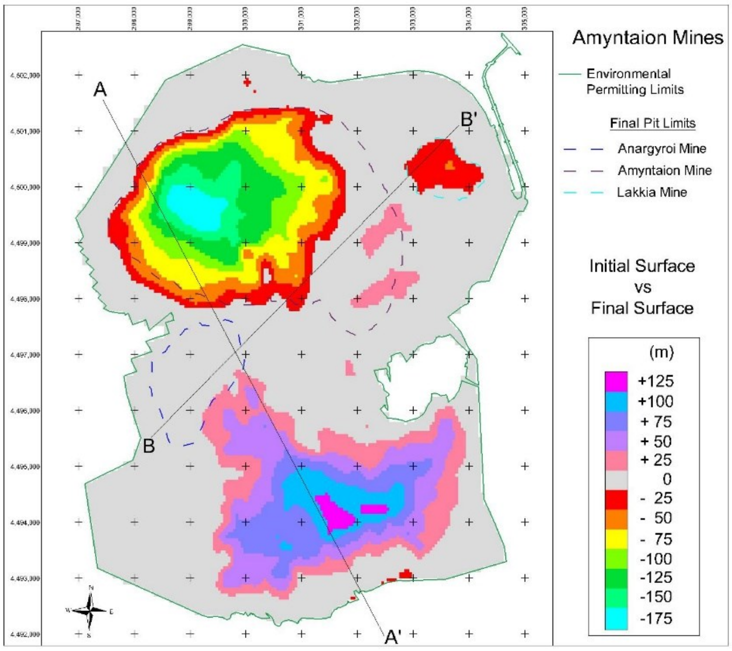


Fig. 10. Spatial differences of the initial and final topography in the Amyntaion mining areas

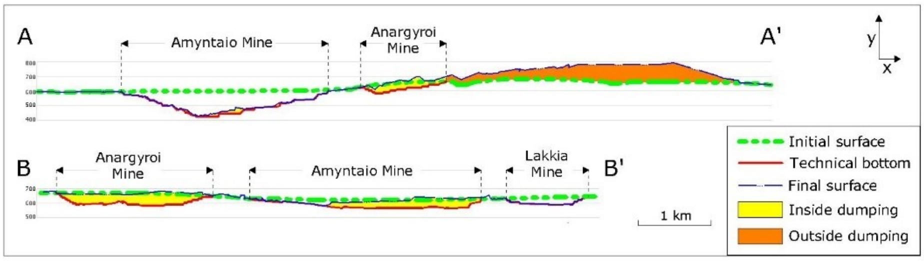


Fig. 11. Cross sections A-A' and B-B’ showing the mining sequence

Furthermore, considering the spatial distribution of the waste dumping materials and the planning of post-mining land uses in the waste dumping areas, Figure 12 shows the land uses according to an old planning, the new land uses according to a just transition development plan, and the overlay of the two land uses plans indicating the revised planning based on a sustainable land use planning towards the energy transition in combination with a variety of different uses placing emphasis on the biodiversity. The Just Transition Plan aims to ensure a fair development transition of the lignite area, which is based on three pillars: employment protection, compensation of the socio-economic impact of the transition and energy self-sufficiency of lignite areas and the country at large [18].

Regarding the long-term experimental design for the investigation of the geochemical stability of the waste dumping sites and the perimeter area of the excavation sites, Figure 13 shows the locations of soil and water sampling points. Indicative results of the soil sampling analysis are shown in Figures 14-16.

The soil chemical analyses were conducted in the waste dumping area for systematic measurements of 15 years (2005-2019). The concentration analyses in mineral and non-mineral materials showed that the mining excavation works did not affect the dumping sites, and the soils were not polluted. More specifically, the soil analyses showed that the pH values range from 6.8 to 8.9 with a mean value of 7.3, while the mean electrical conductivity ranges from 120 to 5050 mS/cm, with a mean value of 950 mS/cm. The soil content in $CaCO_3$ ranges from 0.38 to 9.73%, with a mean value of 4.58%. The soil organic content is between less than 0.17 and 2.10%, with a mean value of 0.59% and the NO^{-3} and NH^{+4} concentrations range from 33.33 to 266.67 mg/kg (mean:115.69 mg/kg) and from 5.93 to 230.89 mg/kg (mean: 28.23 mg/kg), respectively. The geotechnical characteristics of the waste dumping materials regard the cohesion with a value range c=0-10 kPa, internal friction angle, φ=22-35° and $\varphi_{residual}$= 10-20°. The unconfined compression strength (Q_u) ranges from 50 to 150 kPa, while the undrained shear strength (C_u) ranges from 25 to 75 kPa.

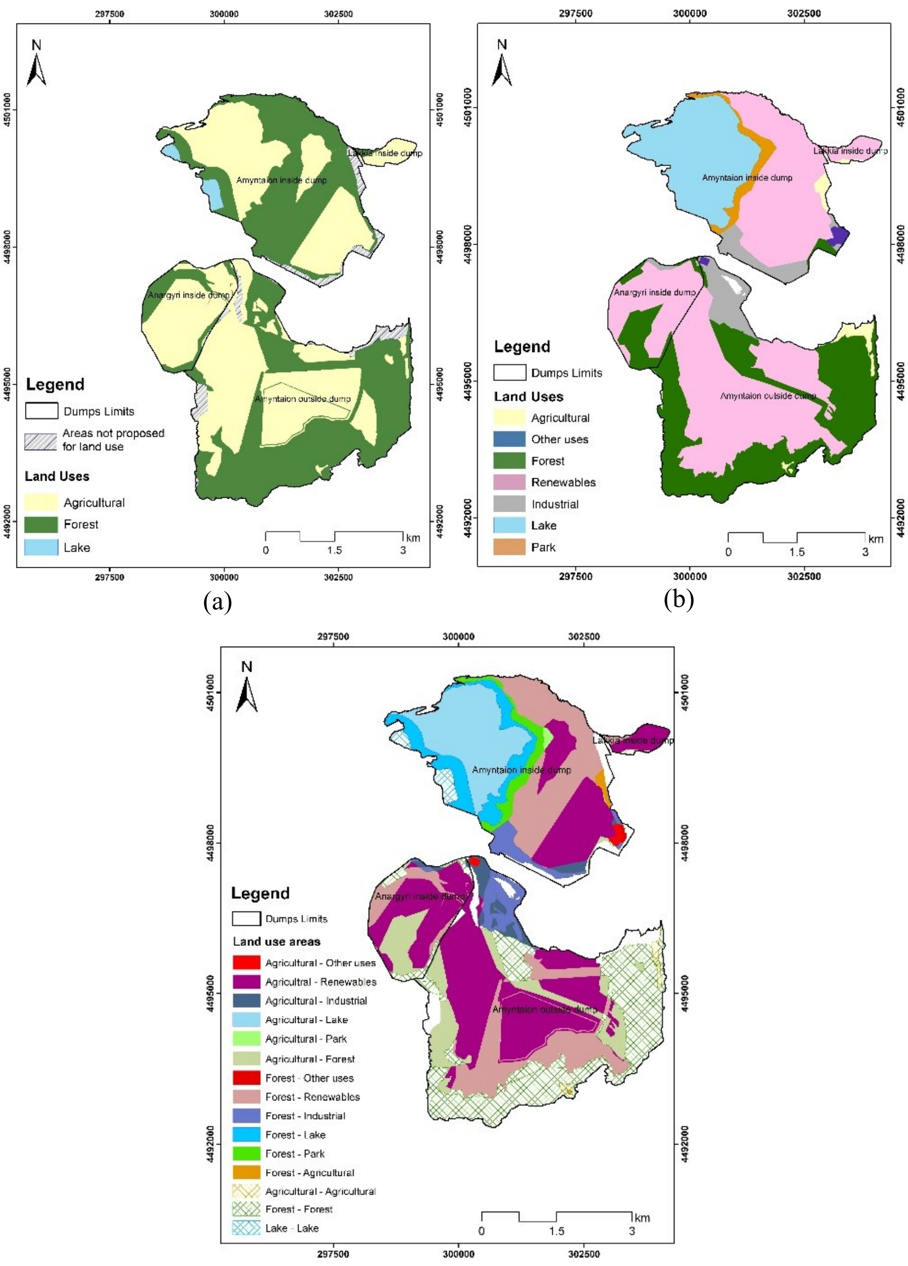


Fig. 12. (a) Land uses according to an old planning, (b) new land uses according to a transition development plan, (c) Overlay of the two land uses plans (only waste dumping sites of the Amyntaion mine)

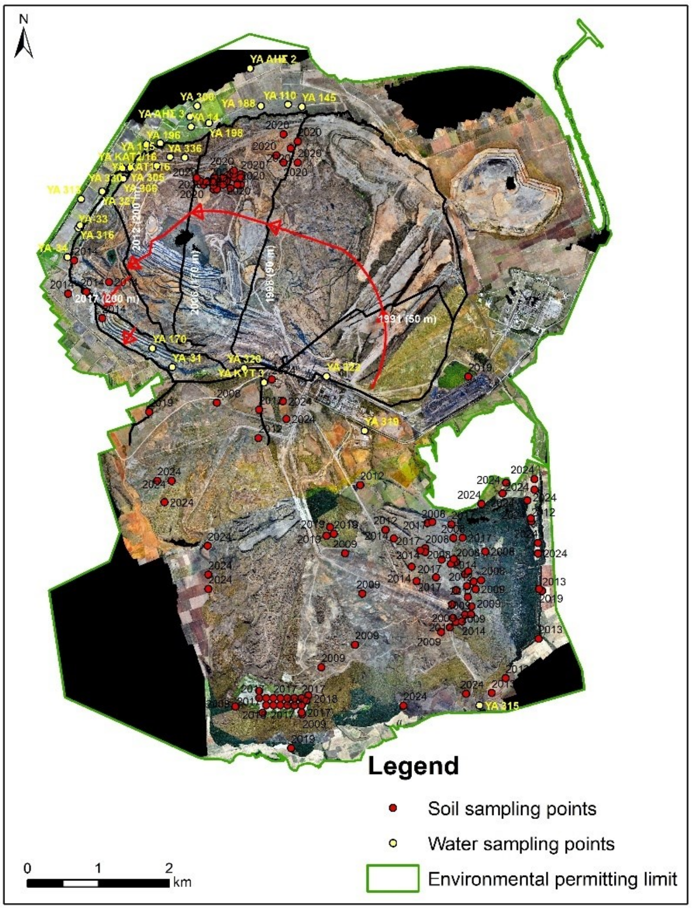


Fig. 13. Experimental design of water and soil sampling and monitoring program (the year in the soil sampling points denotes the starting year of the sampling)

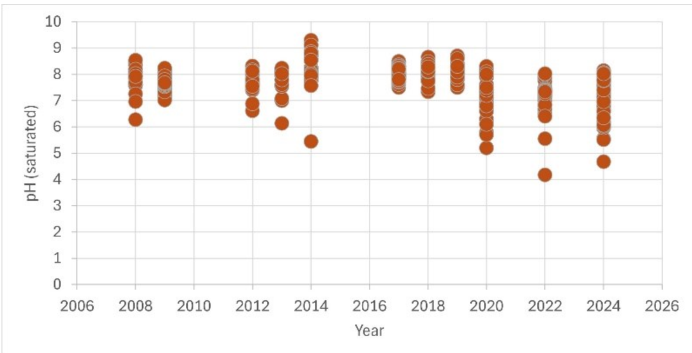


Fig. 14. pH values resulted from soil sampling

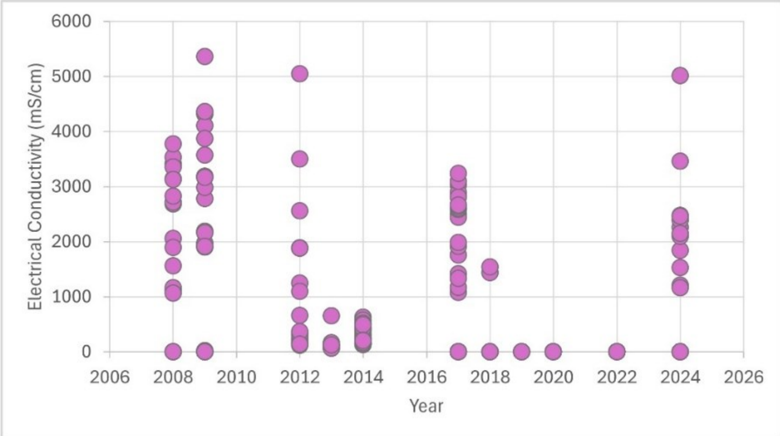


Fig. 15. Electrical conductivity values (mS/cm) resulted from soil sampling

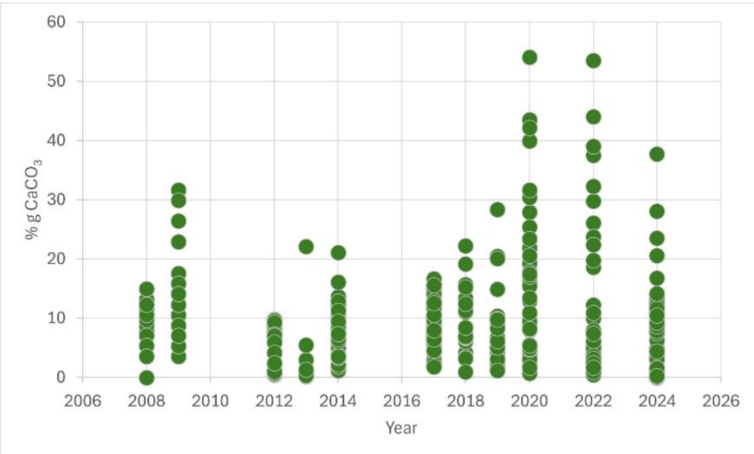


Fig. 16. $CaCO_3$ (%) values resulted from soil sampling

Regarding the groundwater quality, indicative results are shown in Figures 17-21. The results showed that the physicochemical parameters (pH, electrical conductivity, As, Cd, Pb, Hg, Ni, Cr, nitrates, chloride and sulfate ions, ammonium) concentration are inside the legislation's thresholds. For instance, the pH values range from 7 to 8.3, and the electrical conductivity ranges from 500 to 2000 μS/cm, while the bottom and upper threshold for pH are 6.5 and 9.5, respectively, and the upper threshold for electrical conductivity is 2500 μS/cm [10].

From the environmental aspect, all the procedures follow the Approved Environmental Terms. For example, the priority of dumping procedures is to fill the created voids in the exhausted mines and then start the outside dumping. The study of Pavloudakis et al. [19] showed that the air quality parameters correlate better with the total excavations than with the lignite production. In addition, this study showed that the excavation pits and the dumps of Amyntaion mines are unlikely to cause many pollution episodes.

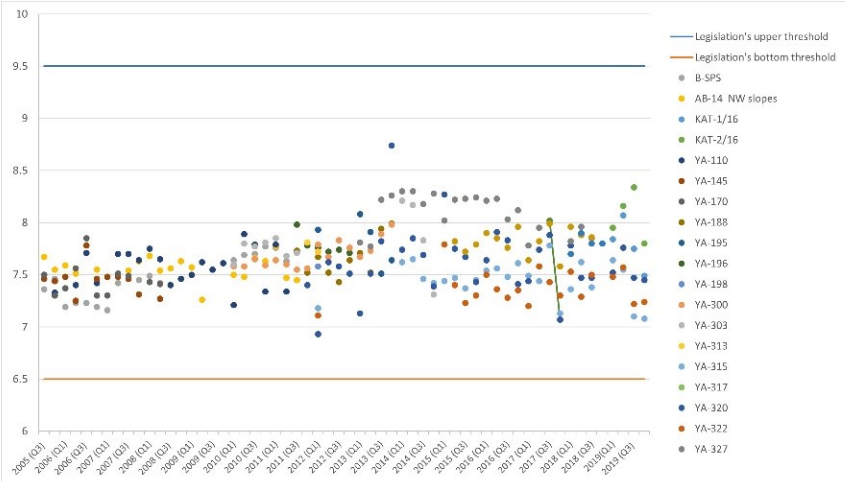


Fig. 17. The values variance of pH resulted from water sampling in water boreholes

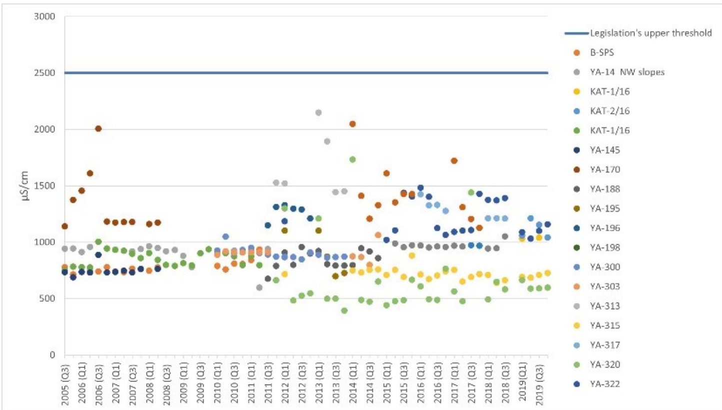


Fig. 18. The values variance of electrical conductivity resulted from water sampling in water boreholes

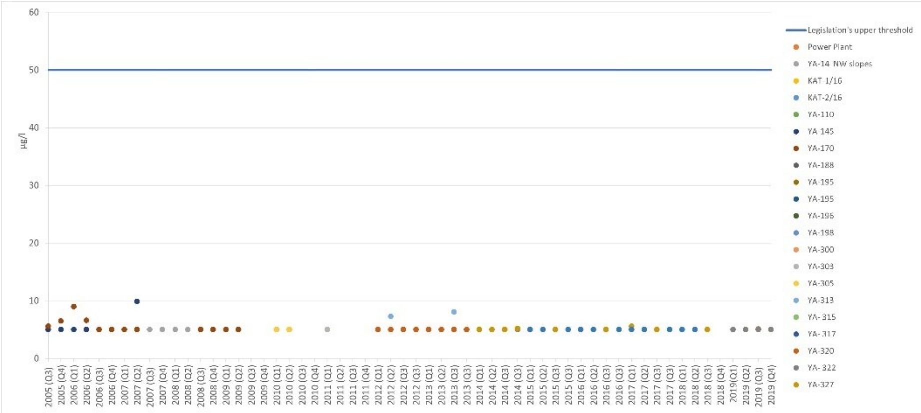


Fig. 19. The values variance of total Cr resulted from water sampling in water boreholes

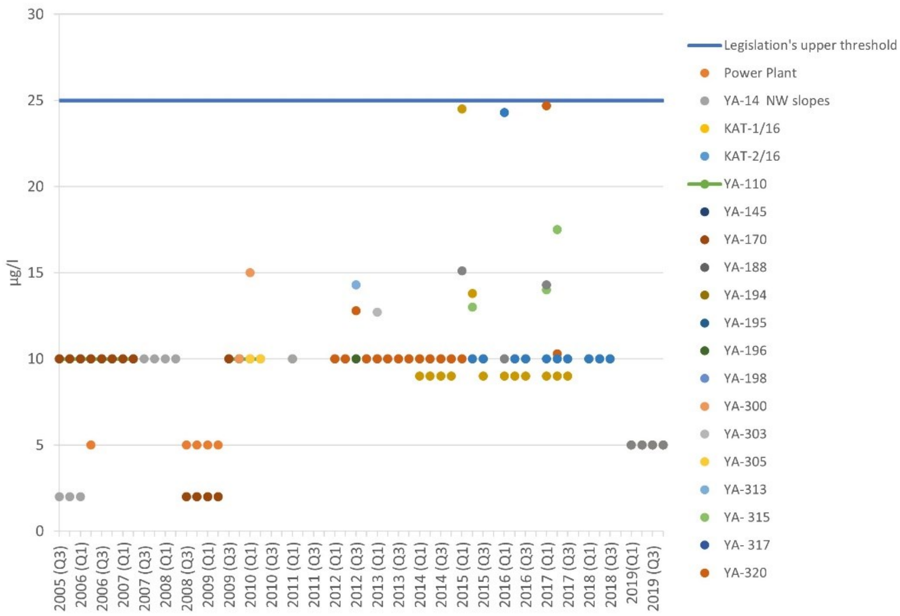


Fig. 20. The values variance of Pb resulted from water sampling in water boreholes

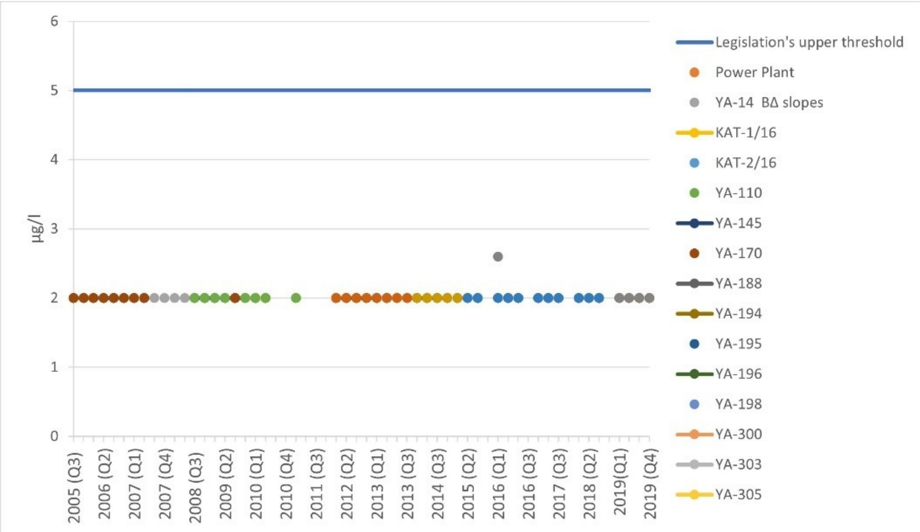


Fig. 21. The values variance of Cd resulted from water sampling in water boreholes

From the results of the soil and water sampling analysis and the geotechnical, hydrogeological, geochemical, and other environmental parameters, the various land uses of post-mining areas are planned based on their suitability to the transition to post-mining activities, emphasizing renewable energy projects. The decision-making process was based on the physical, chemical, biological, and hydrological and hydrogeological stability of the final excavations faces and waste materials dumping sites, as well as on socio-economic considerations. In addition, the transformation of the mining areas to new land uses incorporates circular economy concepts, considering the optimal exploitation of the final topography of the mining areas.

4 Conclusions

Sustainable post-mining waste management in continuous surface coal mines based on circular economy concepts is an essential part of mine closure planning towards a transition to other land uses of mining lands. The planning and scheduling of post-mining activities follows the early stages of strategic mine planning, based on the optimal allocation of the waste material into the outside and inside dumping areas. The success of the long-term mine planning and the following short-term modifications can be validated by suitable mine scheduling models. In the investigated case study of the Amyntaion mine, the physical, chemical, biological, geotechnical, hydrological and hydrogeological stability of the final excavations faces and waste materials dumping sites can be based on a carefully designed sampling and monitoring program. The circular economy principles adopted for this study are based mainly on the utilization of the dumping materials and on the suitable spatial arrangement of the reclamation works which favor the alternative uses, placing emphasis on renewables in combination with other uses ensuring the biodiversity of the broader mining area.

References

1. Pavloudakis, F., Roumpos, C., Spanidis, PM.: Planning the Closure of Surface Coal Mines Based on Circular Economy Principles. Circ.Econ.Sust. 4, 75–96. https://doi.org/10.1007/s43615-023-00278-x (2024)
2. Fecko, P.; Tora, B.; Tod, M. Coal Waste: Handling, Pollution Impacts and Utilization. In The Coal Handbook: Towards Cleaner Production; Elsevier, 2013; pp. 63–84 ISBN 978-1-78242-116-0 (2013)
3. Eurostat: Total Amount of Waste Generated by Households and Businesses by Economic Activity According to NACE Rev. 2, Mining and Quarrying, (2020)
4. Ru-yin, L., and Xiao-ting, Z.: Negative Entropy Mechanism of the Circular Economy Development Countermeasures in Mining Area. Procedia Environ. Sci. 1 (1): 1678–85. https://doi.org/10.1016/j.proeps.2009.09.258 (2009)
5. Aznar-Sánchez, J., García-Gómez, J., Velasco-Muñoz, J., Carretero-Gómez, A.: Mining Waste and Its Sustainable Management: Advances in Worldwide Research. Minerals 2018, 8, 284, doi:10.3390/min8070284 (2018)
6. Pavloudakis, F., Roumpos, C., Karlopoulos, E., Koukouzas, N.: Sustainable Rehabilitation of Surface Coal Mining Areas: The Case of Greek Lignite Mines. Energies 2020, 13, 3995, doi:10.3390/en13153995 (2020)
7. Kalisz, S., Kibort, K., Mioduska, J., Lieder, M., Małachowska, A.: Waste Management in the Mining Industry of Metals Ores, Coal, Oil and Natural Gas - A Review. J. Environ. Manag 2022, 304, 114239, doi:10.1016/j.jenvman.2021.114239 (2022)
8. European Commission: Circular Economy Action Plan for a Cleaner and More Competitive Europe (2008)
9. Kirchherr, J., Reike, D., Hekkert, M.: Conceptualizing the Circular Economy: An Analysis of 114 Definitions. Resour. Conserv. Recycl. 2017, 127, 221–232, doi:10.1016/j.resconrec.2017.09.005 (2017)
10. European Commission. Directorate General for Environment., Vito: Study Supporting the Development of General Guidance on the Implementation of the Extractive Waste Directive: Final Report.; Publications Office: LU (2021)
11. Sokratidou, A.; Roumpos, C.; Paraskevis, N.; Servou, A.; Pavloudakis, F. Extractive Waste Management in Coal Surface Mining Projects—A Circular Economy Approach. Mater. Proc. 2023, *15*, 13. https://doi.org/10.3390/materproc2023015013 (2023)
12. Garbarino E., Orveillon G., Savey H.G.M, Barthe P. & Eder P.: Best available techniques (BAT) reference document for the management of waste from extractive industries, in accordance with Directive 2006/21/EC. JRC science policy report EUR28963 (MWEI BREF). Available at: http://publications.jrc.ec.europa.eu/repository/bitstream/JRC109657/jrc109657_mwei_bref_-_for_pubsy_online.pdf (2018)
13. Vo, T.L., Nash, W., Del Galdo, M., Rezania, M., Crane, R., Nezhad, M.M., Ferrara, L.: Coal mining wastes valorization as raw geomaterials in construction: A review with new perspectives, J. Clean. Prod., 336, 130213, https://doi.org/10.1016/j.jclepro.2021.130213 (2022)
14. Mborah, C., Bansah, K.J. Boateng, M.K.: Evaluating alternate post-mining land-uses: A review. Environ Pollut, *5*(1), pp.14-22 (2016).
15. Al Heib, M., Cherkaoui: A. Assessment of the Advantages and Limitations of Installing PV Systems on Abandoned Dumps. Materials Proceedings, *5*(1), 68. https://doi.org/10.3390/materproc2021005068 (2021)
16. Tengler S, Sehnal D.: Method of Solving the Volume Between Triangulated Mesh Surfaces. In: Świątek J, Borzemski L, Grzech A, Wilimowska Z, editors. Information

Systems Architecture and Technology: Proceedings of 36th International Conference on Information Systems Architecture and Technology – ISAT 2015 – Part III, vol. 431, Cham: Springer International Publishing; 2016, p. 53–62. https://doi.org/10.1007/978-3-319-28564-1_5 (2016)

17. Yilmaz N. Volume Calculation Through Using Digital Elevation Models Created by Different Interpolation Methods. FIG Congress 2018, Embracing our smart world where the continents connect: enhancing the geospatial maturity of societies, Istanbul, Turkey (2018)
18. Ministry of Environment and Energy. (2020). Just Transition Development Plan of lignite areas. https://www.sdam.gr/sites/default/files/consultation/Master_Plan_Public_Consultation_ENG.pdf
19. Pavloudakis, F., Sachanidis, C., Roumpos, C.: The Effects of Surface Lignite Mines Closure on the Particulates Concentrations in the Vicinity of Large-Scale Extraction Activities. Minerals 2022, 12, 347, doi:10.3390/min12030347 (2022)