Volume 22 | Issue 4 Article 2

2023

Multi-criteria analysis of the possibility of retrofitting the system of rainwater drainage from subsidence basins in a liquidated mine

Author(s) ORCID Identifier:
Andrzej Chmiela: 0000-0002-0833-0923
Małgorzata Wysocka: 0000-0002-1538-1294
Adam Smoliński: 0000-0002-4901-7546

Recommended Citation

Chmiela, Andrzej; Wysocka, Małgorzata; and Smoliński, Adam (2023) "Multi-criteria analysis of the possibility of retrofitting the system of rainwater drainage from subsidence basins in a liquidated mine," *Journal of Sustainable Mining*: Vol. 22 : Iss. 4 , Article 2.
Available at: https://doi.org/10.46873/2300-3960.1395

Multi-criteria analysis of the possibility of retrofitting the system of rainwater drainage from subsidence basins in a liquidated mine

Abstract

Mine closure is the natural final stage of mining activity. The process of financing mine liquidation is complex and expensive. The many years of conducted hard coal extraction affect the surface height differences. Analyses of the shifts in hydrogeological conditions and water hazard states in mining plants led to legal regulation adaptations, primarily in terms of hydrogeological documentation preparation, and made it necessary to conduct work concerning new options for water hazard assessment and prevention. Current subjects of particular interest include shifts in terrain morphology and the water regime, resulting in periodic flooding and permanent flooding of the most depressed areas as well as changes in the directions and intensity of surface water flows. This publication presents a multi-criteria analysis of the possibility of reducing the liquidation costs of an inactive mine through the retrofitting of the existing system of rainwater drainage from subsidence basins. The analysis revealed the primary factors disrupting the course of the drainage process and the problems resulting from them. Technically feasible solutions is presented, together with their assessment. Applying the multi-criteria analysis made it possible to select optimal solutions from a group of proposed technical system retrofitting variants

Keywords

multi-criterial analysis; restructuring of mining enterprises; hard coal mine liquidation; water management

Creative Commons License

Multi-criteria analysis of the possibility of retrofitting the system of rainwater drainage from subsidence basins in a liquidated mine

Andrzej Chmiela [a], Małgorzata Wysocka [b],*, Adam Smoliński [c]

[a] Spółka Restrukturyzacji Kopalń S.A., Poland
[b] Główny Instytut Górnictwa, Silesian Centre for Environmental Radioactivity, Poland
[c] Główny Instytut Górnictwa, Spółka Restrukturyzacji Kopalń S.A., Poland

Abstract

Mine closure is the natural final stage of mining activity. The process of financing mine liquidation is complex and expensive. The many years of conducted hard coal extraction affect the surface height differences. Analyses of the shifts in hydrogeological conditions and water hazard states in mining plants led to legal regulation adaptations, primarily in terms of hydrogeological documentation preparation, and made it necessary to conduct work concerning new options for water hazard assessment and prevention. Current subjects of particular interest include shifts in terrain morphology and the water regime, resulting in periodic flooding and permanent flooding of the most depressed areas as well as changes in the directions and intensity of surface water flows. This publication presents a multi-criteria analysis of the possibility of reducing the liquidation costs of an inactive mine through the retrofitting of the existing system of rainwater drainage from subsidence basins. The analysis revealed the primary factors disrupting the course of the drainage process and the problems resulting from them. Technically feasible solutions is presented, together with their assessment. Applying the multi-criteria analysis made it possible to select optimal solutions from a group of proposed technical system retrofitting variants.

Keywords: multi-criteria analysis, restructuring of mining enterprises, hard coal mine liquidation, water management

1. Introduction

Industrial activities, urbanisation and population growth, have affected the hydrological conditions of urban areas. This results in risks associated with both land flooding and the scarcity of drinking water [1]. For example, the risk of urban flooding during periods of heavy rainfall is increasing, while on the other hand, certain areas are suffering from shortages of drinking water due to the drying up of aquifers, chemical or biological pollution. Severe meteorological phenomena caused by climate change often make it difficult to manage water resources. Therefore, various measures are being taken to mitigate the effects of dangerous and adverse phenomena. The management of water resources, taking into account rapid climatic phenomena and their consequences – floods and periods of hydrological drought – is part of modern land-use planning [2–9]. Rational water management, taking into account different water saving measures, can have a positive impact on the quality of life in highly urbanised areas and reduce costs for the inhabitants [10–12]. In recent years, measures known as rainwater harvesting have been introduced to conserve water and reduce flood episodes [13–17]. At the same time, urban planners are proposing better drainage and water retention systems, taking into account the safety of residents in the event of climatic disasters [18–24]. One of the adverse impacts of mines on natural watercourses is the discharge of saline water containing elevated levels of harmful substances [25–27]. Mining activities have caused and perpetuated for decades the management of local catchments. Mine closures

---

Received 26 June 2023; revised 31 July 2023; accepted 5 August 2023.
Available online 10 October 2024

* Corresponding author.
E-mail address: mwysocka@gig.eu (M. Wysocka).

https://doi.org/10.46873/2300-3960.1395

change the way and intensity groundwater discharge into surface watercourses, forcing analysis and planning of the best solutions. Underground deposit extraction affects the environment both during the actual mining activity as well as after a mining plant is liquidated. The most common form of this influence includes mining land deformations [28,29]. Deformations always accompany deposit extraction, regardless of the geological and mining conditions of the conducted activity. Rock mass deformations affect shifts in the water regime [30]. Terrain subsidence results in the formation of subsidence basins, flooding areas and soil desiccation zones as well as changes to the directions and intensity of surface and groundwater flows [31,32]. Shifts in hydrogeological conditions constitute one of the most significant hazards pertaining to mine liquidation. The most important factor preventing this hazard is the efficiency of the water drainage system. When planning the retrofitting of hydrotechnical systems, it is necessary to examine the contaminants, including radioactive pollutants, released into the environment together with mine water. Furthermore, it has to be considered that most rivers and watercourses in heavily urbanized and industrial land have lost their natural character [26,27,33,34]. In the Upper Silesian Coal Basin in Poland (USCB), the majority of the existing 30 hard coal mines will be closed in the coming years. Heavily urbanized post-mining areas struggle with all the hydrological, climatic and environmental problems described above. In addition, local decision-makers and local administrations must rationally plan and design systems for the discharge of mine water into the environment, as the mines will be drained for many years after their closure. The alternative solutions for the management of the pumping station system in the selected area of the USCB presented in this article are an example of the search for new tools to support local institutions responsible for the hydrological condition and safety of the inhabitants of post-mining areas. This publication presents an example analysis of the possibility of retrofitting water drainage from subsidence basins on the example of a selected Branch of SRK S.A. (*Spółka Restrukturyzacji Kopalń S.A.*, Mine Restructuring Company). In the case of the described Branch of SRK S.A., the most significant problems occur in areas that are depressed relative to the beds of potential receivers, such as a river or other adjacent watercourses. These areas are at risk of flooding, particularly during sudden rainwater-related freshets. Currently, no soil contamination or desiccation resulting from surface deformations was reported in the Branch selected for analysis.

The Branch maintains a system of seven rainwater pumping stations in depressed subsidence basins. About 2.46% of the expenditures related to the Branch liquidation is spent annually on maintaining and operating the pumping stations. A significant part of the expenditures is spent on repairs of damage caused by flooding. During periods of heavy precipitation, technical problems resulting from the limited efficiency of the pumping equipment may lead to an increased flooding risk.

2. Materials

2.1. Study area description

The analyzed Branch is one of the biggest branches of SRK S.A. The mine, now constituting the Branch of SRK S.A., with a current surface area and mining area of 28.4 km^2, was established at the end of the 19th century. Over this period, reserve mining panels were identified, and two ventilation shafts were established through the excavations driven west of mine “G”. In 1913, the mine extracted its first million tons of coal. As the shallow-deposited beds were becoming depleted, extraction proceeded to increasingly greater depths and moved southward. In 2016, after extraction was concluded, the mine was closed and transferred to Spółka Restrukturyzacji Kopalń S.A. The mine was a multilevel plant with a stone and coal working layout, developed via five shafts (three mining and two ventilation shafts), with a 90,059.67 m-long network of gallery excavations on three active levels. The Branch is being restructured through a model involving repurposing a part of the excavations and establishing a regional pumping station for draining adjacent mines. This will involve repurposing 2 shafts and about 10 km of underground excavations. The Branch employs about 200 people: 68% underground and 32% on the surface [35].

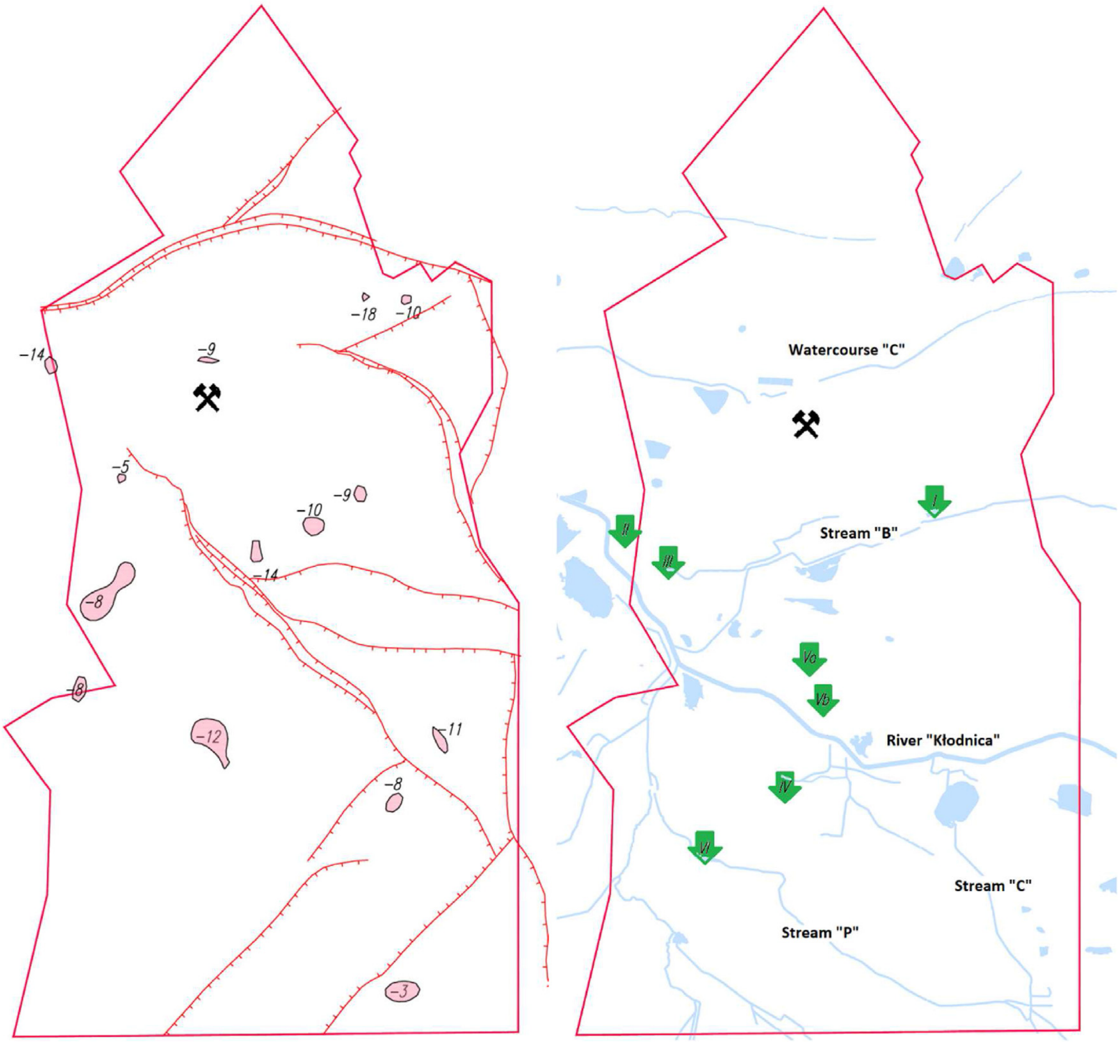
2.2. Deformations resulting from mining activity within the study area

Terrain deformations caused by the prior mining activity often resulted in the generation of subsidence basins [36]. The current terrain morphology of the Branch's mining land should be considered unchanging, given the conclusion of mining activity in 2016. Increases in mining-related terrain subsidence have ceased, and, therefore, the conducted analyses are not burdened with errors resulting from the occurrence of residual terrain subsidence [28,29].

The primary factor influencing the shape of the area subjected to the analysis was terrain subsidence. About 90% of the mining area was within the range of the conducted mining activity's influence. Terrain deformations of influence categories I–IV occurred in the area, particularly subsidence troughs. Fig. 1 presents the regions with the greatest subsidence resulting from underground deposit extraction. These regions stretch over four lines overlapping with the runs of the primary watercourses of the Branch's mining area. The north line converges with WaterCourse “C”, the central line runs together with Stream “B”, the south line is concurrent with the course of the river, and the area by the south border is related to Stream “P”. The presented regions are merely the floors of local subsidence troughs, whereas the combined local subsidence troughs form the general subsidence trough of the Branch. After filling with water, depressed developed areas transform into swamps and peat bogs, after which they become idle land. A number of surface water pumping stations are located within the range of the Branch’s mining influence, draining surface and groundwater from subsidence basins.

The following measures have been used thus far to counteract the effects of excess terrain subsidence within the mining area/limits of the Branch.

- regulating the river and its tributaries through the construction of levees, dredging the watercourse beds, and in the case of Stream “B”,



a. Graphical presentation of areas with maximum terrain subsidence

b. Pumping station locations displayed over watercourses

Fig. 1. The mining area of the Branch, showing terrain deformations (a) and the catchment area of the Klodnica River with the location of the mine water pumping station marked (b) (source: own study).

rerouting its bed at the mouth section at a length of about 1.5 km,

- building drainage ditches and dredging existing land amelioration infrastructure,
- creating new water reservoirs,
- backfilling depressed basins and restoring terrain morphology to reestablish correct water flows,
- building rainwater pumping stations.

2.3. Hydrological characteristics of the study area

The primary watercourse in the study area is a river, whose source is within the administrative borders of Katowice − see Fig. 2. The river length, from the source to where it flows into the Oder, is 75.3 km, while a section of 3.9 km runs through the Branch's mining area. Over this section, the water runs southwest, and the river bed is regulated and bunded on two sides to a height ranging from 1.5 m to 8.0 m relative to its bottom. The slope of the river bottom is negligible over nearly the entire section in the mining area. Consequently, the water table exhibits a minimum flow as a result of the water swelling in the lower river section, which may lead to the generation of considerable sedimentation in this location in the future. The river is fed by three streams.

Stream "C", with a catchment area of 75 km^2. The bed of this stream is bunded on two sides in the mouth area to a height similar to the river levees. Such measures secure the adjacent land from swelling stream waters and river backwater, but this transfers the hazard in question to the upper section of the stream, resulting in local flooding.

The waters of **Stream "P"**, with a length of about 3.9 km and a catchment area of about 2.7 km^2, are pumped to the stream bed in their entirety in its lower course, where the pumped waters can flow by gravity. Water pumping station VI was established in the lowest-situated point of the basin generated as a result of post-mining terrain settling. Water from the station is pumped to the bed of this stream via four ø 450 pipelines and then flows into the river after about one kilometer.

The waters in **Stream "B"** flow westward. A fragment of the stream bed in the Branch's mining area is bunded on two sides. The levee elevation ranges from 226.0 to 224.0 m a.s.l., whereas the terrain elevation at the northland side of the levee ranges from 223.0 to 220.5 m a.s.l., which necessitated the construction of rainwater pumping station I on the right land side of the levee. Due to the surface height difference, the stream bed was rerouted to its current state over its entire section up to where it flows into the river.

2.4. Subsidence basin drainage system

All the pumping stations located in the Branch's mining area are situated within subsidence basins generated as a result of mining activity. They are also in the catchment area of the river. The pumping stations discharge water directly to the river or to its tributaries: Stream "B" or Stream "P". A system of seven surface water pumping stations is maintained in the area of the Branch. Two of these are situated in the south river catchment area, and the rest are in the north catchment area.

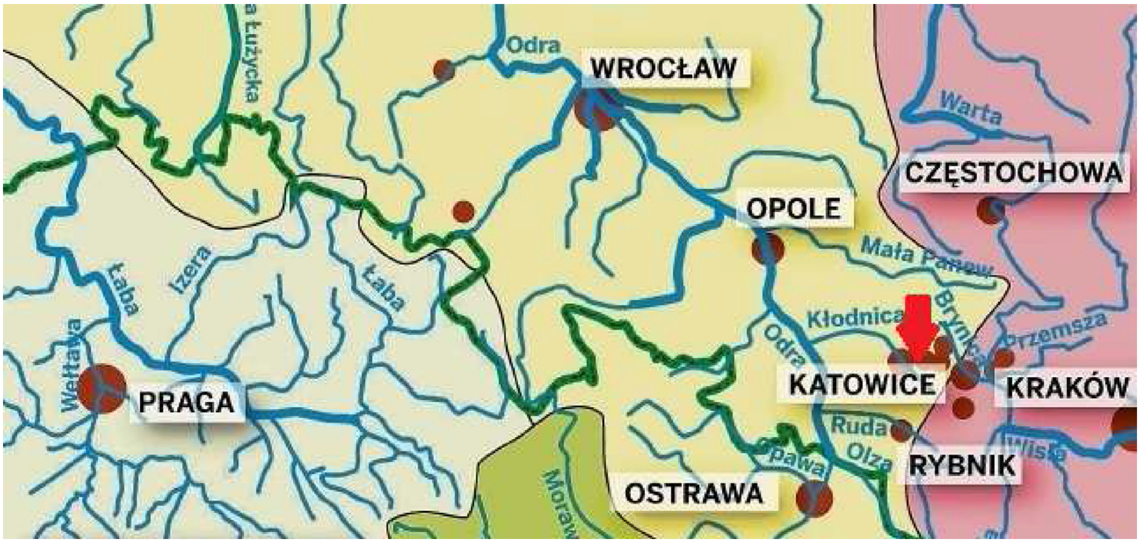


Fig. 2. The Branch location.

2.4.1. Pumping station I

This pumping station is responsible for maintaining the correct water regime in the southern part of the city district. It is established on the right, north land side of the Stream “B” levee. Pumping station I consists of two reservoirs connected by a culvert enabling the flow of the water from the west reservoir to the east. Urban sewage system pipes were introduced only into the east reservoir. From the east reservoir, the water flows into a reinforced concrete intake well, from where it is pumped towards Stream “B”. The pumping station operates two pumps with outputs of 1000 m^3/h and 480 m^3/h.

2.4.2. Pumping station II

The pumping station is located about 500 m northwest of pumping station III, described below. It is equipped with a single reservoir. The water table of the river, located about 50 m west, is higher than the reservoir outlet level by about 3.0 m, which makes the gravitational discharge of the water from the drainage area to the river impossible. The terrain becomes lower towards pumping station III, which indicates that rainwater pumping station II is ineffective, as the water can be discharged by gravity only via an open ditch or an underground sewage pipeline. The drainage area serviced by the pumping station is about 0.9 km^2. Pumping station II operates two pumps with outputs of 600 m^3/h and 220 m^3/h. The water from the reservoir is pumped directly into the river via an underground pipeline.

2.4.3. Pumping station III

Pumping station III is established on the bank of the previous bed of Stream “B”. The pumping station intake well was constructed at the lowest-situated point at the bottom of the watercourse. The pumping station drainage area is 1.5 km^2. The station is equipped with submersible pumps with a total pumping output of 1680 m^3/h. The water from the intake well is pumped to the river via a pipeline.

2.4.4. Pumping station IV

Pumping station IV, established on the slope of a spoil bank, enables the maintenance of water flows down the bed of a perimeter drainage ditch that serves to drain the central part of the south river catchment area. The pumping station intake well is situated in the collector pit of the drainage ditch, from where the water is pumped to a reservoir at the top of a reclaimed land area. The water flows towards the area of the spoil bank slope by gravity via a ditch constructed on the spoil bank surface. Afterwards, it flows further towards the river bed via a ø 600 pipeline. The pumping station is equipped with seven submersible pumps with a total pumping output of 1660 m^3/h and services a drainage area with a surface of about 2.0 km^2.

Usually, the water flowing to the intake well is collected in its entirety, yet minor periodic flooding has been found as well. Upgrading the pumping capabilities of the site should be considered in the future to prepare for the potential occurrence of intense rainfall or increased water inflows.

2.4.5. Pumping stations Va and Vb

Pumping stations Va and Vb are located on the north slope of an area at the right river bank, which was levelled and reclaimed using waste rock. These stations are used almost exclusively to drain woodland areas. The pumping station drainage area, with a surface of about 2.2 km^2, is limited from the west and north by the catchment area watershed of Stream “B”, and in the east, it is confined by a road frame. The natural water flow south towards the river is made impossible by high bunds and a reclaimed elevated area. The inflowing rainwater is pumped by these stations.

Pumping station Vb is situated on the slope of the reclaimed elevated area, and the water pumped by it is discharged to the river via a ø 160 pipeline. It is equipped with a single submersible pump with an output of 200 m^3/h. The water from the intake well is pumped to a ditch at the top of the reclaimed elevated area, after which it flows toward the river by gravity. Pumping station Va is located about 400 m southwest of pumping station Vb. It is equipped with two pumps with a total pumping output of 400 m^3/h. The water from pumping station Va is discharged via a ø 300 pipeline to the ditch at the top of the reclaimed area and then to the river by gravity.

2.4.6. Pumping station VI

Pumping station VI transfers the water flowing in from the upper, depressed bed of Stream “P” towards a higher-situated section of that Stream’s bed in its lower course. Two reservoirs were constructed on Stream “P” above pumping station VI to collect excess water during thaws or particularly intense rainfall. The total reservoir volume is estimated at about 16 m^3. Pumping station VI is equipped with four pumps with a total pumping output of 3456 m^3/h, which pump the inflowing water down the stream via four ø 1400 pipelines, after which the water flows freely into the river. The surface of the serviced drainage area is about 2.5 km^2.

A pause in pumping or a malfunction of the pumping station may result in flooding. This necessitates the continuous transfer of the water from Stream “P” towards its lower section.

3. Methods

A technical analysis of the possibility of liquidation of the existing pumping stations was performed, factoring in the necessity to maintain the correct water regime as well as the costs of such a project. A multi-criteria rainwater pumping station liquidation variant assessment was applied, factoring in all the assessment criteria combined. Data from geodesic surveys in the area of the watercourses and the surface pumping stations were updated. For all geodesic measurements, it was assumed that the measurement error (specific to the devices used) does not exceed 0.05 m.

Supporting solutions used in other countries, the design and cost estimation documentation for establishing the gravitational water flow to the watercourses was updated and adapted as well [37,38].

The analyses utilized the results of regular and additional geodesic surveys of lines of observation located in the mining area of the Branch, as conducted by geodesic services. Topographical geodesic surveys (Fig. 1) were performed to determine the topographic parameters of major watercourses in the mining area of the Branch, which include: the river, Stream “B”, Stream “C”, Stream “P”, and WaterCourse “C”. A lithological analysis of the overlay and aquifer strata was performed based on data obtained from boreholes located in the study area.

The necessary budget that would allow the liquidation of the pumping stations and the establishment of gravitational subsidence basin drainage was estimated and updated. Afterwards, the optimal variants for rainwater pumping station liquidation were selected by means of a multi-criteria analysis.

3.1. Proposed pumping station liquidation variant assessment criteria

It was assumed that the rainwater pumping station system concept should be prepared in a way enabling the automated operation of the remaining pumping stations under the supervision and control of the Branch’s operation dispatcher. The operation and maintenance would be entrusted to an external company. Furthermore, the final rainwater pumping station system concept should factor in the economic, technical, ecological and social aspects related to the accomplishment of the project. A survey was conducted among 12 experts to improve the selection of factors. In the first stage, the experts, selected among professionals in the supervision and accomplishment of tasks related to water regime regulation in active and liquidated mining plants, were presented with a preliminary list of assessment criteria for the liquidation of rainwater pumping stations in subsidence basins. The respondents were asked to add any assessment criteria of such a task to the list they thought were missing. The thus modified list of rainwater pumping station liquidation project assessment criteria was presented to the same experts again. They were asked to weigh all the criteria using a scale of 0–10. A weight of 0 was adopted for criteria an expert would deem unimportant and a weight of 10 for criteria deemed very important. The final list of assessment criteria with their weighting is presented in Table 1.

The multi-criteria assessment of the adopted rainwater pumping station liquidation variants consists in obtaining a comprehensive analysis of the studied problem that factors in all the liquidation variant assessment criteria combined. The obtained index reveals the “distance” of an analyzed variant from a hypothetical ideal variant characterized by optimal parameters among the studied variant group. In the applied quotient transformation, the analyzed parameters should be classified into groups according to their character [28,29]. In this method, the analyzed parameters are divided into parameters of a “stimulant” character, whose absolute value increase is regarded positively, “destimulant”, whose increase in value is regarded negatively; and “nominant”, whose increase in absolute value is regarded in positive or negative ranges. In the studied example, the criteria: “Expenditures for the project”, “Expenditure payback period”, and “Project accomplishment time”, for which an increase in absolute value is regarded negatively, were assigned the character of “destimulants”. For criterion 3, “Drain well surface”, an increase in the absolute value is regarded positively, therefore, this criterion was assigned the character of a “stimulant”. In a multi-criteria analysis, each assessment criterion is assigned a weight that influences the final result. The weights for individual assessment criteria are presented in Table 1.

Table 1. Rainwater pumping station liquidation project assessment criteria (source: own study).

	Criterion	Unit	Weight
Criterion 1	Expenditures for the project	PLN	0.275
Criterion 2	Expenditure payback period	years	0.253
Criterion 3	Drain well surface	m^2	0.276
Criterion 4	Project accomplishment time	years	0.195

The quotient transformation method applied in the multi-criteria analysis eliminates the problem of a potential difference in the analyzed parameter units and the difference in the absolute values of the numbers that describe the individual parameters by expressing the obtained values of the individual parameters as a dimensionless number ranging from 0 to 1 [39,40]. The multi-criteria analysis is conducted according to the following formula:

$$FC_j = w_1\frac{h_{i\,\min}}{h_{1j}} + w_2\frac{h_{i\,\min}}{h_{2j}} + w_3\frac{h_{3j}}{h_{i\,\max}} + w_4\frac{h_{i\,\min}}{h_{4j}} \tag{1}$$

where:

FC_j value of the multi-criteria analysis for variant j,

i - number of the liquidation variant assessment criterion,

j - number of the liquidation variant,

w_i - weight for criterion number i,

$h_{i\,\min}$ - the lowest value in criterion number i,

$h_{i\,\max}$ - the highest value in criterion number i,

h_{ij} - value in criterion i for variant number j.

In the calculations, the expenditures for different pumping station liquidation variants were expressed in study units, constituting a fraction of the annual expenditures required for the maintenance of the rainwater pumping station system in the Branch.

The most important sources of uncertainty of multi-criteria assessment in a decision-making context are: the choice of the attributes, standarisation method, weights, and conversion of values in attributes' original (natural) scale of measurement, prior to conversion to a standardised. In our work, the choice of evaluation criteria and the weights to these criteria are arbitrarily given by the experts, and the uncertainties arising from, for example, the standardisation of attribute sizes are not, in our view, relevant to the decision-making process. The final decision to choose an option is left to the decision-maker, who always makes the decision under uncertainty of its success. The decision-maker may choose the best option in his/her opinion in view of any evaluation criterion or agree with the results of the multi-criteria evaluation and choose the solution suggested in the method. The decision is also always a somewhat subjective process; therefore we have assumed that uncertainty does not affect the outcome of the multi-criteria analysis. The multi-criteria analysis is merely a tool that gives the decision-maker information to support him or her in making a decision, the consequences of which we do not yet know.

3.2. Technical feasibility analysis for pumping station liquidation

Maintaining the surface water pumping stations is costly and problematic. Even when operating under an automated control system, a pumping station still requires supervision and monitoring. A malfunction or inefficiency may quickly result in flooding. In the area of all the Branch pumping stations, the near-surface strata consist of clay or silt with very low filtration characteristics, which will fill up with water should pumping fail to be provided. Data obtained from a borehole located about 100 m northwest of the west reservoir of pumping station I was used to analyze the lithology of the Quaternary strata in its area. The borehole was drilled to a depth of 65.4 m from the surface. The presence of strata with high filtration potential was found in its profile, approximately below two meters, with a total thickness of about 56.5 m. In the case of pumping station VI, the analysis involved data obtained from a borehole located about 200 m south of the east reservoir. It was determined that the thickness of the first stratum with a high filtration capacity was about 25.0 m. Consequently, the construction of drain wells is possible only for pumping stations I and VI. In the areas of the remaining pumping stations, the contribution of filtering strata in Quaternary formations is under 50%, which makes the potential construction of drain wells impossible. For this reason, the complete liquidation of all the pumping stations appears unlikely, but retrofitting the existing rainwater pumping system may lead to measurable budgetary savings as well as to a restoration of the areas for purposes serving the local residents or the needs of the owners [41,42].

The stabilization of the rock mass movements resulting from the conclusion of mining activity makes it possible to present a final rainwater pumping station system model for the Branch [1,25]. The final model should factor in all the aspects related to the project, including the economic, technical, ecological and social aspects altogether.

3.2.1. Technical feasibility analysis for the liquidation of pumping station I

The gravitational discharge of rainwater from the reservoirs of pumping station I, located at about 217.60 m a.s.l., to the river, flowing about 1 m above the reservoirs, is impossible. Lower elevations are found only in the previous bed of Stream "B", located about 2.4 km away in the area of pumping station Va, about 2.2 km from the reservoirs. Making a connection by directional drilling is economically infeasible while making it by trenching is impossible due to the necessity of digging through a railway embankment and a highway.

Limiting the water pumping costs is possible only through the construction of drain wells directing the rainwater to a thick system of permeable strata deposited below an overlay of impermeable strata [43,44]. A hydrogeological analysis revealed the presence of Quaternary formations in the area, with favorable filtration characteristics and a thickness of about 55 m. The filtration capacity of the stratum as well as the surface water quantity and intensity, indicate that water management will be possible after performing a minimum of 4 boreholes in each reservoir of pumping station I. The boreholes should have a minimum cross-section of 4 m^2 and a minimum length of 6 m. Increasing these parameters will considerably improve the reliability of the proposed drain well system functioning [10,45].

3.2.2. Technical feasibility analysis for the liquidation of pumping station II

Pumping station II is situated at 218.0 m a.s.l., whereas the elevation of pumping station III, located about 500 m away, is 214.0 m a.s.l. The easiest solution for shutting down pumping station II is the gravitational discharge of the water towards pumping station III. Two variants for solving this issue were proposed. Variant 1/II assumes the performance of directional drilling towards the old bed of Stream "B". The length of the ø 600 pipeline will be about 510 m, and the average slope will be 4.9‰. Variant 2/II assumes the repurposing of an inoperative ø 1000 pipeline belonging to the local water and sewerage company, which will be used as a protecting tube for the transmission pipeline. This solution should be discussed with the water and sewerage company and then, if necessary, presented to the local administration [45–47].

3.2.3. Technical feasibility analysis for the liquidation of pumping station III

The intake well of pumping station III (the bottom of the previous bed of Stream "B") is situated at 210.0 m a.s.l. and is the lowest spot in the north catchment area of the river in the Branch's mining area. Water discharge is possible only through the performance of directional drilling toward the south catchment area of the river, directly to a reservoir drained by a pumping station belonging to an adjacent active mine. In this case, the planned ø 800 pipeline will be about 540 m long, with a slope of 3.7‰, and it will run about 5 m under the bottom of the river bed. The accomplishment of this variant (variant 3/III) will require the permission of the local government as well as the agreement of the mining company that owns the final pumping station with regard to the necessity of increasing the pumping station's power or upgrading it [18,48,49].

A possible solution for the problem of pumping water from pumping stations II and III (variant 3/III) is to shorten a part of the pipelines to the utmost minimum by constructing a collective well K-2 that would receive the water from pumping stations II and III flowing in via ø 600 pipelines with lengths of 400 m and 250 m. Directional drilling of ø 800 would need to be performed below the river bed at a section of about 140 m from well K-2 to well K-1.

3.2.4. Technical feasibility analysis for the liquidation of pumping station IV

Pumping station IV pumps water from an intake well with a bottom at the level of 210.8 m a.s.l. It is the lowest-situated point in the south catchment area of the river, and a gravitational discharge of the water would be possible only through the construction of a long and wide trench to a pumping station belonging to an adjacent mine (variant 1/IV). However, given that the adjacent mine conducts mining activity, the fact that the surface in the area of this pumping station is not stabilized as well as the considerable costs of such a project, this action is ineffective and economically infeasible. This solution could be considered after extraction in the adjacent mining plant has ceased.

Another variant 2/IV for the liquidation of pumping station IV is to flood an adjacent area of about 35 ha to a water table level of about 218.5 m a.s.l. and follow this up with the gravitational discharge of the water to the river [50]. Such a variant is economically and socially unfounded, as the buyout of the flooded real estate would require about 40 million PLN.

Due to the economic infeasibility of the proposed liquidation variants for pumping station IV, it is proposed to maintain the operation of this station until mining activity has ceased in the adjacent mine.

3.2.5. Technical feasibility analysis for the liquidation of pumping stations Va and Vb

Pumping stations Va and Vb drain woodland areas. Due to the significant water retention of the forests, the inflows into the intake wells of these pumping stations are not very high. The pumping stations are situated about 3 m and 6 m higher than pumping station IV, respectively. It is therefore suggested to shut down these pumping stations according to one of the following proposed variants. Variant 1/V involves the establishment of two water reservoirs located along the foot of the north spoil bank slope.

- reservoir I with a surface of about 46,000 m^2 and a volume of about 2.1 km^3;
- reservoir II with a surface of about 10,500 m^2 and a volume of about 3.7 km^3.

The water would be discharged from both reservoirs via pipelines inserted by directional drilling into the dredged and profiled perimeter drainage ditch of pumping station IV.

Terrain levelling to about 216.0 m a.s.l. is planned as part of variant 2/V, consisting in filling the terrain with earth bulk obtained from the ditch dredging. In this variant, a perimeter drainage ditch must be constructed at a section of about 550 m, from which the water will be discharged via two pipelines inserted by directional drilling into the perimeter drainage ditch of pumping station IV, similar as in variant 1/V.

3.2.6. Technical feasibility analysis for the liquidation of pumping station VI

Pumping station VI pumps out the water flowing in the stream from the lowest-situated point in its depressed bed. The water is pumped over a distance of 470 m downstream and discharged again into the non-depressed part of the same stream's bed, from where it flows towards the river by gravity. The mouth area section is at a level of about 218.75 m a.s.l. Stream "P" reaches the same elevation at a spot about 300 m away upstream from the storage reservoirs of pumping station VI, from where the level of the deep bed exhibits a relatively sharp increase. The construction of a gate is suggested in this spot to swell the water in the stream and enable its gravitational discharge via two ø 800 pipelines in order to upgrade the pumping station system (all variants). The planned pipeline slope would be about 0.5‰. Similarly, as in the case of water originating from the natural flow in the previous bed, excess flood waters would accumulate in the storage reservoirs, which suggests that the pumping station operation should be maintained. Its purpose would be to enable the periodic pumping of the water accumulated in the storage reservoirs towards the stream bed, in the lower part, outside the depressed zone. The pumping capacity of the station can be limited to perform this task, thereby reducing the costs of operation and power.

The possibility of constructing drain wells in the reservoirs should be considered when retrofitting the pumping station (variants 1/VI and 3/VI). According to the data obtained from the borehole located about 200 m south of the east reservoir, there is a sand batch with a thickness of 25 m below the clay stratum with a bed depth of 1 m. Should the absorptivity of the sand formations be confirmed by testing, it will be possible to consider the full liquidation of the pumping station or a significant limitation of its equipment. It is proposed to construct four additional boreholes, with cross-sections of 9 m^2, responsible for channeling (to ground) rainwater originating from surface runoff, at the section between the gate and the culvert. Additionally, the wells would enable the discharge of overflow water through the gate, which is particularly significant during periods of intense rainfall.

4. Discussion – analysis of the proposed pumping station liquidation variants

4.1. Current pumping station maintenance costs

The annual maintenance cost for all seven pumping stations equals about 2.46% of the expenditures spent on the Branch liquidation. The highest pumping station maintenance costs are related to the operation of the stations and amount to about 1.94% of the annual expenditures on the Branch liquidation, which constitutes nearly 80% of all the costs related to maintaining the correct operation of the pumping stations, regardless of atmospheric conditions.

4.2. Multi-criteria analysis for the liquidation variants of pumping station I

Three variants of the liquidation of pumping station I were presented for analysis. The variants differ in the area of the planned drain wells. It was assumed that all the variants would be accomplished within one year. Table 2 presents the original values characterizing each individual variant as well as the results of the multi-criteria analysis for the liquidation variants of pumping station I.

Per the experts' opinions, variant 1/I involving the performance of 2.0 × 2.0 m drain wells was deemed optimal in the multi-criteria analysis.

4.3. Multi-criteria analysis for the liquidation variants of pumping stations II and III

These pumping stations are located close to each other, and water discharge from pumping station II could be directed towards station III. Therefore, the analysis encompassed a plan of the combined liquidation of both stations. Three variants for the liquidation of pumping stations II and III were subjected to analysis. Pumping station II can be liquidated in two variants, and pumping station III in only one variant. Variants 1/II and 2/II involve the independent

Table 2. Multi-criteria analysis for the liquidation variants of pumping station I (source: own study).

Unit	Criterion 1	Criterion 2	Criterion 3	Criterion 4	Multi-criteria analysis
	study unit	years	m^2	years	
Variant 1/I	0.16	2	32	1	
Variant 2/I	0.22	3	72	1	
Variant 3/I	0.30	4	128	1	
Optimal value	0.16	2	128	1	
Criterion weight	0.275	0.253	0.276	0.195	
Variant 1/I	1.000	1.000	0.250	1.000	0.793
Variant 2/I	0.716	0.667	0.563	1.000	0.716
Variant 3/I	0.529	0.500	1.000	1.000	0.744

Table 3. Multi-criteria analysis for the liquidation variants of pumping stations II and III (source: own study).

Unit	Criterion 1	Criterion 2	Criterion 3	Criterion 4	Multi-criteria analysis
	study unit	years	m^2	years	
Variant 1/II	1.91	5	0.000	2	
Variant 2/II	1.64	4.5	0.000	1.5	
Variant 3/III	1.00	3	0.000	2	
Optimal value	1.00	3	0.000	1.5	
Criterion weight	0.275	0.253	0.276	0.195	
Variant 1/II	0.523	0.600	1.000	0.750	0.719
Variant 2/II	0.609	0.667	1.000	1.000	0.808
Variant 3/III	1.000	1.000	1.000	0.750	0.951

liquidation of pumping station II, together with a proposed independent liquidation of pumping station III. Variant 3/III assumes the combined liquidation of both the pumping stations, with pipeline length optimization and collective well construction. All the variants would be accomplished within one year. Table 3 presents the original values characterizing each individual variant as well as the results of the multi-criteria analysis for the liquidation variants of pumping stations II and III.

Analyzing the proposed liquidation variants of pumping stations II and III reveals that variant 3/III is the optimal solution for the project, consisting in the optimization of pipeline lengths. The expenditure payback period should be about three years.

4.4. Multi-criteria analysis for the liquidation variants of pumping stations Va and Vb

The liquidation of pumping stations Va and Vb was planned in two variants. As part of variant 1/V, the inundated area at the north land side of the river levee would be maintained. Variant 2/V involves the levelling of the land side of the levee using soil originating from amelioration work. The expenditures for the liquidation of pumping stations Va and Vb are related to the technical retrofitting of pumping station IV and the various work performed to adapt this station to receiving increased water flows. Such a solution would provide effective preventive measures against flooding in the south river catchment area.

The proposed solutions will not bring savings quickly, as the expenses incurred will be paid back only after about 18 years. Factoring in the inundated area reclamation, the expenditure payback period will decrease to about nine years. Table 4 presents the original values characterizing each individual variant as well as the results of the multi-criteria analysis for the liquidation variants of pumping stations Va and Vb.

Analyzing the proposed liquidation variants of pumping stations Va and Vb reveals that variant 2/V

Table 4. Multi-criteria analysis for the liquidation variants of pumping stations Va and Vb (source: own study).

Unit	Criterion 1	Criterion 2	Criterion 3	Criterion 4	Multi-criteria analysis
	study unit	years	m^2	years	
Variant 1/V	1.62	18	0	1	
Variant 2/V	1.86	9	0	1.5	
Optimal value	1.62	9	0	1	
Criterion weight	0.275	0.253	0.276	0.195	
Variant 1/V	1.000	0.500	1.000	1.000	0.873
Variant 2/V	0.875	1.000	1.000	0.667	0.901

Table 5. Multi-criteria analysis for the liquidation variants of pumping station VI (source: own study).

Unit	Criterion 1	Criterion 2	Criterion 3	Criterion 4	Multi-criteria analysis
	study unit	years	m^2	years	
Variant 1/VI	2.1	12	36	1.5	
Variant 2/VI	2.09	11	0	1	
Variant 3/VI	1.73	10	36	2	
Variant 4/VI	1.57	9	0	1.5	
Optimal value	1.57	9	36	1	
Criterion weight	0.275	0.253	0.276	0.195	
Variant 1/VI	0.748	0.750	1.000	0.667	0.802
Variant 2/VI	0.753	0.818	0.000	1.000	0.610
Variant 3/VI	0.908	0.900	1.000	0.500	0.852
Variant 4/VI	1.000	1.000	0.000	0.667	0.659

is the optimal solution for the project, consisting in the backfilling of inundated areas on the northland side of the river levee using soils originating from amelioration work.

4.5. Multi-criteria analysis for the liquidation variants of pumping station VI

Four variants for the liquidation of pumping station VI were subjected to analysis. The variants differ in the method for constructing two ø 800 pipelines. In variants 1/VI and 2/VI, the pipelines are installed via directional drilling, and in variants 3/VI and 4/VI, the same pipelines are laid down by trenching. Furthermore, equipping the pumping stations with drain wells was considered in variants 1/VI and 3/VI. Flooding prevention requires all the variants to involve a considerable limitation of the pumping capacity of pumping station VI, which would be activated only when receiving increased water flows during periods of intense rainfall or thaw. The costs incurred as part of the project should be paid back within 9–12 years, depending on the variant. Table 5 presents the original values characterizing each individual variant as well as the results of the multi-criteria analysis for the liquidation variants of pumping station VI.

Analyzing the proposed liquidation variants of pumping station VI reveals that variant 3/VI is the optimal solution for the project, consisting in the installation of two ø 800 pipelines by trenching and equipping the depressed section of Stream “P” with four drain wells with a cross-section of 9 m^2.

5. Summary and conclusions

The many years of deposit extraction conducted by the Branch resulted in the generation of subsidence basins, which in turn led to the necessity of building a number of pumping stations to enable the use of areas at risk of periodic or permanent flooding.

The water table of the river flowing through the Branch's mining area is at a level of 218.0 m a.s.l. The lowest depression relative to the level of the river water in the north catchment area is the bottom of the previous bed of Stream “B”, at a level of about 210.0 m a.s.l., whereas in the south catchment area, it is the bottom of the perimeter drainage ditch in the intake well of pumping station IV, situated at about 211.0 m a.s.l.

The north river catchment area, located in the mining area of the Branch, is drained by gravity by Stream “B” and by force by pumping stations I, II, III, Va and Vb, while the south catchment area is drained naturally by Streams “P” and “C” as well as by pumping stations IV and VI.

The possibility of shutting down, optimizing or retrofitting the operation of the existing pumping stations was analyzed. The results of the conducted analyses demonstrated that only one (pumping station IV) of the seven existing pumping stations cannot be shut down. Its liquidation would need to be postponed until extraction in an adjacent mine is concluded.

A terrain morphology analysis revealed no possibility of discharging the water from pumping station I by gravity. Due to the minor water inflows and the favorable shape of the Quaternary bedrock, the limitation of the station's pumping system operation to the utmost minimum was proposed through the construction of drain wells in the reservoirs.

Technically, the liquidation of pumping station II, with water discharge towards pumping station III, is feasible and economically justified. However, the liquidation of pumping station III depends on whether the adjacent mine will agree to receive water flows originating from the combined drainage areas of pumping stations II and III.

The liquidation of pumping stations Va and Vb with water transfer towards pumping station IV will enable the regulation of the water regime in areas exhibiting periodic or permanent flooding. Another advantage is that pumping station IV is the only station owned by SRK S.A., which lowers the costs of its renting. The costs of reclamation and adaptation work equal about 1.86 of the annual expenditure on maintaining the rainwater pumping station system in the Branch.

Replacing pumping station VI with pipelines discharging the water by gravity will be fully possible, as the water accumulating in the previous stream bed section, below the gate, will be directed towards the planned drain wells. The cost of work related to the installation of two ø 800 pipelines, equaling about 1.73 of the annual expenditure on maintaining the rainwater pumping station system in the Branch, will be paid back after about nine years.

All the presented technical solutions (except one) are economically feasible and recommended for implementation from the perspective of increased flooding safety. The accomplishment of the proposed modifications in the Branch's rainwater pumping station system may be carried out in full scope or partially. Decisions in this regard depend on the financial means. The accomplishment of all the proposed projects would require expenses equaling about 5.85 of the annual expenditure on maintaining the rainwater pumping station system in the Branch, and the incurred expenditure payback period should be about nine years.

The multi-criteria assessment method applied to the adopted rainwater pumping station liquidation variants, consisting in the presentation of a comprehensive analysis of the proposed action and factoring in all the liquidation variant assessment criteria combined, is a tool for assisting decision-making by identifying optimal solutions.

Applying the multi-criteria analysis made it possible to determine the optimal variant for retrofitting the subsidence basin drainage system. The analysis results serve only as advice for the decision-maker, who may select a variant he deems the best according to each of the assessment criteria or agree with the results of the multi-criteria assessment and select a variant identified by it as optimal.

Conflict of interest

None declared.

Ethical statement

The authors state that the research was conducted according to ethical standards.

Funding body

None.

References

[1] Xu WD, Burns MJ, Cherqui F, Duchesne S, Pelletier G, Fletcher TD. Real-time controlled rainwater harvesting systems can improve the performance of stormwater networks. J Hydrol 2022;56(9). https://doi.org/10.1029/2020WR027856.

[2] Edraki M, Baumgartl T, David Mulligan, Fegan W, Munawar A. Geochemical characteristics of rehabilitated tailings and associated seepages at Kidston gold mine, Queensland, Australia. Int J Min Reclamat Environ 2019; 33(1):1–15. https://doi.org/10.1080/17480930.2017.1362542.

[3] Ye-Shuang X, Shui-Long S, Yue L, An-Nan Z. Design of sponge city: lessons learnt from an ancient drainage system in Ganzhou, China. J Hydrol 2018;563:900–8. https://doi.org/10.1016/j.jhydrol.2018.06.075.

[4] Vitale C. Understanding the shift toward a risk-based approach in flood risk management, a comparative case study of three Italian rivers. Environ Sci Pol 2023;146:13–23. https://doi.org/10.1016/j.envsci.2023.04.015.

[5] Wang H, Zhou J, Tang Y, Liu Z, Kang A, Chen B. Flood economic assessment of structural measure based on integrated flood risk management: a case study in Beijing. J Environ Manag 2021 Feb 15;280:111701. https://doi.org/10.1016/j.jenvman.2020.111701.

[6] Zhao D, Zha J, Wu J. Changes in rainfall of different intensities due to urbanization-induced land-use changes in Shenzhen, China. Clim Dynam 2021;56(7–8):2509–30. https://doi.org/10.1007/s00382-020-05601-y.

[7] Esmaiel A, Abdrabo KI, Saber M, Sliuzas RV, Atun F, Kantoush SA, et al. Integration of flood risk assessment and spatial planning for disaster management in Egypt. Prog. Disaster Sci. 2022;146:13–23. https://doi.org/10.1016/j.envsci.2023.04.015.

[8] García-Ávila F, Guanoquiza-Suárez M, Guzmán-Galarza J, Cabello-Torres R, Valdiviezo-Gonzales L. Rainwater harvesting and storage systems for domestic supply: an overview of research for water scarcity management in rural areas. Results Eng 2023;18:101153. https://doi.org/10.1016/j.rineng.2023.101153.

[9] Rauter M, Kaufmann M, Thaler T, Fuchs S. Flood risk management in Austria: analysing the shift in responsibility-sharing between public and private actors from a public stakeholder's perspective. Land Use Pol 2020;9(1):105017. https://doi.org/10.1016/j.landusepol.2020.105017.

[10] Juma B, Olang LO, Hassan MA, Mulligan J, Shiundu PM. Simulation of flood peak discharges and volumes for flood risk management in the ungauged urban informal settlement of Kibera, Kenya. Phys. Chem. Earth. A/B/C 2022;128: 103236. https://doi.org/10.1016/j.pce.2022.103236.

[11] Klijn F, Marchand M, Meijer K, van der Most H, Stuparu D. Tailored flood risk management: accounting for socio-economic and cultural differences when designing strategies. Water Secur 2021;12:100084. https://doi.org/10.1016/j.wasec.2021.100084.

[12] Rubio CJP, Yu I, Kim H, Kim S, Jeong SJ. An investigation of the adequacy of urban evacuation centers using index-based flood risk assessment. Korean Soc. Hazard Mitig. 2019;19(2): 197–207. https://doi.org/10.9798/KOSHAM.2019.19.2.197.

[13] Teston A, Teixeira CA, Ghisi E, Cardoso EB. Impact of rainwater harvesting on the drainage system: case study of a condominium of houses in curitiba, southern Brazil. Water 2018;10(8):1100. https://doi.org/10.3390/w10081100.

[14] Vafadarnikjoo A, Chalvatzis K, Botelho T, Bamford D. A stratified decision-making model for long-term planning: application in flood risk management in Scotland. Omega 2022;116:102803. https://doi.org/10.1016/j.omega.2022.102803.

[15] Verweij S, Busscher T, van den Brink M. Effective policy instrument mixes for implementing integrated flood risk management: an analysis of the ‘Room for the River’ program. Environ Sci Pol 2020;116:204–12. https://doi.org/10.1016/j.envsci.2020.12.003.

[16] Parjanne A, Rytkönen AM, Veijalainen N. Framework for climate proofing of flood risk management strategies in

Finland. Water Secur 2021;15(13):100096. https://doi.org/10.1016/j.wasec.2021.100096.

[17] Campisano A, Modica C. Rainwater harvesting as source control option to reduce roof runoff peaks to downstream drainage systems. J Hydroinf 2015;18(1):jh2015133. https://doi.org/10.2166/hydro.2015.133.

[18] Deitch MJ, Feirer ST. Cumulative impacts of residential rainwater harvesting on stormwater discharge through a peri-urban drainage network. J Environ Manag 2019;1(243): 127−36. https://doi.org/10.1016/j.jenvman.2019.05.018. Epub 2019 May 13.

[19] Pochwat K. Assessment of rainwater retention efficiency in urban drainage systems - model studies. Resour 2022;11(2): 14. https://doi.org/10.3390/resources11020014.

[20] Custódio DA, Ghisi E. Impact of residential rainwater harvesting on stormwater runoff. J Environ Manag 2022;326(BB): 116814. https://doi.org/10.1016/j.jenvman.2022.116814.

[21] Wise AFE, Swaffield J. Rainwater drainage. In: Water, sanitary and waste services for buildings. 5th ed. London UK: Routledge; 2002. https://doi.org/10.4324/9780080520797.

[22] Van Linden S, Van Den Bossche N. Review of rainwater infiltration rates in wall assemblies. Build Environ 2022;219(12): 109213. https://doi.org/10.1016/j.buildenv.2022.109213.

[23] Bera A, Prasad Mukhopadhyay B. Identification of suitable sites for surface rainwater harvesting in the drought prone Kumari River basin, India in the context of irrigation water management. J Hydrol 2023;621:129655. https://doi.org/10.1016/j.jhydrol.2023.129655.

[24] Li G, Xiong J, Zhu J, Liu Y, Dzakpasu M. Design influence and evaluation model of bioretention in rainwater treatment: a review. Sci Total Environ 2021;787(2):147592. https://doi.org/10.1016/j.scitotenv.2021.147592.

[25] Niu S, Wang T, Xia Y. Microplastic pollution in sediments of urban rainwater drainage system. Sci Total Environ 2023;868: 161673. https://doi.org/10.1016/j.scitotenv.2023.161673.

[26] Fajklewicz Z, Piwowarski W, Radomiński J, Stewarski E, Tajduś A. Badanie deformacji w górotworze w celu odtwarzania wartości budowlanej terenów pogórniczych *Investigating deformations in the rock mass to restore the building value of post-mining areas*. Publishing House of AGH Kraków; 2004.

[27] Strzałkowski P, Ścigała R. The causes of mining induced ground steps occurrence - case study from Upper Silesia in Poland. Acta Geodyn Geomater 2018;14(3):299−306. https://DOI:10.13168/AGG.2017.0013.

[28] Ignacy D. Metoda oceny zagrożenia zawodnieniem terenów górniczych i pogórniczych. Method of assessment of the flooding threat in mining and post-mining areas. Przeglad Gorn 2017;73(1):26−38.

[29] Bukowski P. Zagrożenia wodne w kopalniach węgla Zagłębiu Węglowym w dobie restrukturyzacji górnictwa kamiennego Water hazards in coal mines in the Coal Basin in the era of coal mining restructuring. 3/1. In: Górnictwo i Geoinżynieria, 31. Publishing House of AGH Kraków; 2007. p. 81−9.

[30] Mercado JMR, Kawamura A, Amaguchi H, Rubio CJP. Fuzzy based multi-criteria M& E of the integrated flood risk management performance using priority ranking methodology: a case study in Metro Manila, Philippines. Int. J. Disaster Risk Reduct 2021;64:102498. https://doi.org/10.1016/j.ijdrr.2021.102498.

[31] Bondaruk J, Janson E, Wysocka M, Chałupnik S. Identification of hazards for water environment in the Upper Silesian Coal Basin caused by the discharge of salt mine water containing particularly harmful substances and radionuclides. J Sustain Min 2015;14(4):179−87. https://doi.org/10.1016/j.jsm.2016.01.001.

[32] Łabaj P, Wysocka M, Janson E, Deska M. Application of the unified stream assessment method to determine the direction of revitalization of heavily transformed urban rivers. Water Resour 2020;47(4):521−9. https://doi.org/10.1134/S0097807820040120.

[33] Wysocka M, Chałupnik S, Chmielewska I, Janson E, Radziejowski W, Samolej K. Natural radioactivity in polish coal mines: an attempt to assess the trend of radium release into the environment. Mine Water Environ 2019;38:581−9. https://doi.org/10.1007/s10230-019-00626-0.

[34] Szpak A, Modrzyńska J, Piechowiak. Resilience of Polish cities and their rainwater management policies. Urban Clim 2022; 44:101228. https://doi.org/10.1016/j.uclim.2022.101228.

[35] Chmiela A, Smoliło J, Gajdzik M. A multifaceted method of analyzing the amount of expenditures on mine liquidation processes in SRK S. A., Manag. Syst. Prod. 2022;30:130−9. https://doi.org/10.2478/mspe-2022-0016.

[36] Simon-Coinçon R, Spain AV, Milnes AR. Landform processes in the post coal-mining landscape, bowen basin, Australia. A geomorphological approach. Int J Min Reclamat Environ 2003; 17(1):20−50. https://doi.org/10.1076/ijsm.17.1.20.8628.

[37] Hu Z, Fu Y, Xiao W, Zhao Y, Wei T. Ecological restoration plan for abandoned underground coal mine site in Eastern China. Int J Min Reclamat Environ 2015;29(4). https://doi.org/10.1080/17480930.2014.1000645.

[38] Hudson P, Raška P, Macháč J, Slavíková L. Balancing the interaction between urban regeneration and flood risk management − a cost benefit approach in Ústí nad Labem. Land Use Pol 2022;120:106272. https://doi.org/10.1016/j.landusepol.2022.106276.

[39] Chmiela A. The choice of the optimal variant of the mine liquidation due to the possibility of obtaining methane from goafs. Eur. J. Manag. 2023;8(3). https://doi.org/10.24018/ejbmr.2023.8.3.1947.

[40] Przybyła H, Chmiela A. Projektowanie rozwiązań techniczno−organizacyjnych stosowanych w wyrobiskach ścianowych (*Design of technical and organisational solutions applied in longwall workings*). Publishing House Silesian University of Technology Gliwice; 1997.

[41] Korski J, Korski W. Underground mine as a system of processes. Min. Inform. Autom. Electr. Eng.. 2015;2(522):19−27.

[42] Turek M. Analiza i ocena kosztów w górnictwie węgla kamiennego w Polsce (*Analysis and evaluation of costs in hard coal mining in Poland*). Difin Warszawa; 2013.

[43] Dudeney AWL, Chan BKC, Bouzalakos S, Huisman JL. Management of waste and wastewater from mineral industry processes, especially leaching of sulphide resources: state of the art. Int J Min Reclamat Environ 2013;27(1):2−37. https://doi.org/10.1080/17480930.2012.696790.

[44] Ortiz S, de Barros Barreto P, Castier M. Rainwater harvesting for domestic applications: the case of Asunción. Paraguay. Results Eng 2022;16:100638. https://doi.org/10.1016/j.rineng.2022.100638.

[45] Rodrigues de Sá Silva AC, Mendonça Bimbato A, Perrella Balestieri JA, Nogueira Vilanova MR. Exploring environmental, economic and social aspects of rainwater harvesting systems: a review. Sustain Cities Soc 2021;76:103475. https://doi.org/10.1016/j.scs.2021.103475.

[46] Puzyreva K, Henning Z, Schelwald R, Rassman H, Borgnino E, de Beus P, et al. Professionalization of community engagement in flood risk management: insights from four European countries. Int J Disaster Risk Reduc 2022;71(4): 102811. https://doi.org/10.1016/j.ijdrr.2022.102811.

[47] Nariné Torres M, Fontecha JE, Zhu Z, Walteros JL, Rodríguez JP. A participatory approach based on stochastic optimization for the spatial allocation of Sustainable Urban Drainage Systems for rainwater harvesting. Environ Modell Softw 2019;123:104532. https://doi.org/10.1016/j.envsoft.2019.104532.

[48] Disse M, Johnson TG, Leandro J, Hartmann T. Exploring the relation between flood risk management and flood resilience. Water Secur 2020;9:100059. https://doi.org/10.1016/j.wasec.2020.10005.

[49] Ghorbani Y, How Kuan S. A review of sustainable development in the Chilean mining sector: past, present and future. Int J Min Reclamat Environ 2017;31(2). https://doi.org/10.1080/17480930.2015.1128799.

[50] Shahbaz A, Yan-Fang S. Implementing rainwater harvesting systems as a novel approach for saving water and energy in flat urban areas. Sustain Cities Soc 2022;89:104304. https://doi.org/10.1016/j.scs.2022.104304.