A Teamwork-Based Protocol for a Holistic Approach to Selecting a Sustainable Mine Dewatering Management Plan

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Protocol

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Abstract: The primary objective of the protocol is to establish and develop several scientific methodological procedures applicable to the design and selection of a suitable mine dewatering management plan. A significant challenge and contribution of the research lies in the initial hypothesis, which posits the feasibility of organizing a multidisciplinary team to collaboratively determine the optimal solution for long-term mine dewatering. Protection against groundwater is a highly complex hydrogeological challenge, particularly in mining operations. Mines are inherently dynamic systems, constantly expanding both horizontally and vertically, from the very beginning of mining, also reaching significant depths. Given the inherent uncertainty in geologic systems, such as ore deposits, the entire dewatering process requires continuous "learning" and hierarchical problem-solving. Addressing these complexities involved forming a team of experts, leveraging their knowledge and experience, as well as several methodological procedures based on applied mathematics in geosciences and mining engineering, such as numerical modeling and simulation, fuzzy optimization and decision analysis. These circumstances necessitated continual adjustment to evolving operating conditions and prompted the development of a protocol for effective dewatering planning and mineral ore protection against groundwater. Such a protocol generates alternative mine dewatering solutions and considers their individual characteristics. Additionally, it defines and analyzes multiple criteria for evaluating the solutions and selecting a method that ensures optimal decision-making. The applied methods constitute a holistic system, represented by a single protocol, which includes an interdisciplinary approach to creating sustainable groundwater management strategies.

Keywords: expert knowledge; groundwater; applied mathematics; numerical simulation; fuzzy optimization; holistic system; sustainable management strategies

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1. Introduction

A significant number of scientists have grappled with the issue of drainage, as both surface and underground water pose risks to mining facilities and hinder operations. Conversely, mining operations and facilities can threaten both underground and surface water bodies, constituting a substantial ecological factor [1]. Advances in dewatering methods are crucial to addressing these challenges. Mitigating the environmental impact of mine dewatering and water recycling is paramount to preventing potential disasters and long-term risks [2]. Various approaches hold the promise of optimizing the dewatering process and minimizing environmental harm. Numerical modeling has become widely adopted in selecting optimal dewatering solutions for ore deposits [3]. Additionally, the layered model concept is employed in mine dewatering to identify the influence of technical, management, and economic system parameters. This layered approach enables a holistic analysis and management of complex dewatering systems, ensuring efficient water collection, transport, purification, and drainage while safeguarding the environment. Quantitative research methods [4] are valuable tools when dealing with quantitative data or other data amenable to statistical analysis. Applied research methods [5], on the other hand, emphasize the practical application of scientific knowledge for specific purposes.

Alongside the dewatering process, it is estimated that a significant volume of solid tailings will accumulate globally, further exacerbating the challenge of tailings management [6]. Tailings dams represent substantial reservoirs of water within mining operations. Ineffective management of water content in tailings can compromise their stability, potentially leading to accidents and environmental disasters [7]. To mitigate environmental impact, mining companies are exploring alternative dewatering methods, with numerous techniques available worldwide [8]. The implementation of new dewatering technologies contributes to addressing these challenges [1]. Some commonly employed methods include decanter centrifuges [9], mechanical-electric dewatering [10], and dewatering by vibrating screens [11]. These approaches offer theoretical and technical support for efficient dewatering, resulting in significant environmental benefits. Additionally, the utilization of geotextile pipes [12] for dewatering can reduce sludge volume, enhance tailings strength, and confine contaminants within the pipe. Another emerging method for improving wastewater management is acid mine drainage [13], which serves as a catalyst for solar photo-Fenton treatment of wastewater generated by dewatering systems. Through effective treatment, the solar photo-Fenton method can substantially reduce pollution levels in wastewater before its release into the environment.

Generally, dewatering approaches are often reduced to the application of individual methods, lacking a comprehensive, detailed overall procedure. Advancements in fundamental science can enhance existing techniques and pave the way for the development of future solutions. This necessitates the creation of an innovative protocol. The protocol for selecting an effective solution in mine dewatering management planning is best created through a holistic interdisciplinary approach. This approach involves several stages [14]. The first stage is related to the projection of alternative solutions for mineral ore protection against groundwater [15]. The protocol includes numerical modeling and simulation of the groundwater regime, along with predictive hydrodynamic calculations generating various alternative solutions. The criteria affecting the selection of the optimal mine dewatering solutions are analyzed in the second stage. The third stage involves a multiple-criteria decision-making model [5]. It involves the construction of evaluation matrices for all criteria and subcriteria, as well as for all alternatives against the set criteria and subcriteria. Finally, mathematical optimization calculations are performed to select the most suitable mine dewatering management plan (MDMP).

When studying the hydrogeological parameters of mineral ore deposits and developing an MDMP, it is often challenging to find a solution that satisfies all criteria simultaneously. A suitable compromise must be sought, balancing various interests. The investor(s) are looking for an economically viable solution, as it directly impacts product pricing. Social groups are not as interested in the price. Instead, they focus on environmental protection. On the other hand, engineers tend to prioritize the technical effectiveness of the solution, ensuring reliable dewatering while considering financial and environmental factors [16].

A significant challenge in mining hydrogeology is the insufficiency of data [17,18]. In addition, available data are frequently imprecise due to complex geological and hydrogeological conditions associated with mineral ore deposits. These are limiting factors for the application of standard and conventional multiple-criteria optimization methods in MDMP decision-making [19].

Due to the inherent complexities of mine dewatering, expert knowledge, logical reasoning, past experience, intuition, and judgment are crucial factors in MDMP development. Expert decision-making is a multi-faceted process requiring "multidimensional" opinions about numerous intertwined factors that influence the selection of an optimal MDMP. This hierarchical decision-making process requires experts to consider both high-level and low-level dilemmas [20].

Given these complexities, it is clear that decision-making in mine dewatering is a challenging process.

The contribution to science of decision-making methods based on fuzzy logic is the ability to focus on how to overcome the shortfalls implied above [5]. The fuzzy analytic hierarchy process (FAHP) has a number of advantages over other fuzzy multiple-criteria decision analysis (MCDA) approaches. By leveraging the expert judgment (evaluation) and experience of the decision maker assessing information about the entire hydrogeological system of a mine, FAHP enables the optimal decision to be made from several projected alternative MDMP solutions. Given that the easiest way for an expert to express their informed opinion is to verbalize, along with numerical advantages, FAHP allows the use of the natural human language in the multiple-criteria decision-making (MCDM) process. Answers are given in the form of linguistic variables, which assume their numerical values from the FAHP scale and prioritize one element (criterion, subcriterion) over another. Consequently, the application of fuzzy logic in MCDM is an integral part of the protocol for selecting a mine dewatering strategy, which is described below.

By performing all the operations according to the proposed protocol, it is possible to ensure effective and sustainable management of mine protection against groundwater inflow.

2. Background

The protocol for a holistic approach to select a sustainable MDMP is grounded in research conducted for a doctoral thesis [14]. A specialized segment of this research involved applying fuzzy logic to hydrodynamic analyses for designing groundwater protection systems and developing dewatering strategies in different cases. This holistic, interdisciplinary approach, encapsulated in a single protocol, has been applied to various contexts, including urban areas, farmland, industrial facilities, and mines, providing a comprehensive framework for groundwater management strategies. High groundwater levels in urban areas can pose significant risks to buildings or have an adverse effect on the geomechanical properties of soil. Building foundations may experience deformation, such as collapse or subsidence, due to weakened soil conditions. Additionally, landslides can be triggered in susceptible soil types. The same applies to hydraulic structures and areas that are irrigated or drained. For example, high groundwater levels can saturate soils, negatively impacting crop growth and yield. The underlying principles of dewatering planning in groundwater management are universal and have been extensively explored in the literature [5]. Effective solutions for these issues have been proposed in [15].

The hydrogeological complexity of mineral ore deposits is a key factor in developing effective MDMPs. Some experts, like [21–26], believe that geological, geophysical, geotechnical, hydrological and hydrogeological investigations are essential for future sustainable management of mine development and dewatering. Morton and van Mekerk [27], Brassington [28] and Deb [29] specifically focus on analyzing the hydrogeological factors that influence ore deposits.

Many scientists have conducted detailed analyses of hydrogeological systems and their parameters. Theoretical background and numerical modeling concepts are widely discussed in the literature [30–32]. Numerical codes like MODFLOW [33], coupled with software like Visual MODFLOW Flex Pro version (Waterloo Hydrogeologic, Inc. Waterloo, ON, Canada) or Groundwater Vistas [34], are commonly used to simulate and predict future groundwater regimes. These tools have also been applied to design MDMPs. An interesting case study of groundwater management using predictive hydrodynamic simulations of future groundwater levels is described in [35].

Zadeh [36] described the application of a fuzzy logic concept, a scientifically based approach that makes use of expert experience and intuition. This approach overcomes problems of imprecision, uncertainty and vagueness. Where elements of a multiple-criteria decision model are analyzed, they need not be described by exact numerical values. Unstructured heuristic reasoning and expert knowledge are described using linguistic terms, which can be coded into a mathematical algorithm. In other words, fuzzy logic bridges the gap between natural human language and numerical data used by the computer from a preferred conventional scale [37–39], or fuzzified scale [40–42]. Chang [43] was the first to propose an optimization method through FAHP, using triangular fuzzy numbers and an FAHP scale. The method was further advanced by Deng [44]. This multiple-criteria decision-making model was developed in the special-purpose application FUZZY-GWCS [14]. The authors of this protocol have extensively explored the use of both conventional and fuzzy MCDA methods for groundwater management planning and forecasting [5].

3. Methodology: Protocol Development

Dewatering strategies, protection against groundwater and dewatering management planning are essential for any underground activity, particularly mining. Mines are dynamic environments, constantly expanding both horizontally and vertically, as well as over time (from mine opening to closure). Additionally, the deep penetration of mining operations into rock formations, often intersecting aquifers with varying hydrodynamic characteristics, further complicates the dewatering challenge.

Groundwater has an adverse effect on ore excavation and other mining operations. Therefore, the slope stability of mine benches needs to be protected due to increased rock moisture and pore pressure, which can lead to ground deformation and potential disruption of the mining activities.

To ensure safe and efficient mining operations, a well-designed dewatering management plan, or an optimal groundwater dewatering system, is crucial. This plan involves implementing a system of components to lower groundwater levels below the current bench and prevent water ingress. Common components of such a system include drainage wells, impervious screens, pumping stations, canals, water collectors, pipes, shafts, horizontal drainage spaces (halls), horizontal drainage elements (drain pipes, trenches, horizontal drains), embankments, and various types of filters (pipes connected to pumps).

An effective MDMP requires the selection of an optimal layout of the dewatering components in plain view and elevation, which will support the configuration of the mining operations. In addition, it necessitates dewatering component installation scheduling synchronized with the rate of mining. The main MDMP task is to provide "dry" conditions on the lowest mine bench at any time. "Dry" conditions ensure bench slope stability and uninterrupted work of miners and machinery. This ensures ore deposits are in a condition that allows for technically safe and viable mining operations, transportation, and processing using appropriate mining technologies.

In addition to the primary task, an effective MDMP must consider several other critical factors, such as adequate technical characteristics for the dewatering system, providing economic viability and minimized environmental impact. Consequently, the following factors require special attention:

- The MDMP needs to ensure proper and safe mining conditions (excavation, operation of machinery, transportation).
- The MDMP needs to provide protection against groundwater from all aquifers identified in the mine area.
- Technical and economic efficiency of the MDMP.
- The MDMP must comply with environmental principles associated with groundwater level reduction. This reduction can be considerable, depending on the depth of the ore deposits.
- The MDMP needs to be consistent with environmental principles relating to the evacuation of mine water, with potentially high chemical aggressiveness.
- Because of the preliminary dewatering required before mine development, the MDMP needs to ensure a seamless transition from the mine development phase to the production phase.
- The MDMP should be adaptable to changes in mining plans and unexpected events, allowing for adjustments to the dewatering system as needed.

- The ancillary equipment used for/in the dewatering components needs to be in line with the specifications of the components.
- The dewatering system components and groundwater levels need to be monitored continuously.
- Finally, it is crucial to synchronize the MDMP (or the groundwater control system) with the pace and evolution of mining operations.

Given the complexities and challenges associated with mine dewatering, favorable mining conditions require a sustainable MDMP. A key component of sustainable mine management is the development of a protocol for designing and selecting optimal MDMPs.

As shown in Figure 1, the proposed protocol is composed of three parts. Knowledge, experience, expert judgment and intuition significantly influence all three stages, ultimately impacting the design of the MDMP and the overall strategy for mine dewatering and groundwater protection.

The initial stage of the protocol involves the projection of alternative MDMP solutions. This process begins with the development of an appropriate conceptual hydrogeological model, followed by the creation of a numerical model. By calibrating and validating the numerical model, predictive hydrodynamic calculations or simulations can be performed to generate and evaluate various alternative groundwater management system solutions.

Hydrodynamic analyses play an important role in numerical modeling. A hydrodynamic analysis is a set of various hydrodynamic calculation methods, with three-dimensional hydrodynamic modeling being the most complex and widely used approach for modeling aquifer regimes. This method is based on numerical solving of differential equations that describe groundwater flow and related processes in the porous environment. On one hand, a numerical model (or hydrodynamic model of ore deposits) offers insights into the local water balance, the interaction between groundwater and mining operations, and the hydraulic connection between surface water and groundwater. On the other hand, predictive hydrodynamic simulations conducted on the numerical model help define the characteristics and effectiveness of the groundwater management systems. In multicriteria optimization language, this process generates alternative solutions.

In this specific case, the primary challenge addressed by numerical modeling for MDMP development is the lowering of groundwater levels below the elevation of the mining operation (or mine dewatering). In addition, numerical modeling and predictive simulations enable the analysis of the effectiveness and differentiation of various proposed alternatives.

A well-defined numerical model for MDMP development, from an engineering and groundwater management perspective, is a mathematical and physical set of facts which contribute to the understanding of the operational behavior of the dewatering system components in a given hydrogeological setting.

The second phase of the protocol sets and evaluates criteria that influence optimal decision-making and MDMP selection. This innovative approach is a pivotal component of the overall decision-making process. Three primary criteria have been identified for MDMP development and alternative solution design: technical (TC), economic (EC), and environmental (EN). A total of eleven subcriteria have been set: time (TC1), hydrogeological compatibility (TC2), efficiency (TC3), flexibility (TC4), reliability (TC5), capital expenditure (EC1), operating expenses (EC2), maintenance costs (EC3), drawdown (EN1), pumped groundwater quality and quantity (EN2), and energy efficiency (EN3).

The third phase of the protocol generates a multicriteria decision model and employs the fuzzy-GWCS application developed by the authors of this paper. Generally, optimization models facilitate decision-making by enabling experts to integrate all relevant data and relationships within a given scenario, leading to the selection of the optimal alternative after addressing the complexities of the task at hand. There are many multicriteria optimization methods that tackle decision-making problems in pursuit of optimal solutions. Recognizing this flexibility, the third phase of the protocol is adaptable. A fuzzy multicriteria decision model is developed to overcome the imprecision, uncertainty and vagueness inherent in mine hydrogeology. Procedures like fuzzification, mathematical optimization calculations, and subsequent defuzzification and ranking of alternatives lead to optimal MDMP decisions. The entire MDMP selection process involves the following nine steps.

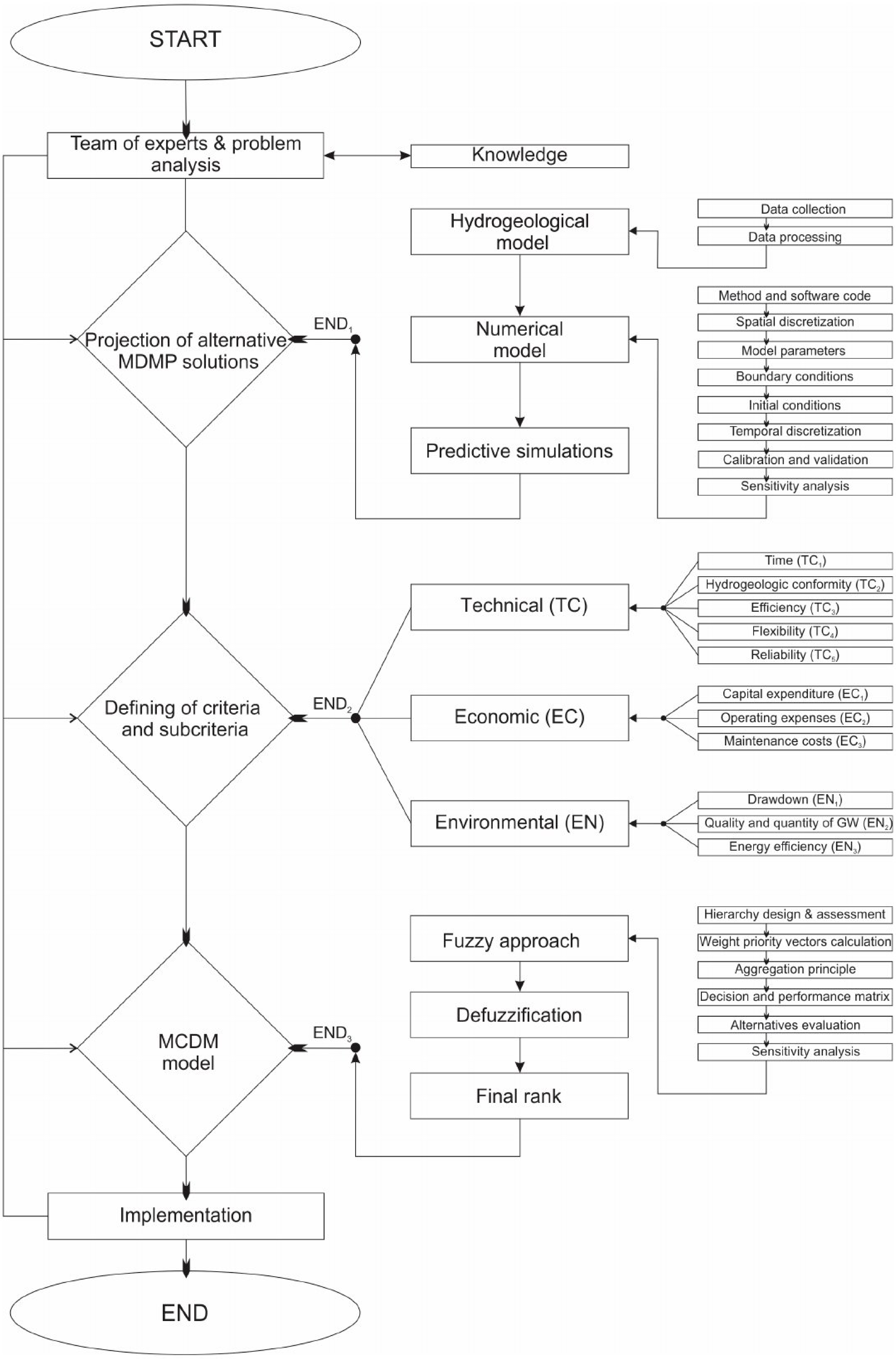

Figure 1. Protocol for designing and selecting the optimal mine dewatering management plan.

Step 1—Assembling a team of experts and leveraging their knowledge and experience (problem analysis). While studying mineral ore deposits, experts often face geological and hydrogeological identification challenges. The successful development of an MDMP and alternative solutions requires expertise in various disciplines, including geology (particularly hydrogeology), groundwater dynamics, hydrology, rock mechanics, installation of wells and other dewatering components, hydraulic engineering, and mining (including mining technologies). Consequently, various types of investigations of mineral ore deposits are undertaken to fully define their characteristics. The quality of the identification of all prevailing local conditions directly impacts the design of a mine dewatering plan.

From a hydrogeological perspective, when considering numerical model input parameters, available data often lacks sufficient accuracy (e.g., the effective infiltration or spatial distribution of hydraulic parameters). Due to the inherent difficulty in precisely measuring certain parameters, experts frequently resort to approximations based on various subjective assessments. This is how the initial values of the parameters are established and then quantified through numerical model calibration with varying degrees of success.

A dewatering system and its components need to be carefully defined and, more importantly, appropriately sized. This process requires a team effort and the expertise of both (hydro)geologists and miners. Extensive knowledge of the hydrogeological systems of mineral ore deposits enables the judicious selection of groundwater management system components as well as the definition of criteria and subcriteria for decision-making and optimal MDMP selection.

Similarly, expert knowledge plays a key role in the generation of MCDM models, as well as the evaluation and pairwise comparison of alternatives, criteria and subcriteria.

Step 2—Hydrogeological (conceptual) modeling. Hydrogeological modeling precedes numerical modeling. An inaccurately defined hydrogeological model will compromise the accuracy and utility of the subsequent numerical model. A hydrogeological model is established by collecting diverse data from the study area (the extended area of the mineral ore deposits). It constitutes a summary of geological and hydrogeological investigations. The end result is a representation of the hydrogeological system or, in other words, the spatial (3D) distribution of rock masses. Aquifers (their interrelationships and spatial distribution) and groundwater levels are highlighted and visualized in 3D.

Step 3—Numerical (hydrodynamic) modeling. In general, hydrodynamic modeling involves dividing the entire hydrogeological system into a certain number of small 3D cells. A partial differential equation of groundwater flow [45,46] is formulated and subsequently solved for each cell. These equations describe groundwater flow and other physical processes in the porous setting. The system of equations is solved using computer software and numerical methods (e.g., finite difference, finite element, boundary element, or finite volume). Eight substeps (a–h) are analyzed consecutively to transform the hydrogeological model into a numerical (or hydrodynamic) model. This is followed by calibration, validation and sensitivity analysis.

(a) Numerical method and modeling software code: a suitable numerical method for solving differential equations is selected based on the specific schematization of the hydrogeological system. As previously mentioned, MODFLOW [33] is the most commonly used code for simulating groundwater flow.

(b) Spatial discretization: this pertains to the geometry of the modeled area. The size of the model grid is defined, followed by the importation of elevation matrices for the overlying and underlying strata of the lithostratigraphic units.

(c) Model parameters: these represent the hydraulic parameters of the porous environment (e.g., hydraulic conductivity, specific storage, specific yield, porosity). Their values can be imported as spatial distribution matrices.

(d) Boundary conditions: these represent the conditions along the contours of the groundwater flow region, typically expressed as piezometric head or flow (model inflow and outflow). In natural settings, these boundaries may include rivers, lakes, aquifer recharge or drainage zones, hydrogeologic features or occurrences, hydraulic structures, and the vertical water balance parameters of the aquifer (infiltration, evapotranspiration).

(e) Initial conditions: these represent the assumed piezometric heads in the study area, specifically at all points of the flow net at a particular initial time.

(f) Temporal discretization: this involves defining the time intervals for hydrodynamic simulations, considering factors such as the availability of data (model parameters), their quality and temporal distribution, and, ultimately, the task at hand.

(g) Model calibration and validation: calibration is a process where model parameters and boundary conditions are adjusted, based on the adopted schematization of natural and operating conditions, to obtain results consistent with predefined criteria. Model calibration relies on parameter data collected from the study area through continuous monitoring of groundwater regime elements. The calibration process is deemed completed when values derived from model simulations match those observed in nature. This process can be implemented in two ways. The first involves “manual” calibration, based on a trial-and-error approach guided by expert knowledge and experience. The second is automated calibration, commonly using the PEST sub-routine [47]. Model validation is a process that verifies model calibration. A known state of the hydrogeologic system, not used for model development, is simulated. This new state includes some other hydrologic and hydrodynamic conditions related to the groundwater regime status and boundary conditions for the model calibration time interval. Other model parameters, such as the geometry and groundwater flow parameters, remain unchanged.

(h) Model sensitivity analysis: this examines the impact of variations in input parameter values on model output. It is typically conducted concurrently with hydrodynamic model calibration. A specific parameter or boundary condition is varied within a reasonable range, guided by expert judgment, while all the other parameters are held constant. The resulting changes in model calibration outcomes, usually piezometric head or groundwater balance, are recorded. This process is repeated for each selected parameter. The most sensitive parameter is identified as the one that induces significant changes in model output even with minor variations.

Step 4—Predictive simulations. Predictive hydrodynamic calculations for MDMP development are the final stage of the overall effort aimed at producing possible alternatives. The solution of a calibrated and validated numerical model serves as the initial state for all planned prognoses and alternatives of the groundwater management system. In hydrodynamic terms, this means that a future groundwater regime is predicted. On the other hand, it signifies the definition of an MDMP, encompassing the initial dewatering phase, mine development, and eventual mine closure, all measured in years.

Step 5—Defining criteria and subcriteria. For illustrative purposes, Figure 1 shows eleven subcriteria that are integral components of three primary criteria (technical, economic and environmental). These criteria characterize the main properties outlined below.

(TC1) typically represents the timeframe during which groundwater levels are lowered below a design mine elevation. In this sense, given that predictive simulations define the time when each dewatering system component is put online and offline during the mine’s lifespan, subcriterion TC1 represents this specific time slice.

(TC2) describes the advantages and shortfalls in terms of consistency between the installation/operation of dewatering system components and the hydrogeological parameters of the ore deposits.

(TC3) represents the effectiveness of the MDMP in mitigating adverse impacts on the mine. It is related to experience and the assessment of dewatering system efficiency in terms of “drying” the hydrogeological setting, relative to past applications in mineral ore dewatering.

(TC4) represents the flexibility of the MDMP, or how effectively the dewatering system can adapt to unforeseen mining activities or events (e.g., groundwater inrush during drilling). It pertains to the construction of additional dewatering system components or the shutdown of the existing ones. The key question for the expert evaluator is: "Can the MDMP be partially modified?"

(TC5) represents the reliability, or the assessed safety, of the MDMP in the event of mining accidents. In addition to effective mine dewatering, a primary objective of the MDMP is to minimize the risk to miners, machinery and the environment. The key question for the expert evaluator is: "Will the MDMP ensure absolute safety, or a certain level of safety with an acceptable level of risk?"

(EC1) refers to capital expenditure. This subcriterion describes the economic value or unit cost of each mine dewatering system component (including auxiliary equipment).

(EC2) represents the operating expenses of the dewatering system, including power supply (e.g., for well pumps), mine water evacuation, and labor (miners and personnel for 24 h dewatering system monitoring). Subcriterion EC2 also includes the cost of dewatering system monitoring (e.g., piezometric head observations).

(EC3) represents the dewatering system maintenance costs. This subcriterion relates to repairs and scheduled replacements of dewatering system components.

(EN1) pertains to the overall groundwater drawdown in the mine area. Dewatering significantly reduces groundwater levels, directly adversely impacting the mine's environment (surface water, springs, water supply wells, soil, people, plants and animals). This subcriterion assesses the level of impact of the MDMP alternatives on the overall environmental status.

(EN2) relates to the quality and quantity of the water evacuated from the mine. It describes and assesses the impact of varying degrees of mine water aggressiveness on the environment. From a hydrogeological perspective, it is also expressed as the total volume of water evacuated by each MDMP alternative.

(EN3) pertains to the energy efficiency of each MDMP alternative, which does not compromise the technical effectiveness of the dewatering system. In all cases, the expert will prioritize a management plan that includes measures to reduce energy consumption.

Step 6—Application of the fuzzy approach in MCDA. From a geological and hydrogeological perspective, mineral ore deposits constitute a system characterized by a certain degree of uncertainly. When studying mines, experts encounter various challenges associated with the identification and quantification of different parameters, which can ultimately be expressed inaccurately. Similarly, when developing a long-term MDMP, natural uncertainties (e.g., meteorological forecasting), economic uncertainties or uncertainties related to a dewatering system's technical characteristics arise. The advantage of using a fuzzy multicriteria decision model over conventional multicriteria optimization approaches lies in its ability to address these uncertainties. By applying FAHP, a fuzzy multicriteria decision model was developed for decision-making regarding optimal MDMPs. It comprises six substeps, as outlined below. The simulations were conducted using the special-purpose fuzzy-GWCS application [5,14], previously described.

(a) Problem hierarchy design and assessment. Hierarchy design involves identifying tiers (objective > criteria > subcriteria > sub-subcriteria > . . . > alternative solutions). The objective is mine dewatering and to select the optimal MDMP alternative (Step 4), the criteria and subcriteria (Step 5) are analyzed. Through evaluation and pairwise comparison, the elements of the following matrices are defined: set criteria (Equation (1)), set subcriteria (Equation (2)), and resulting alternatives (Equation (3)).

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1m} \\ a_{21} & a_{22} & \cdots & a_{2m} \\ \cdots & \cdots & \cdots & \cdots \\ a_{m1} & a_{m2} & \cdots & a_{mm} \end{bmatrix} \tag{1}$$

where a is the matrix element; $a_{ij} = 1$ for all $i = j$, $(i, j = 1, 2, \ldots, m)$ and $a_{ij} = \frac{1}{a_{ji}}$

$$A_j = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1k_j} \\ a_{21} & a_{22} & \dots & a_{2k_j} \\ \dots & \dots & \dots & \dots \\ a_{k_j1} & a_{k_j2} & \dots & a_{k_jk_j} \end{bmatrix} \quad (2)$$

where the analyzed criterion comprises k_j subcriteria, and

$$Y_k = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1N} \\ a_{21} & a_{22} & \dots & a_{2N} \\ \dots & \dots & \dots & \dots \\ a_{N1} & a_{N2} & \dots & a_{NN} \end{bmatrix} \quad (3)$$

where N is the alternative solution, with regard to each of the K subcriteria; $k = 1, 2, \dots, K$.

(b) Calculation of weight priority vectors (Equation (4)) for the subcriteria matrices defined in Substep 6-a. It involves standard mathematical procedures—fuzzy extent analysis and the fuzzy synthetic extent template [43]:

$$w_i = \sum_{j=1}^{m} a_{ij} \otimes \left[\sum_{k=1}^{m} \sum_{l=1}^{m} a_{kl} \right]^{-1} \quad (4)$$

where $i = 1, 2, \dots, m$.

The calculated weights (w_i) are then normalized. The extension principle [48] is recommended as it significantly reduces uncertainty [44]. Using Equations (5)–(7), weight priority vectors are calculated for the two hierarchy tiers as follows:

$$w_j' = \left(\sum_{l=1}^{k_j} a_{il} \otimes \left[\sum_{i=1}^{k_j} \sum_{l=1}^{k_j} a_{il} \right]^{-1} \right) \otimes w_j \quad (5)$$

where $j = 1, 2, \dots, m$; $p = 1, 2, \dots, k_j$

$$W = \left(w_1^1, w_1^2, \dots, w_1^{k_1}; w_2^1, w_2^2 \dots w_2^{k_2}; \dots; w_j^1, w_j^2, \dots, w_j^{k_j}; \dots; w_m^1, w_m^2, \dots, w_m^{k_m} \right) \quad (6)$$

where W is the weight of the subcriterion, whose total "length" is K.

$$W = (W_1, W_2, \dots, W_K) \quad (7)$$

Similarly, when the evaluation matrices of the alternatives are defined (Substep 6-a), the fuzzy extent analysis is repeated. The merit of an alternative V_i $(i = 1, 2, \dots N)$ relative to j subcriteria $(j = 1, 2, \dots, K)$ is determined using Equation (8):

$$x_{ij} = \sum_{k=1}^{K} a_{ik} \otimes \left[\sum_{l=1}^{N} \sum_{m=1}^{N} a_{lm} \right]^{-1} \quad (8)$$

where $i = 1, 2, \dots, N$; $j = 1, 2, \dots, K$.

(c) Implementation of the aggregation principle. This procedure aggregates the criteria and subcriteria levels, or "removes" one tier from the hierarchy. They are thus set at a single tier. It means that if k_j is the number of subcriteria under the j-th criterion, the total number of subcriteria is defined by Equation (9) and the result is expressed as the final subcriteria weights as follows:

$$K = \sum_{j=1}^{m} k_j \quad (9)$$

(d) Defining the fuzzy decision matrix and fuzzy performance matrix by mathematical operations. The fuzzy decision matrix (Equation (10)) of the alternatives is derived from the fuzzy extent analysis in Substep 6-b, and the overall effectiveness of each alternative relative to all the analyzed subcriteria is calculated and represented by a fuzzy performance matrix (Equation (11)):

$$X = \begin{bmatrix} x_{11} & x_{12} & \dots & x_{1K} \\ x_{21} & x_{22} & \dots & x_{2K} \\ \dots & \dots & \dots & \dots \\ x_{N1} & x_{N2} & \dots & x_{NK} \end{bmatrix} \quad (10)$$

$$Z = \begin{bmatrix} x_{11} \otimes W_1 & x_{12} \otimes W_2 & \dots & x_{1K} \otimes W_K \\ x_{21} \otimes W_1 & x_{22} \otimes W_2 & \dots & x_{2K} \otimes W_K \\ \dots & \dots & \dots & \dots \\ x_{N1} \otimes W_1 & x_{N2} \otimes W_2 & \dots & x_{NK} \otimes W_K \end{bmatrix} \quad (11)$$

(e) Evaluation of projected alternatives. The final score of each MDMP alternative is calculated by mathematical operations used for fuzzy sets, applying Equation (12). The results are represented by triangular fuzzy numbers:

$$F_i = \sum_{j=1}^{K} x_{ij} \otimes W_j \quad (12)$$

(f) Sensitivity analysis of projected alternatives. The sensitivity analysis is conducted in parallel with the evaluation of the alternatives, using Equation (13) which expresses the expert's risk assessment [49,50]. The total integral value is calculated as the following:

$$I = \frac{(d\lambda + s + (1-\lambda)l)}{2}, \quad \lambda \in [0,1] \quad (13)$$

where λ is the optimization index ("0" pessimistic, "1" optimistic and "0.5" neutral expert judgment) and l, s and d are the parameters that constitute a triangular fuzzy number.

Step 7—Defuzzification. In this step the score of each MDMP alternative is converted from a fuzzy to a real number using one of the defuzzification methods [51]. The sum of the scores assigned by the expert to all the alternatives is equal to one ("1").

Step 8—Ranking. The optimal MDMP is the projected alternative, or the dewatering system from Step 4, which received the highest score in Step 7.

Step 9—Implementation of the solution. Experts synthesize the entire analysis, per the protocol, into a detailed report. This results in a multiyear MDMP that incorporates predefined future mining activities. Successful implementation of this plan will standardize mining and related activities, leading to efficient ore extraction, increased productivity, and enhanced market competitiveness. Improper implementation can lead to adverse consequences, even after a thorough analysis and synthesis of all criteria to ensure safe mining operations. Therefore, solution implementation requires a responsible and serious approach, commitment from the project team, and strong management support. This underscores the critical role of expert knowledge throughout the entire protocol process.

4. Study Status of MDMP Protocol Application

To demonstrate the proposed protocol for optimal MDMP selection and to address groundwater management problems, a case study was undertaken at the Buvač mine of limonite ore in the Republic of Srpska, Bosnia and Herzegovina, [5,14,15].

The study area of limonite ore body "Buvač" exemplifies the gradual implementation of all three parts of the protocol. Initial research and field measurements were conducted between 2008 and 2012. Subsequently, a problem analysis was undertaken to identify a solution for sustainable mine protection against groundwater.

The defined components of the groundwater control system, along with the components of the mine protection system scheduling (on/off), served as dynamic landmarks when creating estimation variants for the period from 2013 to 2024, which encompassed the pre-planned period of mine operation and ore exploitation.

All planned activities for surface mine defense against groundwater are based on an annual level (beginning 1 January), which dictates the activation and cessation of specific water defense system elements and aligns with the progress of mining operations. Since the mine's opening in 2013, the selected mine dewatering management plan has been monitored and will continue until the end of 2024, when all mine activities will cease.

During this extended period, from the initial stage of limonite exploitation and drainage, a comprehensive monitoring system has been established. This involves remote sensing and monitoring of ground subsidence and overall area morphology, measurement of groundwater levels in piezometers, assessment of groundwater depletion, analysis of groundwater physical and chemical parameters, monitoring of surface water levels and quality, and other relevant parameters.

The data processing procedure for the 12-year period will follow, and a comprehensive analysis of the system is expected to be completed by the end of 2025. This future study will involve a comparative analysis of the estimated results obtained from pre-operation model tests and the actual data observed over the long-term period of mine operation. All processed data will be visualized on maps (groundwater maps, land subsidence maps, geohazard risk maps, etc.) according to the criteria and subcriteria outlined in the MDMP protocol application.

5. Conclusions

The protocol for a sustainable mine dewatering management plan, based on decision-making, presents a modern approach to investigations in geoscience and groundwater management.

This protocol utilizes contemporary scientific methods to develop an optimal mine dewatering management plan (MDMP). Numerical modeling, specifically predictive hydrodynamic simulations, is employed to inform dewatering strategies. Additionally, fuzzy logic within a multiple-criteria decision analysis framework is used to select the most suitable MDMP alternative.

The specific features of the protocol are reflected in the set criteria and their subcriteria, which may be deemed universal for dewatering plans. Importantly, the protocol is adaptable, allowing for the selective application and modification of certain parts. This is particularly true for the third part, which involves fuzzy optimization for decision-making. As science and technology advance, alternative fuzzy optimization approaches may be incorporated into the protocol.

The special-purpose fuzzy-GWCS application has been developed to facilitate decision-making in connection with multiple-criteria decision modeling. By enabling score entry and pairwise comparison of the hierarchical sequence "criteria-subcriteria-alternative solutions", the application simplifies extensive mathematical simulations and allows for easy monitoring of model sensitivity to input parameter changes.

A key aspect highlighted in the protocol is the reliance on expert knowledge, intuition, and experience to gather information about the natural mine system through investigations. This expert input is crucial throughout the protocol, as MDMP developers often encounter challenges that can be effectively addressed through heuristic approaches.

The need for an interdisciplinary approach to various scientific problems is emphasized. In the context of the proposed protocol, this is particularly relevant to mine hydrogeology. The proposed complex interdisciplinary protocol contributes to robust and sustainable management of mine protection against groundwater. Such an integrated approach to developing an optimal MDMP, verified by a real-world case study, is highly valuable in practical scenarios where areas threatened by groundwater require dewatering.

On the one hand, the protocol significantly contributes to both the academic community, fostering future research, and the scientific community, by applying mathematical principles to geosciences. On the other hand, by emphasizing the heuristic approach and teamwork, the protocol highlights the importance of human resource management in engineering–geological surveys and ecological assessments.

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