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Categorization of the Potential Impact of Italian Quarries on Water Resources through a Multi-Criteria Decision Aiding-Based Model

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Abstract: Quarrying has great importance for economic development and, at the same time, can have several adverse environmental impacts; specifically, it may have a significant influence on water resources. There are approximately 4000 quarries in Italy, and knowledge of their potential impact on water resources is limited. To this end, a procedure for categorizing Italian quarries was devised by combining the methods of Geographic Information Systems and Multi-Criteria Decision Aiding, selecting the potentially impactful criteria, and parametrizing the latter through the available databases. Using the ELECTRE models (ELECTRE TRI and ELECTRE III), the impact category of each quarry was assessed separately for surface water and groundwater and then the overall impact on water resources was assessed. The simulations were carried out by varying the weights of the various selected criteria, which allowed the grouping of Italian quarries into five categories with increasing potential impact on water resources. The ranking of quarries falling into the two highest-impact categories was further refined using ascending and descending distillations. The categorization can be interpreted as a first national assessment of the sustainability of quarrying activities with reference to water resources. The methodological approach of the study proved to be appropriate for the quarry-sorting and -ranking processes, lending itself to the introduction of other criteria and weights, including those arising from the participation of different stakeholders.

Keywords: quarry; multi-criteria decision aiding; water resources; sustainable mining; Italy

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1. Introduction

Extractive industries play a relevant part in promoting social and economic well-being by providing raw materials, facilitating the development of infrastructure, generating wealth for the communities and creating job opportunities [1]. However, mining operations may have several negative environmental and social impacts, including changes in the natural environment, soil erosion, air and water pollution, noises, vibrations, conflicts among local communities and threats to human safety [2–7].

Mining and quarrying may have a significant impact on water resources. Several factors, including the mining and quarrying operations as well as local hydrogeological and meteorological conditions, determine how water interacts with extractive activities [8–10]. Various negative environmental effects, such as declining water quality and groundwater levels, sinkhole formation, and soil subsidence, are linked to the inadequate drainage of quarry water [6,11]. Quarry excavations, particularly those located in plain areas, usually develop below the potentiometric surface of the local aquifer, which has no natural defenses provided by soil and unsaturated zone [10,12,13]. These types of quarries require dewatering operations, which can affect groundwater flow paths and natural flow toward wells, springs, and streams [14,15]. A more complex challenge may be posed by acid mine drainage. Unaltered rocks can react with air and water to generate extremely corrosive acids and poisonous heavy metals when disturbed and oxidized during mining operations or waste storage [16–19]. These acids and heavy metals can contaminate groundwater and surface water, causing serious harm to the environment and human health [20–24]. To mitigate these potential damages, in addition to optimizing mining and quarrying operations, effective planning of the activities in the area can be developed to reduce the impact of such operations on water resources, which means making mining sustainable.

In the case of groundwater, information can be obtained by estimating the vulnerability of the aquifer [25–27]. Several methods have been employed to assess the vulnerability of aquifer systems to negative impacts caused by quarries and other human activities, such as DRASTIC and SINTACS methods [28–30]. Other more targeted studies focus on the development of an interaction index to assess the impact of quarry deepening on the regional hydrogeology and nearby water catchments for public distribution [31,32]. This index serves as a tool for recommending feasibility studies and minimizing the environmental impact of quarry activities [31]. The concept of the interaction index is further applied in the work of Barthélemy et al. [32], where a machine learning process was developed. In these above-mentioned studies, the main factors considered to assess the impact of the quarry on groundwater are the local geological and hydrogeological setting, the location of the quarry in relation to the discharge area of groundwater flow (springs, wells and streams), and the potential quality of the groundwater.

In Italy, 3429 authorized and active extraction sites were surveyed in 2018 [33], divided into mines and quarries according to Italian legislation [34]. Mines are defined as extractive sites of high-value materials, such as metals, metalloids and their compounds, gemstones and combustibles. In the quarries, the extractive activities primarily focus on materials for the building industry and ornamental stones. This census shows that the number of quarries (3335) is much higher than that of the mines (94). In 2018, a total of 152.4 million tons of material was extracted from the quarries, earning revenues of about EUR 2.9 billion, equivalent to 0.2% of Italian GPD. The main materials extracted include limestone, travertine and sandstone, accounting for approximately 46% of the total volume, while sands and gravels represent about 32% of the total volume [33].

Despite the intense extractive activity in Italy, there is limited knowledge about the actual impact of these operations on water resources. The aim of this research is to outline a comprehensive overview of the potential impact of quarries on water resources in Italy. This nationwide analysis is also valuable for informing future decisions on the sustainability of quarrying with specific reference to water resources. In this regard, the wide range of Italian cases offers a broad sample of varying hydrogeological settings, providing general-purpose information. To achieve the above mentioned goal, a categorization procedure of Italian active quarries was devised by combining methods of Geographic Information Systems (GIS) and Multi-Criteria Decision Aiding (MCDA). This approach is grounded in Italy's geological and hydrogeological features, along with the collection of data on quarries.

2. Materials and Methods

The method followed to categorize active quarries in Italy, based on their potential impact on water resources, has been developed in three phases, illustrated schematically in Figure 1. In the first phase, the conceptual model has been designed to identify parameters that may have significant weight in determining the impact of the extractive activities on the water resources. In the second stage, the spatial information about Italian quarries was managed in a GIS environment, determining for each quarry the previously identified parameters using available databases. In the third phase, applying MCDA models, parameter values were weighed based on the conceptual model developed in the first stage, in order to rank the potential impact of quarries on water resources.

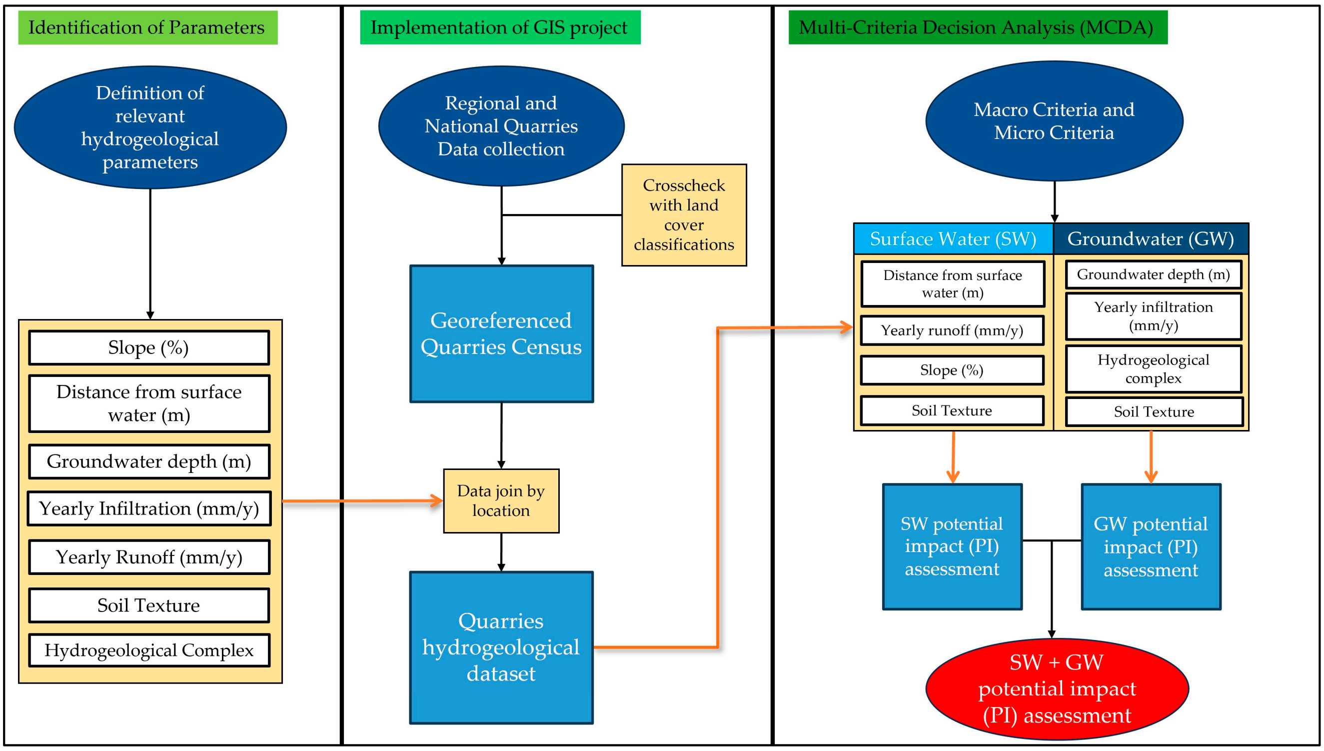

Figure 1. Flowchart of categorization of Italian quarries depending on their potential impact on water resources.

2.1. *Conceptual Model of the Impact of Quarries on Water Resources: Identification of Parameters*

The initial phase of quarry categorization involved the identification of parameters that could potentially affect the quality and quantity of water resources in extraction areas. For this purpose, relevant parameters from models discussed in existing literature have been considered [7,11,15,31,32,35], taking into account their availability in the databases. Due to the considerable number of quarries, the scale of investigation and the actual availability of data, a simplified version of the conceptual model of the impact has been adopted. Seven main parameters were identified (Figure 2), distinguishing among those that have an impact on surface water and groundwater. Most of these parameters align with those considered in methods adopted to carry out aquifer vulnerability maps [35] and with those assessing the interaction index of the quarry on water resources [31,32].

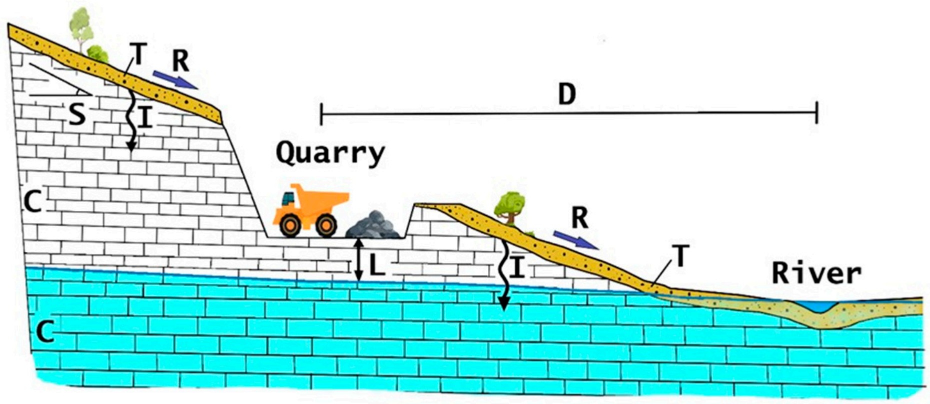

Figure 2. Conceptual scheme of parameters influencing the impact of quarries on water resources: **D**, distance from surface water body; **R**, runoff; **I**, effective infiltration; **S**, slope; **C**, hydrogeological complex; **L**, depth of groundwater level; **T**, soil texture.

In the existing literature, the potential impact of quarrying on surface water is primarily associated with the deterioration in its quality [15,16,20]. Therefore, the four parameters selected are the following:

- The distance of the quarry from surface water bodies (D), which influences the dilution of any contaminant load from the quarry area into the surface water body;
- The amount of runoff (R) on which the contaminant load discharging into the surface water body depends;
- The surface slope of the quarry area (S), which affects the velocity of surface runoff and then the time for pollutants to reach the surface water body;
- The soil texture of the quarry area (T), which determines the components of the runoff, specifically the distribution between the overland flow and the interflow that can reach the surface water body.

As known in the literature, the impact of quarry activities on the groundwater resources can be both quantitative, affecting the local hydrogeological equilibrium, and qualitative, leading to an increase in groundwater pollution [16,19,23]. Based on the factors considered in assessing groundwater vulnerability to pollution, the four parameters selected to simplify the categorization of the potential impact of the quarries are the following:

- The groundwater level depth in the quarry area (L), influencing the hydrodynamic interactions and exposure to groundwater pollution;
- The amount of effective infiltration (I), which determines the contaminant load that can reach the groundwater;
- The hydrogeological complex of the quarry area (C), that is, a geological unit or more geological units united by a homogeneous degree and type of permeability, with a size which is significant for the scale of the groundwater flow [36,37]. The recharge, flow and discharge of groundwater depend precisely on the different hydrogeological complexes identified in Italy [38];
- The soil texture of the quarry area (T), which acts as initial filter in mitigating groundwater pollution from surface sources.

2.2. Database of the Italian Quarries: Implementation of GIS Project

The census of the quarries located in Italy was conducted primarily through the available data, including the following:

- The ISTAT's database on quarries and mines [33], which reports information on extraction activities categorized by site and material type;
- Twenty-one Regional Mining Activity Plans (PRAEs); i.e., the regulatory instruments for planning mining activities on a regional scale, where quarrying data are updated according to different Italian regions;
- Other reports prepared by environmental organizations [39].

The results of this survey, aimed at identifying the location and the areal extent of the active quarries, were compared and integrated with available land use maps. Specifically, Corine Land Cover 2018 [40], which identifies 44 thematic classes of land use, and the National Land Use Map [41], which updated the previous land use classification, were considered.

The data obtained from the censuses and the checks carried out through the land use maps allowed the definition of the location and surface area of the quarries. QGIS 3.28.00 software was used to store this information and each quarry surface area has been represented by a georeferenced polygon. In the same GIS file, data for the seven selected parameters for each quarry have been stored and managed.

- Specifically, the surface slope (S) was calculated using a Digital Elevation Model (DEM) with a 25 m resolution [42], through an algorithm derived from the GDAL DEM utility (included in the QGIS package), which generates a slope map from any GDAL-supported elevation raster file. To estimate the distance of quarries from surface water (streams, rivers and lakes) (D), a specific layer was created by merging data from the Italian Ministry of Environment and Energy Security's database on hydrographic network and lake location [43]. Annual effective infiltration (I) and runoff (R) were derived from the model "BIGBANG 4.0" [38], which calculates the water balance equation for the entire Italian territory using square cells of 1 km^2. Soil texture (T) information was obtained from the European Soil Data Centre 2.0 [44], where soil texture is mapped according to the USDA classification with a cell size of 500 m. The hydrogeological complex (C) of quarry areas was derived from the map of hydrogeological complexes carried out by ISPRA [45], which identified 11 hydrogeological complexes based on the lithological map of Italy [46]. The groundwater-level depth in the quarry areas (L) was determined considering the following: (i) the national borehole dataset [47], providing information on wells and boreholes deeper than 30 m; (ii) the Regional Water Protection Plans, containing details on wells and springs; and (iii) a 1 km-resolution raster file of water table depth [48], adopted only when no data on wells and springs close to the quarry were available from the aforementioned databases.

2.3. Multi-Criteria Decision Aiding (MCDA)

Several approaches and methods have been proposed in the literature for vulnerability and risk assessment when complex problems involve human activities and environmental protection in the context of sustainable development [49–54]. Considering that the aim of this study is to obtain an initial categorization of the Italian quarries based on their potential impact on water resources, as a tool for a future broader analysis of the sustainability of mining, a simplified approach using Multi-Criteria Decision Aiding (MCDA) [55–60] has been adopted. We deal with a large number of alternatives (i.e., the number of quarries being a few thousand), compared based on specific hydrological and hydrogeological criteria. These criteria include selected parameters for surface water and groundwater, sometimes interdependent or interconnected, expressed both in numerical and ordinal scales. The solution to the problem is certainly not easy when relying on the simple maximization or minimization of an objective function. It must be approached with the use of more flexible tools capable of contextualizing the decision-making process in a global inter-system context, also taking into account the data currently available for Italian quarries.

The large number of alternatives made the choice fall on the ELECTRE models [61–63]. These models can incorporate a vast range of data and are related to criteria, weights, indifference, weak preference, strong-preference thresholds and even veto thresholds. The objective of sorting the quarries from the most impactful to the least impactful, giving their considerable number, cannot be pursued by solving a ranking type problem (γ problematic) through the ELECTRE III. Instead, it requires the application of a sorting type problem (β problematic), involving the division of quarries into categories based on different levels of impact; this is accomplished through the application of the ELECTRE TRI model [64–66]. The software chosen to apply this decision analysis procedure was MCDA-ULaval v0.6.28, developed at the Université Laval of Quebec [67].

Before initiating the sorting process among all the quarries, it is essential to establish gradual levels of criticality within the evaluation scales of each criterion. These levels serve as the basis for formulating judgments for each quarry. Therefore, for each criterion, five levels of criticality have been defined, which are determined by the minimum and maximum values of the related judgment scale, along with four separating values, appropriately identified through specific technical parameters. The impact degree of a quarry is then summarized through the various levels of criticality that combine the different judgment criteria. Quarries which, on average, across various criteria, receive evaluations falling into the highest levels of criticality, will be categorize with the highest impact. Conversely, those falling into the lowest levels of criticality will be considered as having lower impact. Within the set of quarries identified with the highest impact, considering their potentially reduced number compared with the total, a refinement of the results can be performed.

This involves a further evaluation of the quarries, in this case strictly ordinal, ranging from those with the most critical impact to those with the least critical impact.

The mathematical algorithm used for the quarry categorization can be summarized as follows.

Given a set G of m criteria, for each criterion g_j, where $j = 1, 2, \ldots, m$, the preference and indifference thresholds (q_j and p_j, respectively) and potentially a veto threshold (v_j) must be set. Subsequently, to each pair of alternatives, a and b, the classification algorithm associates a restricted outranking relation aS_jb. The latter relation is based on the premise that sufficiently strong reasons converge for the truth of the statement "*a*, *with respect to criterion j*, *is at least as good as b* (*not worse than*)". From all m restricted outranking relations, a complete outranking relation "*aSb*" is derived.

For each j-criterion and for each pair of alternatives (a,b), the construction of relation aS_jb involves three subsequent phases:

1. The calculation of a concordance index $c_j(a,b)$, so if
   - $g_j(b) - g_j(a) \leq q_j$ is $c_j(a,b) = 1$, there is no contradiction with the statement "*aSb*";
   - $q_j < g_j(b) - g_j(a) \leq p_j$, is $0 < c_j(a,b) < 1$, there is weak contradiction with the statement "*aSb*";
   - $g_j(b) - g_j(a) \geq p_j$, is $c_j(a,b) = 0$, there is a total contradiction with the statement "*aSb*".

   Once the indices $c_j(a,b)$ have been computed and the weights w_j associated with each j-criterion (g_j) have been considered, the global concordance index $c(a,b)$ is constructed as follows:

$$c(a,b) = \sum_j w_j c_j(a,b)$$

   The global concordance indices are summarized in a global concordance matrix $C(a,b)$.

2. The calculation of a discordance index $d_j(a,b)$, such as to indicate the extent to which the relation between the a and b on j-criterion disagrees with the statement "*aSb*" and its effect on the relation *aSb*, so if
   - $g_j(b) - g_j(a) \leq p_j[g_j(a)]$ *is* $d_j(a,b) = 0$, there is no contradiction with the statement "*aSb*";
   - $p_j[g_j(a)] < g_j(b) - g_j(a) \leq v_j[g_j(a)]$, is $0 < d_j(a,b) < 1$, there is weak contradiction with the statement "*aSb*";
   - $g_j(b) - g_j(a) \geq v_j[g_j(a)]$, is $d_j(a,b) = 1$, this prohibits any outranking of a over b, regardless of the evaluations on all the remaining criteria.
3. The construction of the outranking relation is completed by establishing the degree of credibility $\sigma(a,b)$, a value between 0 and 1. This value, considering both the concordance and discordance indices, summarizes the strength of the "*aSb*" relation.

The calculation of $\sigma(a,b)$ starts from the concordance index $c(a,b)$, weakened through the discordance indices $d_j(a,b)$ if and only if its value is sufficiently high, and that is if the condition $d_j(a,b) > c(a,b)$ is true.

In general, let $G(a,b)$ be the set of criteria for which the discordance index is greater than the concordance index:

$$G(a,b) = \left[j/j \in G, d_j(a,b) > c(a,b) \right]$$

we have the following:

if $G(a,b) = 0$, an absence of discordant criteria, then $\sigma(a,b) = c(a,b)$;

if $G(a,b) \neq 0$, then $\sigma(a,b) = c(a,b) \prod_{j \in G} \frac{1-d_j(a,b)}{1-c(a,b)}$.

The classification algorithm, summarizing the outranking relation, provides a partial ordering of the alternatives. Two orders are constructed: the first by selecting the alternatives from best to worst (descending distillation), the second by starting from the worst alternatives to arrive at the best (ascending distillation). To construct the two orders, we proceed through the cutting algorithm with specific characteristics [68]. The intersection between the ascending and descending orders highlights the relationships between alternatives and underlines some incomparability. In particular, alternative a is considered as the following:

- Better than alternative b, if, in at least one classification (ascending or descending), a is positioned better than b, and in the other a is classified at least as well as b;
- Equivalent to alternative b, if the two belong to the same class in both systems;
- Incomparable with alternative b, if there is a contradiction in the two classifications; for example, a is in a better position than b in the ascending classification, but b is positioned ahead of a according to the descending distillation.

All selected data of the quarries, exported from GIS, have been summarized in a matrix with the number of rows equal to the number of quarries and eight columns, corresponding to the selected criteria, specifically four for surface water (SW) and four for groundwater (GW) (Figure 3).

Macro-Criteria	Surface Water **(SW)**				Groundwater **(GW)**				**PI Growth**
Micro-Criteria	Distance from surface water (m) **D**	Runoff (mm/yr) **R**	Slope (%) **S**	Soil Texture **T**	Groundwater depth (m) **L**	Infiltration (mm/yr) **I**	Hydrogeological Complex **C**	Soil Texture **T**	
Micro-criteria Thresholds	>500	<50	<7	Sand	>40	<50	Medium/fine alluvial Pelitic	Clay	**VL**
	300 – 500	50–100	7 – 14	Sandy Loam Sandy Clay	20 – 40	50 – 100	Crystalline rock Flysch	Silty clay-loam Silt	**L**
	100 – 300	100 – 300	14 – 27	Clay - Loam Loam	8 – 20	100 – 300	Sandstone/Conglomerate Pyroclastic Dolostone	Clay - Loam Loam	**M**
	50 – 100	300 – 500	27 – 47	Silt Silty clay-loam	2 – 8	300 – 500	Volcanic Evaporitic	Sandy Clay Sandy Loam	**H**
	<50	>500	>47	Clay	<2	>500	Coarse alluvial Carbonate	Sand	**VH**

Figure 3. Macro–criteria (SW surface water, GW groundwater) and micro-criteria (D, distance from surface water body; R, runoff; S, slope; T, soil texture; L, depth of groundwater level; I, effective infiltration; C, hydrogeological complex) and their class of potential impact (PI) on surface water and groundwater considered in the MCDA model.

Three criteria refer to qualitative evaluations (T for SW and T and C for GW); they were transferred and summarized on an ordinal scale (Figure 3). As mentioned earlier, to apply the ELECTRE TRI, five predefined levels of critical impact on water resources were established within the evaluation scales of each criterion (Table 1). The levels were identified through four separating values, chosen based on technical considerations (Figure 3). These values, for each criterion, categorize an alternative into different bands of more- or less-accentuated potential impact. For each criterion, indifference and preference thresholds were inserted, representing evaluations within which there is indifference or dominance of one over another in a pairwise comparison. These thresholds must be proportionally related to the evaluations being compared.

Table 1. Category classification of quarry impact according to the ELECTRE TRI model.

MCDA Classification	Level of Impact
Category 1 (C1)	Very low impact (VL)
Category 2 (C2)	Low impact (L)
Category 3 (C3)	Medium impact (M)
Category 4 (C4)	High impact (H)
Category 5 (C5)	Very high impact (VH)

Finally, weights were assigned to the criteria, initially to the two macro-criteria (SW and GW), and then to the micro-criteria into which each of the two macros has been divided

(Figure 3). The choice of weights w_j for the various criteria plays a crucial role. Initially, the AHP (Analytic Hierarchy Process) method of pairwise comparisons [69] was applied, considering the eigenvector associated with the pairwise comparison matrix obtained from the particular value judgments made on each possible pair of criteria, as well as the different criteria deemed to have weight within the final categorization by the conceptual model. A second application involved the determination of weights through the ordinal method of the cards [70,71], in which the set of criteria is divided into several possible subsets of decreasing importance relative to the conceptual model, each of which is assigned the corresponding rank. A third application refers exclusively to expert judgements which consider a gradually decreasing weight for the micro-criteria to be deemed less influential on the potential impact of the quarries.

3. Results

By combining the information contained in the databases concerning the quarries with the land use maps, it turns out that 4043 quarries are active in Italy, showing a non-homogeneous distribution across the territory, as illustrated in Figure 4. Although there is no updated database concerning the type of material extracted from each quarry, an initial characterization of the quarried materials has been achieved in a GIS environment by correlating the quarry's position with the outcropping geological units. As shown in Figure 5, quarrying activities predominantly involve granular material (mostly sands and gravels) and carbonate rocks, with volcanic, siliciclastic and crystalline rocks being secondary.

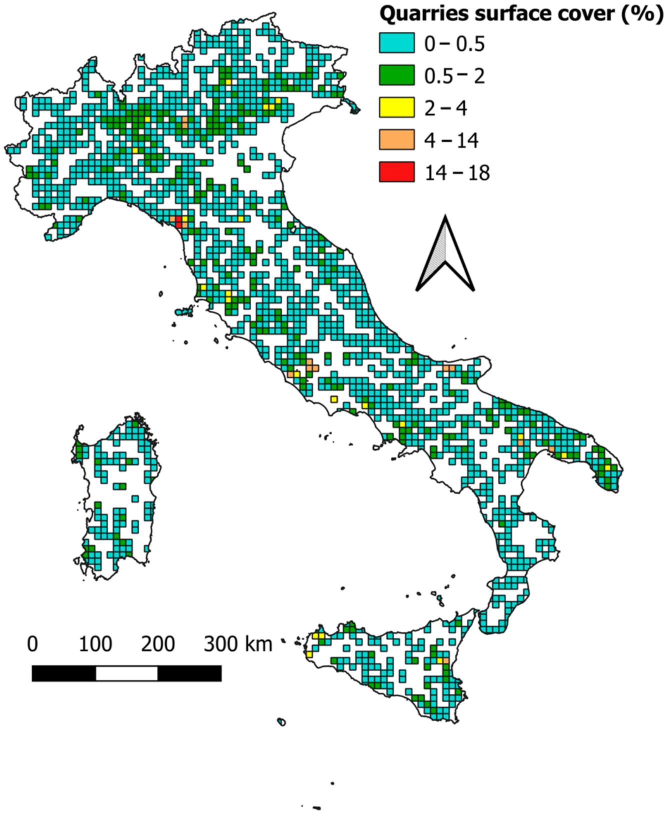

Figure 4. Percentage distribution of quarry areas in Italy (calculated on 100 km^2 cells).

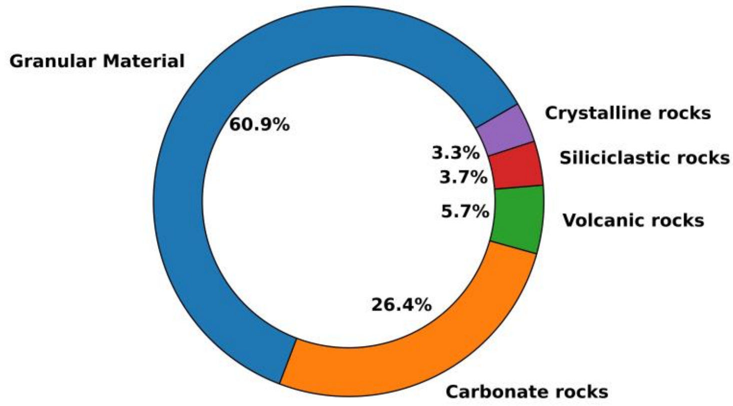

Figure 5. Percentage distribution of materials extracted in Italy.

The identification of seven potentially impactful parameters for each quarry, subsequently employed in applying the MCDA model (Figure 3), allowed for the definition of the ranges of their variation and frequency distribution within the respective classes for the entire dataset. Regarding the distance of the quarries from surface water bodies (D), the most represented class has a distance greater than 500 m, followed by the class with a distance less than 50 m (Figure 6a). Annual runoff (R) presents a wide variation in quarry areas (from 20 to 600 mm/yr): as depicted in Figure 6b, the most prevalent class among the five distinguished has an annual runoff of 100–300 mm/yr, followed by classes of 300–500 mm/yr and 50–100 mm/yr. The surface slope of quarry areas (S) ranges between 0.2% and 150%. Among the five distinct classes for this parameter, the most represented is the one which has a slope measuring less than 7% (Figure 6c). The depth of the groundwater level in quarry areas (L) varies from a few meters (or even excavations directly below the groundwater level) to about 80 m. Among the five classes distinguished for this parameter, the most represented classes are those with a groundwater-level depth less than 2 m and greater than 40 m, while the other classes are almost homogeneously represented (Figure 6d). The annual effective infiltration in the quarry areas (I) shows significant variations (ranging from 10 to 600 mm/yr) in relation to the climate zones of the peninsula and the permeability of the outcropping geological units. The ranges of the identified classes resemble those of annual runoff, and a comparable frequency distribution is evident (Figure 6e). Based on the eleven hydrogeological complexes defined in the recent hydrogeological map of Italy [45], five classes of hydrogeological complex (C) have been distinguished based on the degree of permeability, which is useful for the MCDA model (Figure 3). As shown in Figure 6f, the most prevalent complexes are the coarse alluvial and carbonate complexes, which also have the highest degree of permeability. Soil texture (T), according to the USDA classification, has been grouped into five classes of interest for the MCDA model application (Figure 3). Two classes are represented more: silt and silty-clay-loam soils, along with sandy-clay and sandy-loam soils (Figure 6g).

The seven parameters and their respective classes were used in the application of the ELECTRE TRI model. Initially, the impact category was assessed separately for surface water (SW) and groundwater (GW) and then the overall impact on water resources was assessed.

As a result, a matrix of 4043 rows, representing the number of quarries or alternatives, and eight columns, corresponding to the selected criteria, has been obtained (Figure 3). For six of the chosen criteria (R, S, and T for SW and I, C, and T for GW) the potential impact being directly proportional to the reported evaluations means that they require maximization. Conversely, for two of the selected criteria (D for SW and L for GW) the potential impact is inversely proportional to the evaluations, and thus, minimization is necessary (Figure 3). Subsequently, weights were assigned to the two macro-criteria

(SW and GW) and the eight micro-criteria. For macro-criteria, an equal weight has been considered for surface water (w_{SW}) and groundwater (w_{GW}), obtaining a total weight (w_{WR}):

$$w_{WR} = 0.5\ w_{SW} + 0.5\ w_{GW}.$$

Therefore, surface waters and groundwater have been considered as resources to be safeguarded just as deservedly (also in accordance with the relevant European directives [4]) in an overall assessment of the potential impact of quarries on waters.

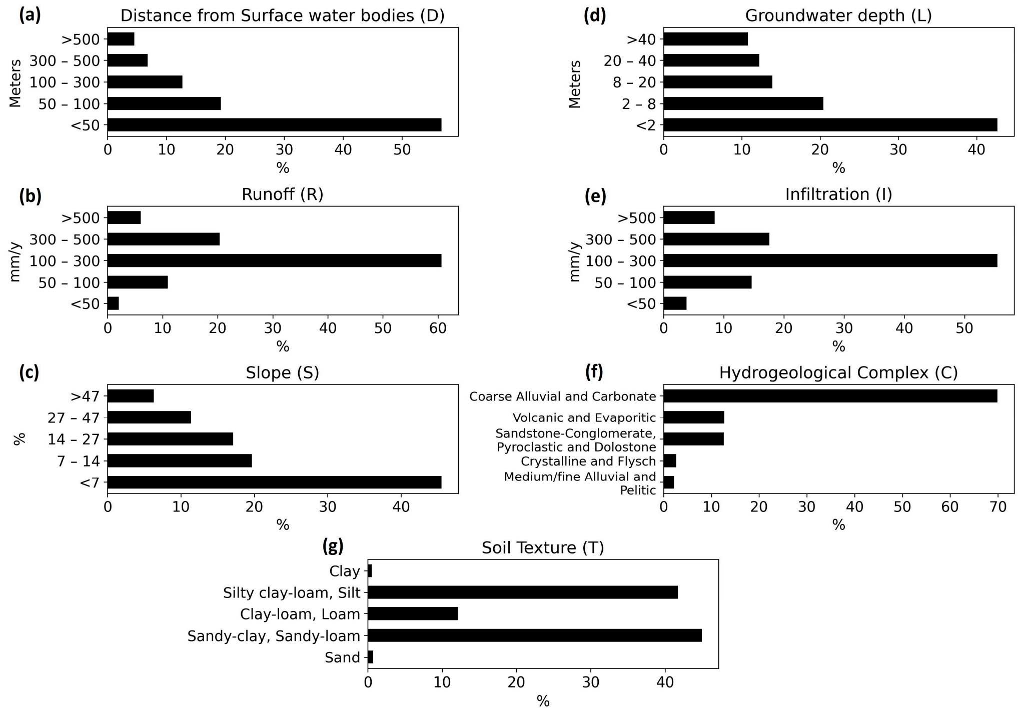

Figure 6. Percentage distribution of the classes related to the seven parameters considered for the MCDA model: (**a**) distance from surface water (D); (**b**) runoff (R); (**c**) slope (S); (**d**) depth of groundwater level (L); (**e**) effective infiltration (I); (**f**) hydrogeological complex (C); (**g**) soil texture (T).

The weight of the micro-criteria underwent different tests using various methods, including the AHP method of pairwise comparisons [69], the ordinal method of the cards, specifically using the methods of one white card (1CW) and two white cards (2CW) [70,71], and halving the weight for the four micro-criteria, depending on their considered importance on the determination of the impact category (Table 2). In the three weight-assignment methods, micro-criteria D, R, S and T have always been considered, in this order, to be the most important for determining the impact category on surface water, according to the conceptual model. For groundwater, among the parameters considered in the conceptual model, the micro-criteria L, I, C and T have always been considered, in this order, to be the most important in the three weight-assignment methods (Table 2). The consistency of the weights assigned to micro-criteria was verified by evaluating the local geological, hydrological and hydrogeological conditions of a hundred quarry samples falling into impact categories C1 and C5.

The data processing through the ELECTRE TRI model, involving the matrix of performances and the decision configuration table, did not result in the expected subdivision of the alternatives into five categories but rather an almost double number, either nine or ten. This discrepancy arises because a considerable number of alternatives presented conflicting levels of impact across various criteria, as shown in the examples of Figure 7.

Table 2. Weights assigned to different micro-criteria in the four simulations.

Micro SW	AHP	1CW	2CW	Halving
D	0.253	0.222	0.216	0.267
R	0.137	0.158	0.148	0.133
S	0.084	0.078	0.091	0.067
T	0.026	0.039	0.034	0.033
Micro GW	**AHP**	**1CW**	**2CW**	**Halving**
L	0.236	0.222	0.216	0.267
I	0.144	0.130	0.148	0.133
C	0.077	0.112	0.113	0.067
T	0.043	0.039	0.034	0.033

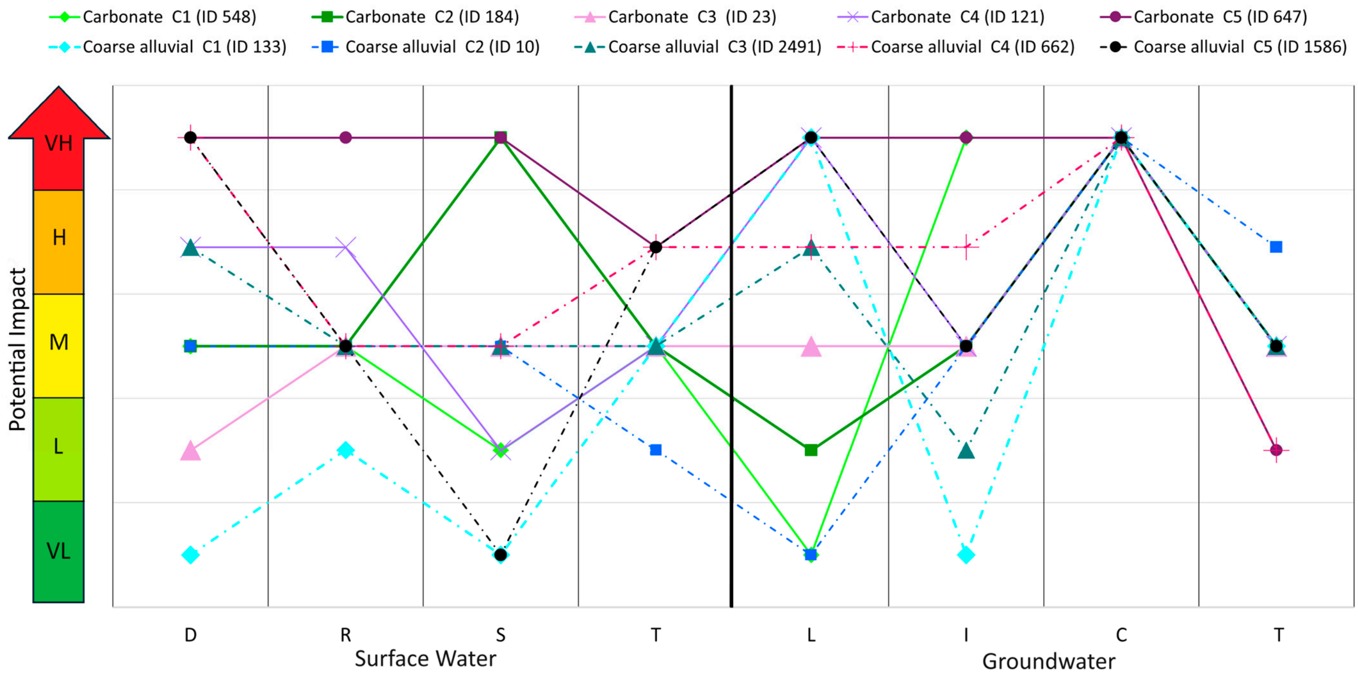

Figure 7. Examples of quarry categorization and its dependence on the different selected criteria.

As a result, the algorithm assigned them to not-well-defined positions, indicating intermediate performances among categories. This outcome, far from being counterproductive, allowed the identification of differentiations between alternatives that might have been missed otherwise. Moreover, each quarry is classified into two different categories, one indicating a more optimistic impact and another reflecting a pessimistic impact.

The final categorization of the 4043 quarries with reference to surface water is shown in Figure 8, where the percentage distribution of the quarries in the different impact categories is displayed, comparing the outcomes of the four simulations with the different weights of the micro-criteria. If we consider the quarries falling in the categories from C3-C4 to C5-C5, i.e., those most potentially impacting surface water, the percentage ranges in all simulations from 18.6% to 19.5%.

Figure 9 shows the comparison of quarry categorization as a function of groundwater macro-criteria obtained from simulations with the different weights assigned to micro-criteria. In this case, quarries falling in the categories C3-C4 to C5-C5, namely, those most potentially impacting groundwater, the percentage results are significant in all simulations (from 43.2% to 45.5%).

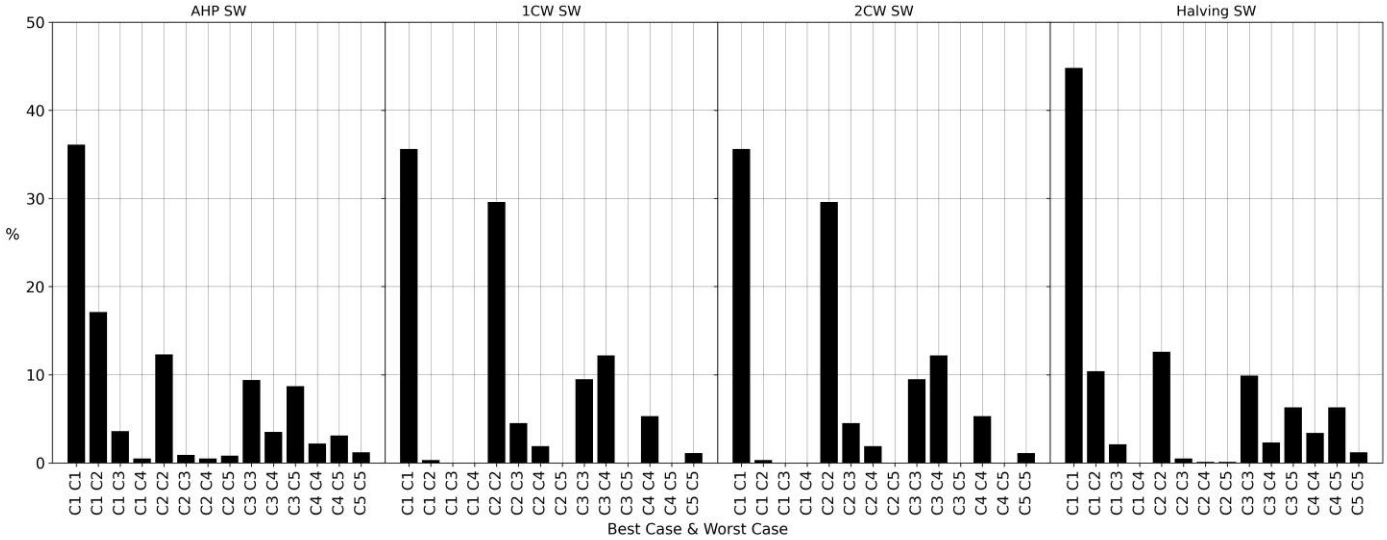

Figure 8. Percentage distribution of quarries in different categories for the potential impact on surface water resulting from the four simulations (AHP, 1CW, 2CW, and halving models of micro-criterion weights).

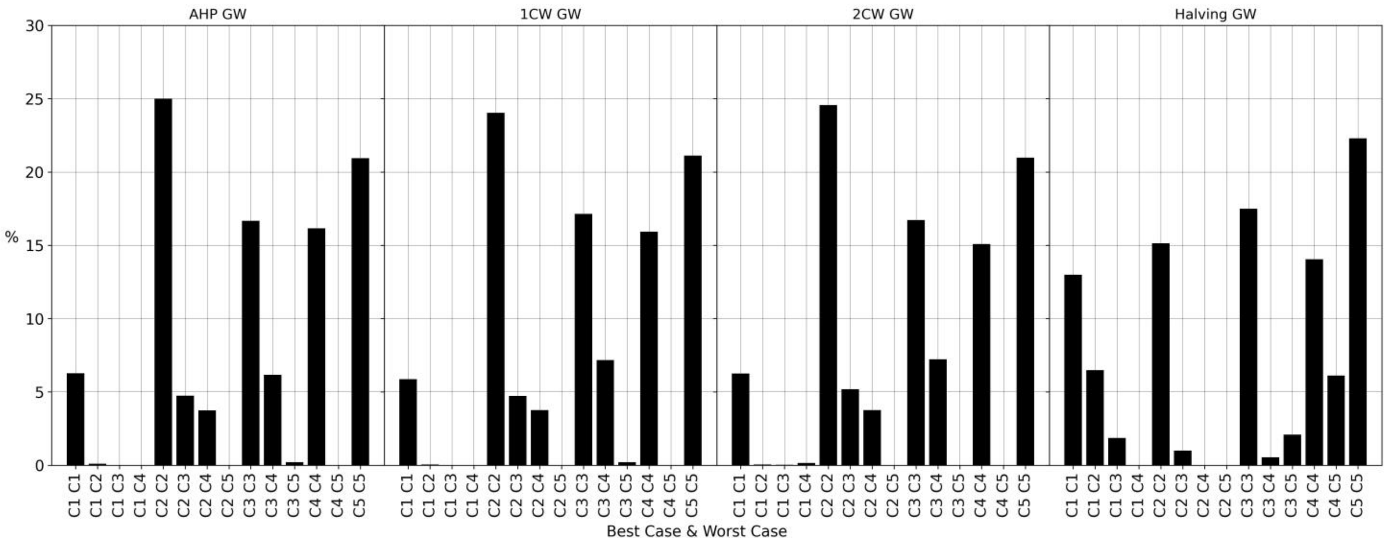

Figure 9. Percentage distribution of quarries in different categories for the potential impact on groundwater resulting from the four simulations (AHP, 1CW, 2CW, and halving models of micro-criterion weights).

The comprehensive potential impact assessment is achieved by combining the two macro-criteria. The percentage distribution of quarries in the different categories is shown in Figure 10 as resulting from the four simulations with the different weights of the micro-criteria. Here, the percentage of quarries falling into intermediate categories increases (C2-C3 to C3-C3, ranging from 32.7% to 38%) due to the equal weighing of the two macro-criteria (SW and GW), and thus there is a higher percentage of quarries potentially more impactful on groundwater.

The alternatives falling into the two categories of highest impact (category C4-C5 and category C5) for the last simulation (halving the weight for the four micro-criteria) were further examined using the ELECTRE III model with the same decision-making parameters (thresholds, weights, and decision configuration table). This model allowed the obtaining of a ranking for these alternatives, enabling the identification of the most critical and highly impactful quarries, as well as those of less-critical but still high impact. This refined ranking process provided an improvement in the results, initially judged unattainable for the entire dataset. The final ranking process confirmed a certain reliability of the results; there was a general consistency between the ascending distillation, which starts from the selection of the quarries of minimum impact, and the descending distillation, which starts from the selection of the quarries of maximum impact. In fact, as shown in Figure 11, most of the 173 quarries in categories C4-C5 and C5 fall around the x = y equation line, representative of the same ranking in ascending and descending distillations, with a mean error, root-mean-squared error (RMSE) and normalized RMSE (NRMSE) of 6.06, 19.99, and 0.22, respectively.

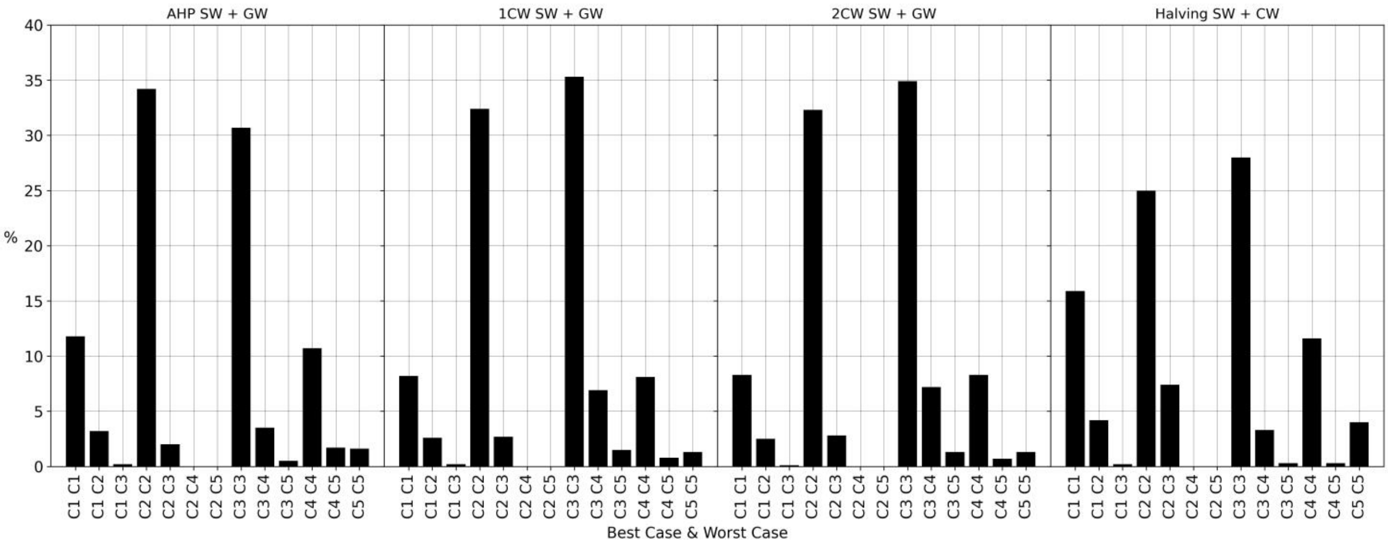

Figure 10. Percentage distribution of quarries in different categories for the potential impact on water resources resulting from the four simulations (AHP, 1CW, 2CW, and halving models of micro-criterion weights).

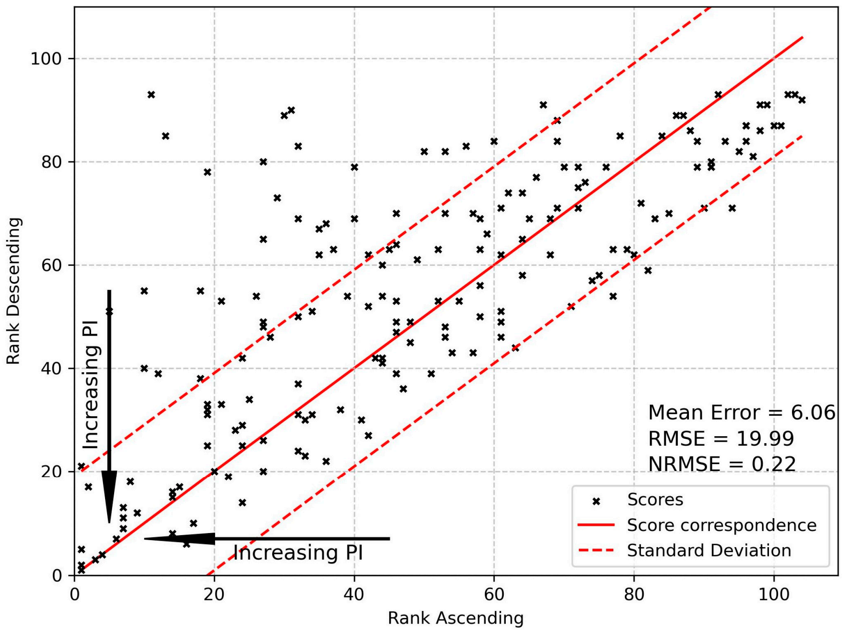

Figure 11. Comparison of ranking of potential impact on water resources (PI) of ascending and descending distillations for the two categories C4-C5 and C5 (halving model for the micro-criteria weights).

4. Discussion

The significant number of quarries in Italy (about 4000) poses a challenge in defining their impact on water resources. For this purpose, a categorization has been developed through the MCDA-based model. The application of the MCDA model highlighted both advantages and disadvantages. On the positive side, the model allows for the inclusion of a large number of quarries, considering different criteria for impact assessment, dividing the analysis into smaller parts, and then integrating them to determine the final categorization. However, challenges arise from the subjectivity related to the choice of criteria and weights assigned to them. Balancing these pros and cons depends on the objective of the analysis. In this case, the favorable factors prevail, given the large number of quarries to be categorized based on available data. With an awareness of the subjectivity of the method of setting criteria weights, the results obtained from applying the two selected decision-making models, ELECTRE TRI and ELECTRE III, seem to be useful for distinguishing the most impactful categories on a national scale. The validity of the approach is evident from the consistency of the results observed when varying the weights of the different criteria, showing minimal variation in the percentages of quarries falling into the most-impacting categories (categories C4-C5 and C5) (Figures 8–10). In addition, the general convergence of the ascending and descending distillation for these two categories supports the robustness of the ranking, at least in comparative terms (Figure 11).

The limitations of the categorization lie in the selection of criteria that determine the potential impact of quarries and the weight assigned to them using the AHP, ordinal and halving methods: different simulations assume distance and runoff as more significant micro-criteria for the potential impact on surface waters, and the depth of the groundwater level and effective infiltration as more significant for potential impact on groundwater. Although these assumptions are subjective, they seem reasonable for a preliminary categorization of quarries on a national scale, and also in comparison with what is reported in the literature (for example, [15,21,24]). Under these assumptions, and with reference to the halving model of weights (although it does not change significantly by adopting other weight values), the framework resulting from separate categorization for the two macro-criteria appears meaningful; at least in relative terms, for the potential impact on surface water, a small percentage of quarries falls into the most-impacting categories. On the other hand, the percentage of the most-impacting categories is much higher when considering the macro-criterion of groundwater (Figure 12). This representation can be interpreted as a first national assessment of the sustainability of quarrying activities with specific regard to water resources. At the same time, the analysis provides directions for future investigations, such as the refinement of the ranking within the most-impacting categories by adding other micro-criteria, like water quality. Direct assessments on significant quarry samples of the most-impacting categories should be conducted to calibrate the weights of the different criteria using, for example, the indices of the ecological and chemical status of surface water bodies and of the quantitative and chemical status of groundwater, adopted by the European Union [72]. In any case, although the different level of impact cannot indicate the absolute sustainability of the extractive activities, which depends on many other factors such as environmental, social and economic criteria (for example, [73]), the categorization of quarries with reference to surface water and groundwater serves as a screening tool for selecting the worst cases to be evaluated in a wider context, involving stakeholders.

Regarding the methodological approach of the study, data processing through the two selected decision-making models, ELECTRE TRI and ELECTRE III, proved to be an appropriate choice as it allowed us to shed light on a large number of data and identify highly impacting quarries. The method is also open to participatory management, allowing the inclusion of social criteria, not quantitatively parameterized, but generally expressed by preferences. Furthermore, ascending and descending distillation within categories seems to be useful as an indirect verification of the robustness of the ranking under the conditions of the selected criteria and the weights attributed to them.

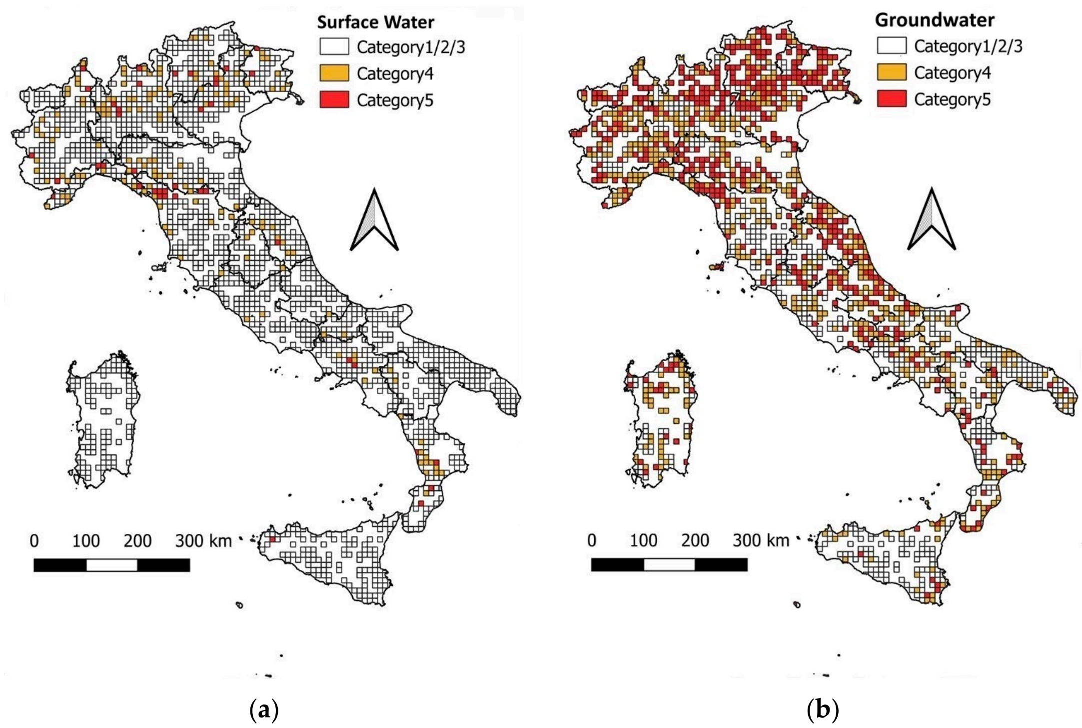

Figure 12. Distribution of quarries into different categories of potential impact on (**a**) surface water and (**b**) groundwater (halving model of weights).

In this context, it is planned to direct future insights, which also provide vulnerability and risk assessments for the potentially more-impactful categories of quarries (categories C4-C5 and C5), taking into account quarry management plans and quarry rehabilitation plans, using more advanced analysis methods (e.g., [49–54]), which obviously require more detailed data not currently available in the datasets.

5. Conclusions

Italian quarries have been categorized for their potential impact on water resources using a simplified conceptual model and applying MCDA methods. The potential impact categories were determined by selecting various parameters which were easy to find and accessible, combined and weighted based on their influence using the ELECTRE models. The distribution of quarries into different categories for surface water and groundwater provides an initial assessment of the potential impact on water resources, classifying the quarries in relative terms. The results therefore offer a nation-wide perspective of the sustainability of extractive activities, indicating the most-impacting categories that need further investigation.

The study emphasizes the potentiality of combining the ELECTRE TRI and ELECTRE III models in the quarry-sorting and -ranking processes. While these models allow the processing of a large number of data, their outcomes depend on the choice of criteria and weights. However, by varying the weights of criteria, in ad hoc simulations, they prove to be powerful tools for the quarry-sorting process and for testing the robustness of the obtained results. Moreover, the method allows for numerous simulations with reduced calculation time, and is open to the introduction of other criteria which may derive, for example, from the participation in the process of the various stakeholders.

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