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# GIS-based Multi-criteria Assessment of Areas Suitable for the Construction of a Repository for Low and Intermediate Kevel Radioactive Waste in Slovenia

**Tim Gregorčič**[A*], **Marko Krevs**[B], **Blaž Repe**[B]

[A] *Institute for Health and Environment, Slovenska cesta 56, SI-1000 Ljubljana, ORCID TG: https://orcid.org/0009-0006-9767-9428*
[B] *University of Ljubljana, Faculty of Arts, Department of Geography, Aškerčeva 2, SI-1000 Ljubljana, ORCID MK: https://orcid.org/0000-0002-3239-5540, ORCID BR: https://orcid.org/0000-0002-5530-4840*

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ABSTRACT

This study evaluates the site selection for a new repository for low and intermediate level radioactive waste in Slovenia. The ordered weighted average method is used in combination with the TOPSIS method to evaluate the current site and its alternatives considering eight criteria and five constraints. The results show that 52.37% of the country's area falls into five suitability classes for the two decision alternatives, while others do not fulfil the criteria at all. In both cases, the most suitable areas are located in the north-eastern part of Slovenia. The current site tends to be less suitable (categorised as moderately suitable and very unsuitable) and should be reassessed by the relevant stakeholders.

## Introduction

Krško Nuclear Power Plant (KNPP) is the only nuclear power plant in Slovenia that has been in commercial operation since 1983 (NEK, 2023). It is located in the south-eastern part of the country near the town of Krško. Low and intermediate level radioactive waste generated during electricity production is currently stored on the site of the nuclear power plant or in the central radioactive waste storage facility in the village of Brinje. Radioactive waste from medical, scientific, and other industrial projects is also disposed of there. As the amount of waste is constantly increasing, the Republic of Slovenia has decided to build a new repository. It took more than a decade to finalise the selection of the area suitable for construction, which is located next to the current nuclear power plant in the village of Vrbina (RS, 2009).

The final selection of the site was the subject of much public and expert debate because of the potential risks of radioactive waste to humans and the environment, such as contamination of groundwater and soil and displacement of radioactive materials, and because the selected site is located in one of the most earthquake-prone areas in Slovenia (SEA, 2021a). Due to these risks, great caution is required when selecting a site for the final disposal of radioactive waste. Although new repositories for low and intermediate level radioactive waste are already under construction, a reassessment of the site selection is necessary based on the remaining conflicting opinions.

When selecting a site for the disposal of nuclear waste, many important spatial variables should be considered that are similar to those relevant to the selection of the site for a nuclear power plant, such as land use, population density, lithology, groundwater discharge rate, slope gradient, landslide potential, precipitation, seismicity, soils,

* Corresponding author: Tim Gregorčič; email: tim.gregorcic@izo.si
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protected areas, freshwater areas, distance from agglomerations and possible others (Abudeif et al, 2015; Bilgilioğlu, 2022; Lim & Afifah Basri, 2022; Susiati et al., 2022). Since the number of important factors can and should be high, complex spatial multi-criteria methods are required to consider all factors and constraints in the final site selection. Geographic information systems (GIS) offer many spatial quantitative multi-criteria evaluation (MCE) methods to overcome this challenge. One of these methods is the ordered weighted average (OWA), which was used in this study.

OWA was introduced by Yager (Yager, 1988). It is a multi-criteria aggregation technique that considers two types of weights, namely criteria and order weights, and allows the generalisation of weighted linear combination (WLC) and Boolean AND and OR logic in a methodological framework (Valente & Vettorazzi, 2008). A criterion weight is assigned to a given criterion, which is usually standardised using fuzzy functions for the entire study area and indicates its relative importance, while the ordinal weight for a given criterion varies from site to site. The ordinal weights are associated with the trade-off measure of compensation between the criteria, which leads to a certain risk that the final decision will be wrong (Drobne & Lisec, 2009). To determine the criteria weights, the analytical hierarchy process (AHP) method is often used in various MCE approaches (Cunden et al., 2020; Khazaee Fadafan et al., 2022; Kocabaldır & Yücel, 2023). The weights are assigned by the pairwise comparison of the importance of the criteria. The weights of the order are determined based on a selected decision risk taking approach and the degree of trade-off between the criteria (Drobne & Lisec, 2009).

The TOPSIS (Technique for Order Preference Similarity to Ideal Solution) method is another MCE method that can be used to rank location alternatives based on the shortest distance to the ideal solution (Makwakwa et al., 2023). It is useful for ranking spatial results derived from GIS MCE analyses (Foroozesh et al., 2022; Rane et al., 2023).

The aim of this study is to identify which locations in Slovenia as a whole are most suitable for construction when selected criteria are taken into account. The two main research questions are:

Q1: Which other potential sites could be suitable for construction if a GIS-based MCE assessment is performed?

Q2: Is the current site selection acceptable based on the selected criteria?

The objectives of this study are as follows:

G1: Identification of relevant evaluation criteria based on a literature review.

G2: Creation of GIS layers for the selected evaluation criteria and constraints.

G3: Assessment of different suitability classes for the placement of a repository for low and intermediate level radioactive waste in Slovenia with maximum trade-off between the criteria and the moderate risk of the selected site using OWA.

G4: Assessment of different suitability classes for the placement of a repository for low and intermediate level waste in Slovenia with moderate trade-off between the criteria and low risk of the selected site using the OWA.

G5: Evaluation of the current site selection for the repository for low and intermediate level radioactive waste near the village of Vrbina based on the results of the third and fourth objectives.

G6: Identification of the most suitable site for a repository for low and intermediate level waste using the TOPSIS method based on the results of the third and fourth objectives.

## Study area

The analysis was carried out for the entire territory of Slovenia (Figure 1), which is located in Central Europe between 46° 52' 37.52" and 45° 25' 18.34" latitude and 16° 36' 07.69" and 13° 23' 47.81" longitude (SORS, 2004). The country has around 2,117,000 inhabitants and a total area of 20,271 km2 (SORS, 2023). It is bordered to the north by Austria, to the north-east by Hungary, to the east and south by Croatia and to the west by Italy. The Alpine region forms the highest part of the country in the north-east and north. Approximately half of the country's relief is karst (Stepišnik, 2024). The KNPP and the site selected for the repository for low and intermediate level radioactive waste are located in the Pannonian region, which forms the western edge of the Pannonian Basin.

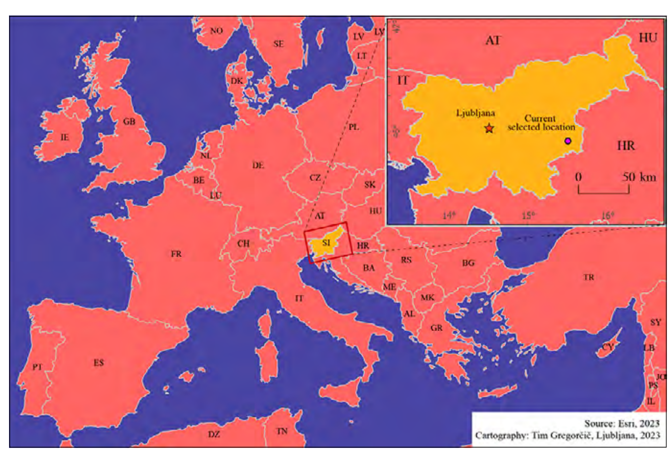


**Figure 1.** Study area with marked location of the capital city and currently selected location of the repository

## Methodology

The processes of the study consisted of seven main steps, which are shown in Figure 2. All spatial analyses were carried out using ArcGIS Pro 3.1.0 and TerrSet 2020, a spatial monitoring and modelling software.

### Literature review

Based on a review of the relevant literature, we identified the criteria and constraints that should have been used in our study to achieve its objectives. As mentioned above, the factors relevant to the siting of a nuclear waste repository are similar to the factors relevant to the siting of a nuclear power plant. The biggest difference is the lack of a freshwater source in the case of nuclear waste storage. We have therefore analysed the MCE studies in both areas.

Table 1 shows the results of this review. The final selection of criteria and constraints is shown in Figure 2.

### Input data preparation

This phase of the study was divided into two parts. In the first part, criteria raster layers with a cell size of 100 m and constraints raster layers were created. In the second part, they were standardised using fuzzy logic.

### GIS layers creation

All layers used for the analyses were created in raster format. A vector layer of the Slovenian landslide areas at a scale of 1:250,000 was used for the landslide potential (SWA, 2020b). A seismic intensity layer was created using maximum ground acceleration data at a scale of 1:500,000 with a return period of 475 years (SEA, 2021a). The original ground acceleration values were used in the conversion from vector to raster format. To obtain the rock permeability layer, we transformed the classes of the hydrogeo-

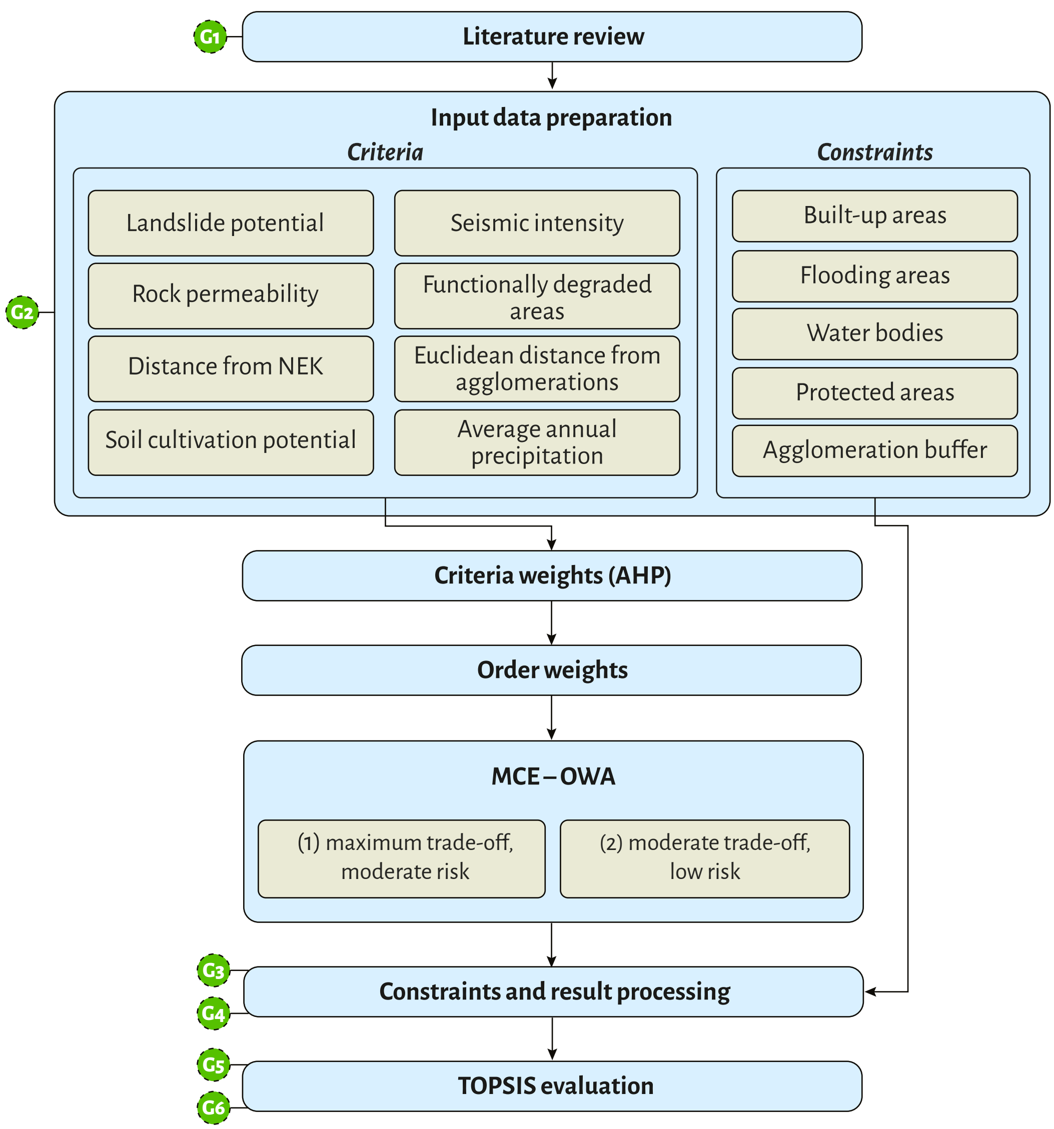


**Figure 2.** Methodological flowchart

**Table 1.** Literature review results

| Paper | Criteria | Constraints |
|---|---|---|
| Lim & Afifah Basri, 2022 | Land use, population density, lithology, lineament density, groundwater discharge rate, slope, landslide potential, rainfall, seismicity intensity, elevation | Flooding area, river area, protection area |
| Bilgilioğlu, 2022 | Elevation, slope, aspect, lithology, soil map, land use, lineament density | Land use, protected areas, proximity to faults, roads, rivers, settlements, water surfaces |
| Susiati et al., 2022 | Elevation, slope, groundwater, soils, rainfall, climate, land use & land cover, land system, distance from settlements, accessibility, central business district, vital and dangerous infrastructure, geological structures, disaster risk | / |
| Baskurt & Aydin, 2018 | Proximity to national borders, hazardous facilities, transport infrastructure and electrical grid | Capable faults, seismicity, existence and sufficiency of cooling water, population, elevation and flood level, topography and slope, environmental sensitivity |

logical vector map layer at a scale of 1:250,000, which was created using the LAWA method (DSS, 2008), according to the method of Lampič et al. (2021). Twelve LAWA classes were summarised into five new classes, with class 1 representing the parent rock with the lowest permeability and class 5 the parent rock with the highest permeability. The details of the grouping are listed in Table 2.

**Table 2.** Reclassification of LAWA classes.

| Class | Hydrogeological class |
|---|---|
| 1 | Intergranular silicate aquifers<br>Fissured silicate aquifers<br>Fissured silicate/carbonate aquifers<br>Special cases: strata reach with organic material |
| 2 | Fissured carbonate aquifers |
| 3 | Poorly karstified carbonate cavern aquifers<br>Other special cases |
| 4 | Moderately karstified carbonate cavern aquifers<br>Moderately karstified organic/carbonate cavern aquifers |
| 5 | Intergranular carbonate/silicate aquifers<br>Intergranular carbonate aquifers<br>Very karstified carbonate cavern aquifers |

We created the Functionally Degraded Areas (FDA) layer (Lampič et al., 2020) according to the status of the polygons (FDA or non-FDA). The distance to the KNPP was calculated using the Make Service Area Analysis Layer tool based on the transport network created by Esri. The transport network was not limited to Slovenia, so the method was able to determine the shortest route to a given location, partly via Croatia. We calculated the distance from KNPP in kilometres and in one-kilometre increments. The layer representing the Euclidean distance from the agglomerations (SEA, 2019) was created using the Euclidean Distance tool. The soil quality vector layer (Rupreht, 1991) at a scale of 1:25,000 (MAFF, 2008), which was used to consider the yield potential of the soil, was initially merged with the FDA layer. The FDA was assigned a non-agricultural category. For the average annual precipitation layer, adjusted mean annual precipitation data for 1981-2010 were used (SEA, 2022b).

The land use dataset (MAFF, 2022) was used for the constraint layers for built-up areas and water areas. The floodplain layer was created using the Q500 flood risk area (SWA, 2022). Missing data was replaced by an older layer with very rare floodplains from the flood warning map (SWA, 2020a). The protected areas layer consisted of three different vector layers: Nature 2000, protected areas at national level and protected areas at local level (SEA, 2022a, 2022c, 2022d). The agglomeration layer (SEA, 2019) was used again to create agglomeration buffers with a radius of 500 metres. This decision was influenced by the examples of existing repositories for low and intermediate level waste in Europe, including those at Drigg, Lakenheath and Morsleben.

## GIS layers standardisation

The values in the raster criteria layers were standardised using the fuzzy tool of the TerrSet software. Increasing linear, decreasing linear and decreasing J-shaped membership functions were used. In the case of the linear membership functions, all values were arranged in the interval from 0 to 1, while the interval for the J-shaped function ranged from 1 to near 0 (infinity). Information on the standardisation of the criterion levels can be found in Table 3, while the standardised levels are shown in Figure 3.

**Table 3.** Standardisation of criteria layers

| Layer | Fuzzy function | Limit A | Limit B | Unit |
|---|---|---|---|---|
| Landslide potential | Decreasing linear | 1 | 6 | Unit of landslide potential |
| Seismic intensity | Decreasing linear | 0.1 | 0.325 | PGA |
| Rock permeability | Decreasing J-shaped | 1 | 3 | Unit of rock permeability |
| Functionally degraded areas | Increasing linear | 0 | 1 | Unit of FDA |
| Distance from KNPP | Decreasing linear | 0 | 237 | km |
| Euclidean distance from agglomerations | Increasing linear | 750 | 13,261 | m |
| Soil cultivation potential | Decreasing linear | 1 | 80 | Unit of soil cultivation potential |
| Average annual precipitation rate | Decreasing linear | 900 | 4000 | mm |

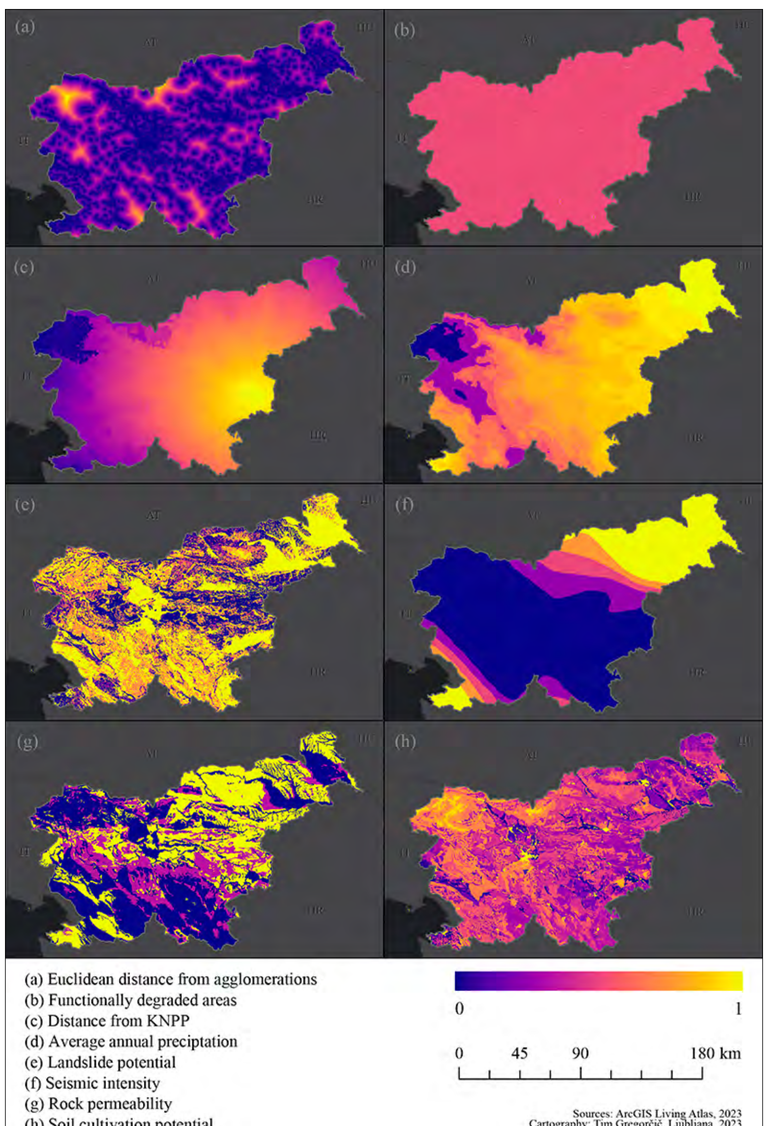


**Figure 3.** Standardised criteria layers

### Weighting of the criteria

The weighting of the criteria was determined by the authors using the AHP method (Table 4). The factor with the greatest weighting was rock permeability, because in the event of an accident, the permeability of the geological structures determines how quickly radioactively contaminated groundwater spreads into the surrounding area and possibly into the aquifers used for drinking water supply. This risk was also emphasised in the environmental permit (SEA, 2021b: 21). This is followed by the factors of landslide potential and seismic intensity, which in the case of Slovenia were also emphasised by the French Institute for Radiological Protection and Nuclear Safety (IRSN) and the International Atomic Energy Agency (IAEA) (SEA, 2021b: 16). As landslides of a magnitude that can damage infrastructure occur more frequently than such earthquakes, they are weighted with a higher value. The fourth highest weighting was assigned to the productive potential of the soil. Although the difference between the third and fourth weights is relatively large (x = 0.0905), the fourth position is appropriate to protect the highest quality soils. Some factors, such as landslide potential, favour the lowlands, where the highest quality soils are also found, so the appropriateness of a high weighting is even higher. Distance to KNPP is the fifth most heavily weighted factor and ranks sixth in terms of Euclidean distance from agglomerations. This is due to the fact that when we standardised the Euclidean distance layer, we had already established that suitability increases from 750 m, limiting the risk of living near the landfill, but we had not yet addressed the risk of an accident during hazardous waste transport. In addition, during the public consultation on the landfill project, the public expressed concerns about the safe transport of waste (SEA, 2021b, p. 12). The average annual precipitation factor is the least weighted, as it is a factor in the leaching of radioactive materials in the event of an accident. Most of the other factors are aimed at preventing accidents involving the release of hazardous waste into the environment itself and are therefore weighted more heavily. Accordingly, the Euclidean distance from the agglomerations is also one of the less weighted factors.

### Order weights

Table 5 shows the order weighting values based on the selected MCDE directions: maximum trade-off between the criteria values at a selected location and moderate risk of wrong choice and moderate trade-off between the criteria values at a selected location and low risk of wrong choice. After determining both types of weights, the OWA method was performed using the MCE module of the TerrSet software.

### Applying constraints and processing of the results

After obtaining the raw OWA results, constraint layers were applied using ArcGIS Pro software. In the next step, the results were reclassified into five classes based on the values of the grid cells:

- Highly suitable area (0.801-1.000),
- Suitable area (0.601-0.800),
- Moderately suitable area (0.401-0.600),
- Unsuitable area (0.201-0.400),
- Highly unsuitable area (0.000-0.200).

**Table 4.** Criteria weights based on the AHP method

| | AHP matrix | | | | | | | | AHP weights | |
|---|---|---|---|---|---|---|---|---|---|---|
| | A | B | C | D | E | F | G | H | Weights (consistency = 0,06) | Rank |
| A | 1 | | | | | | | | 0,0680 | 6 |
| B | 1/2 | 1 | | | | | | | 0,0543 | 7 |
| C | 2 | 2 | 1 | | | | | | 0,0932 | 5 |
| D | 1/3 | 1/4 | 1/5 | 1 | | | | | 0,0328 | 8 |
| E | 3 | 4 | 3 | 4 | 1 | | | | 0,2206 | 2 |
| F | 2 | 3 | 2 | 4 | 1 | 1 | | | 0,1956 | 3 |
| G | 4 | 5 | 3 | 6 | 1 | 1/1 | 1 | | 0,2302 | 1 |
| H | 3 | 3 | 2 | 2 | 1/4 | 1/4 | 1/3 | 1 | 0,1051 | 4 |

**A** – *Euclidean distance from agglomerations*, **B** – *FDA*, **C** – *Distance from KNPP*, **D** – *Average annual precipitation rate*, **E** – *Landslide potential*, **F** – *Seismic intensity*, **G** – *Rock permeability*, **H** – *Soil cultivation potential.*

**Table 5.** Order weights

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Maximum trade-off, moderate risk** | Weight 1 | Weight 2 | Weight 3 | Weight 4 | Weight 5 | Weight 6 | Weight 7 | Weight 8 |
| | 0,125 | 0,125 | 0,125 | 0,125 | 0,125 | 0,125 | 0,125 | 0,125 |
| **Moderate trade-off, low risk** | Weight 1 | Weight 2 | Weight 3 | Weight 4 | Weight 5 | Weight 6 | Weight 7 | Weight 8 |
| | 0,25 | 0,25 | 0,25 | 0,25 | 0 | 0 | 0 | 0 |

The classified results were converted into locally homogeneous regions using the Region Group tool. Based on information from the National Spatial Plan for the disposal site for low and intermediate level radioactive waste in Vrbina in the municipality of Krško, we obtained information on the coordinates of nine points delimiting the disposal area selected by the state. The points were imported into GIS and used to create a polygon representing the planned area. We calculated its area, which was 9.47 ha, and the areas of the polygons that were categorised as highly suitable. We identified areas in this suitability class that had an area equal to or greater than the area of 9.47 ha. As part of the selection process, we also identified the three sites with the highest average OWA value and the three sites with the highest average suitability value according to the OWA.

### TOPSIS evaluation

The TOPSIS method was used to assess the suitability of sites for the disposal of low and intermediate level waste that met the final selection criteria described in the previous section. A detailed description of this method was provided by Zeng et al. (2021). First, we evaluated outcome sites with the highest average OWA values. Second, given that the method certainly does not account for all factors relevant to repository site placement, we scored the outcome sites with the largest area, as a larger area implies greater flexibility in the final decision, which may depend on further evaluation of the sites at the micro-spatial level, with additional factors and constraints not considered in this study.

## Results

### Suitability classes assessment

Figure 4 shows the final spatial results of the selected decision scenarios. 40.08% of the area of the country was available for evaluation (8124.66 km²). The differences in suitability between the two scenarios are significant. In the case of the maximum trade-off between the criteria and the moderate risk, the north-east of the country (the Pomurska and Podravska statistical regions) tends to be the most suitable for placement, as most of the areas classified as highly suitable are found there. Nevertheless, only 1.37% of the areas were categorised as very suitable (Table 6). The largest proportion of areas (62.26%) was categorised as moderately suitable. In the second decision scenario, no area was categorised as very suitable, only 0.003% as suitable and more than a half (57.21%) as unsuitable. In addition, the "very unsuitable" class increased dramatically (by 30.00%).

The proportions of the two decision scenarios are shown in Figure 5. The figure also shows the relationship between the two. It can be seen that more than 80% of the highly suitable areas in the first scenario skipped a suitable class in the second scenario, where they were categorised as moderately suitable. A similar pattern was observed for the suitable areas, where more than a half (54.95%) were categorised as unsuitable in the case of the moderate trade-off and low risk scenarios. Very unsuitable areas in the second scenario were mostly categorised as moderately suitable or unsuitable in the first scenario.

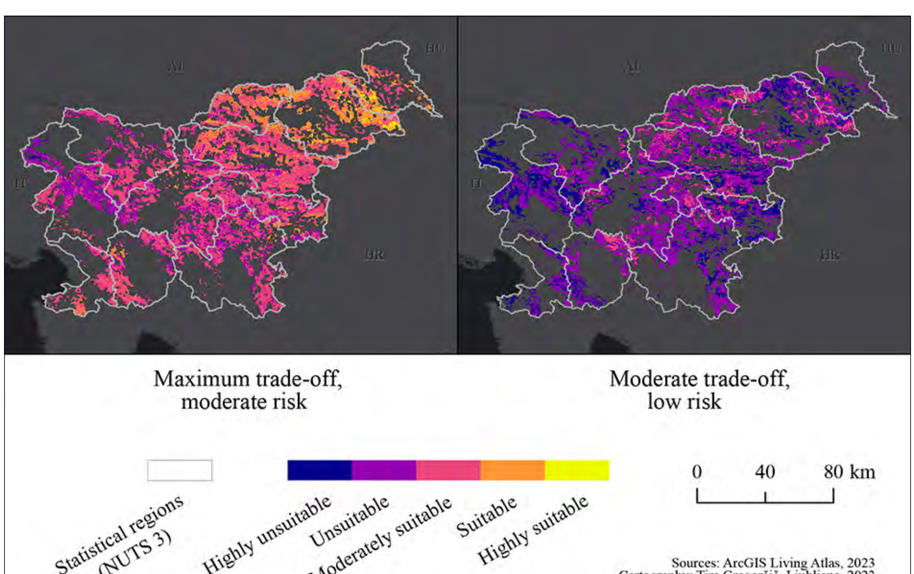


**Figure 4.** MCE results

**Table 6.** Areas of classified MCE classes

| | Maximum trade-off, moderate risk | | Moderate trade-off, low risk | |
|---|---|---|---|---|
| | km² | % | km² | % |
| Highly unsuitable | 22.64 | 0.28 | 2459.71 | 30.27 |
| Unsuitable | 1765.93 | 21.74 | 4648.1 | 57.21 |
| Moderately suitable | 5058.6 | 62.26 | 1016.57 | 12.51 |
| Suitable | 1165.86 | 14.35 | 0.28 | 0.003 |
| Highly suitable | 111.63 | 1.37 | 0 | 0.00 |
| Total | 8,124.66 | 100.00 | 8,124.66 | 100.00 |

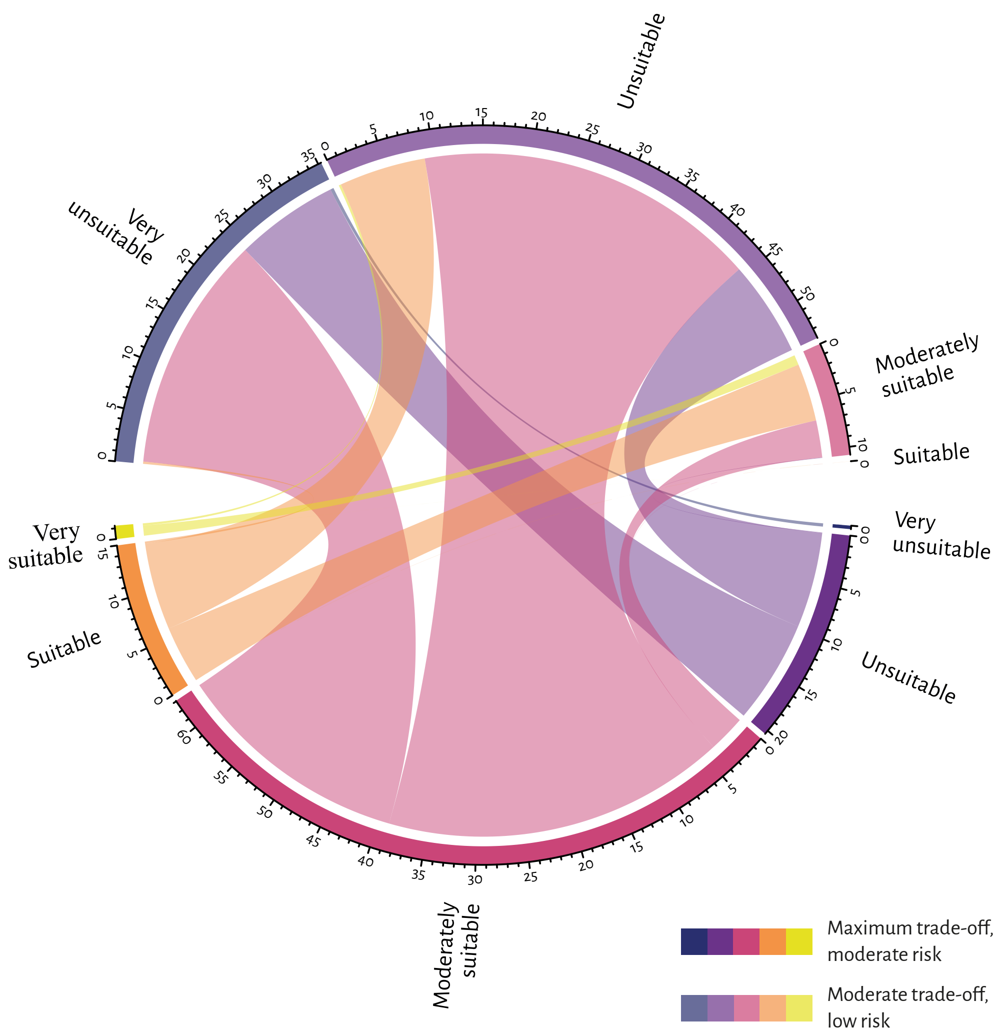


**Figure 5.** Class shares in both MCE alternatives and their relationships

## Maximum trade-off, moderate risk

The results of the TOPSIS site suitability assessment are shown in Table 7. The results refer only to the scenario with the maximum trade-off between the criteria and the moderate risk of site selection, as there are no highly suitable and suitable sites with an area of at least 9.47 ha in the second scenario. Based on the TOPIS assessment of the sites with the highest average OWA value, the third most suitable site is located north of Slovenska Bistrica, the second most suitable site is located northwest of the village of Majšperk and the most suitable site is located south of Ptuj near Podlehnik with an area of 13 ha (Figure 6). The site had a soil cultivation potential of 34 and the rock permeability fell into class 1, which represents the lowest permeability and thus the highest suitability. The peak ground acceleration was 0.1, placing the site in the lowest seismic hazard class. In terms of landslide potential, the site fell into class 1, which represents the highest suitability. The

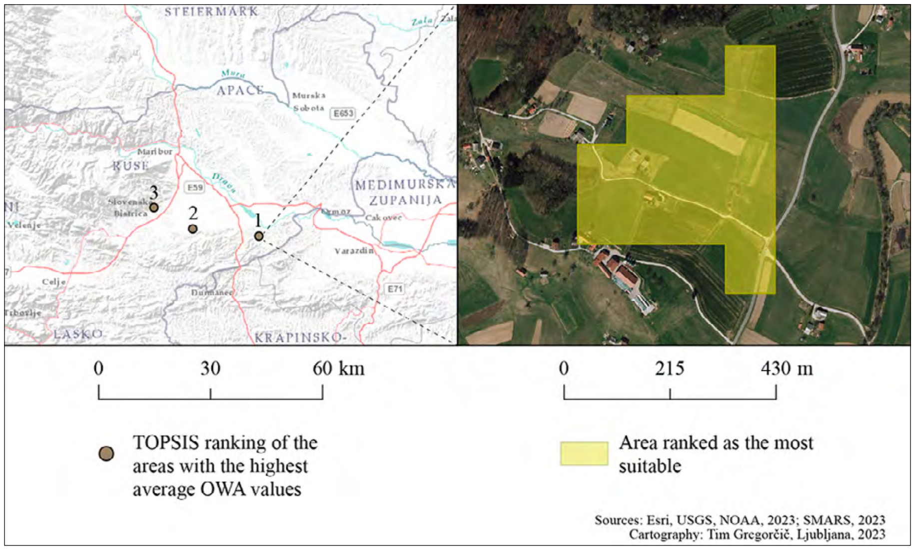


**Figure 6.** TOPSIS evaluation of the locations with the highest average OWA values

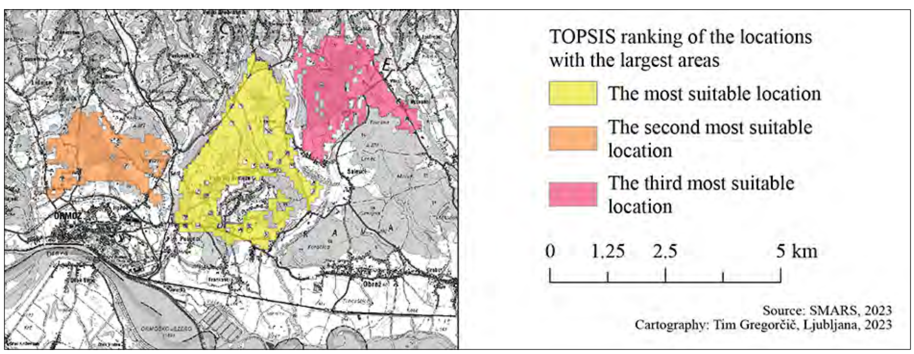


**Figure 7.** TOPSIS evaluation of the locations with the largest areas

average annual rainfall was 1100 mm (the 3rd lowest in the country). The average distance to the KNPP was 78.38 km and the average distance to agglomerations was 3.70 km. The area is not functionally degraded.

When analysing the locations with the largest areas, the three largest areas were in close proximity to each other. The seemingly uniform area was divided into lower suitability classes not only by constraints, but also by the categorisation of the areas in between. These areas are shown in Figure 7. In the most suitable area, which covers 668 ha, there are several areas with different soil cultivation potentials. The highest value was 56, the lowest was 40 and the average value was 45. The permeability of the rocks fell into class 1, which represents the highest suitability. The peak ground acceleration value was 0.1, placing the area in the lowest seismic hazard class. In terms of landslide potential, the area falls into class 1, which is the highest suitability. The average annual rainfall was 1053 mm. The average distance to the KNPP is 101.11 km and the average distance to agglomerations is 2.65 km. No part of the area was categorised as functionally degraded. Compared to the preferred area with the highest average OWA values, this area has a higher yield potential, is further away from the Krško Nuclear Power Plant and is less distant from agglomerations. The average annual precipitation is lower.

**Table 7.** Results of TOPSIS evaluation

| Value [a] | Euclidean distance from the agglomerations | Functionally degraded areas | Distance from KNPP | Average annual precipitation | Landslide potential | Seismic intensity | Rock permeability | Soil cultivation potential | $Si^{+}_{i}$ | $Si^{-}_{i}$ | $P_i$ | Rank |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Evaluation of the locations with the highest average OWA values[a] | | | | | | | | | | | | |
| 0.831 | 0.008269 | 0.03135 | 0.054675 | 0.018712 | 0.127363 | 0.113045 | 0.132906 | 0.060727 | 0.090359 | 0.002862 | 0.030705 | 3 |
| 0.833 | 0.016255 | 0.03135 | 0.054882 | 0.085572 | 0.127363 | 0.113045 | 0.132906 | 0.060585 | 0.049348 | 0.067405 | 0.577329 | 2 |
| 0.843 | 0.065509 | 0.03135 | 0.051816 | 0.088627 | 0.127363 | 0.113045 | 0.132906 | 0.060727 | 0.003066 | 0.090358 | 0.967185 | 1 |
| $V^{+}_{j}$ | 0.065509 | 0.03135 | 0.054882 | 0.088627 | 0.127363 | 0.113045 | 0.132906 | 0.060727 | | | | |
| $V^{-}_{j}$ | 0.008269 | 0.03135 | 0.051816 | 0.018712 | 0.127363 | 0.113045 | 0.132906 | 0.060585 | | | | |
| Evaluation of the locations with the largest areas[a] | | | | | | | | | | | | |
| 339 ha | 0.011088 | 0.03135 | 0.054429 | 0.085167 | 0.127175 | 0.113045 | 0.132906 | 0.064927 | 0.045878 | 0.066261 | 0.590885 | 2 |
| 416 ha | 0.056946 | 0.03135 | 0.052568 | 0.019265 | 0.127457 | 0.113045 | 0.132906 | 0.058587 | 0.067571 | 0.045859 | 0.404295 | 3 |
| 668 ha | 0.035471 | 0.03135 | 0.05441 | 0.086512 | 0.127457 | 0.113045 | 0.132906 | 0.058293 | 0.022476 | 0.071555 | 0.760977 | 1 |
| $V^{+}_{j}$ | 0.056946 | 0.03135 | 0.054429 | 0.086512 | 0.127457 | 0.113045 | 0.132906 | 0.064927 | | | | |
| $V^{-}_{j}$ | 0.011088 | 0.03135 | 0.052568 | 0.019265 | 0.127175 | 0.113045 | 0.132906 | 0.058293 | | | | |

### Moderate trade-off, low risk

As mentioned above, when assessing the suitability of the sites in terms of moderate trade-off and low risk, only one site was found to be suitable and none were found to be particularly suitable. Therefore, we did not perform a TOPSIS assessment in this scenario.

The suitable site was again located near Ormož (north-east Slovenia), as shown in Figure 8. Part of the site is located on soil unsuitable for agriculture and part of the site is located in an area with a soil cultivation potential value of 41. In terms of rock permeability, the site fell into class 1, which represents the highest suitability. The design acceleration value was 0.1, which also placed the site in the class of areas with the lowest seismic intensity. In terms of landslide potential, the site fell into class 1, which represents the highest suitability. The average annual rainfall is 1100 mm. The average distance to the KNPP is 100.36 km and the average distance to agglomerations is 956 m. Today, this area also has the status of a functionally degraded area.

### Assessment of the current site selection for the construction of a repository for low and intermediate level radioactive waste near Vrbina

Most of the area selected for the construction of the KNPP nuclear power plant is located within 500 metres of agglomerations. Therefore, the selected restrictions make the site unsuitable for construction (Figure 9). If they were not a limiting factor, the selected area would be classified as moderately suitable for the repository in the case of a scenario with a maximised trade-off between the criteria and a moderate site selection risk. In the case of the as-

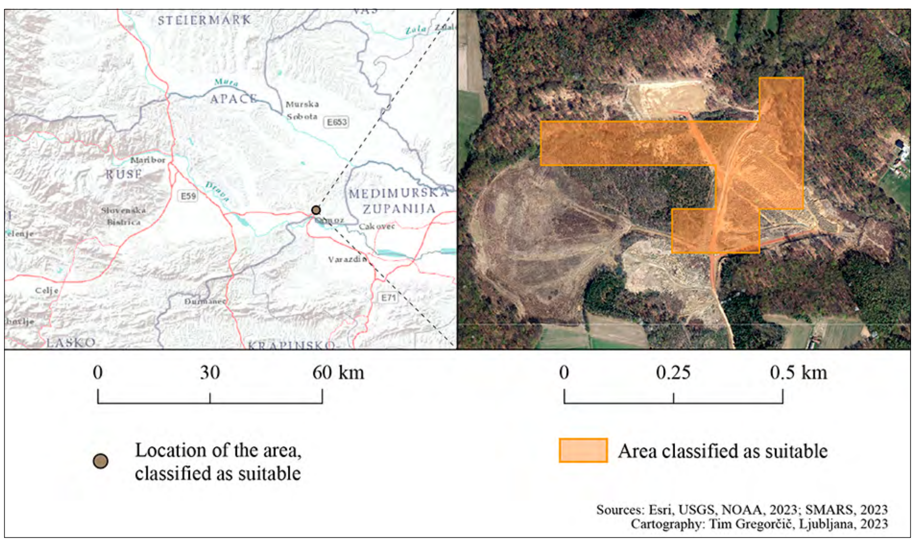


**Figure 8.** Location classified as suitable

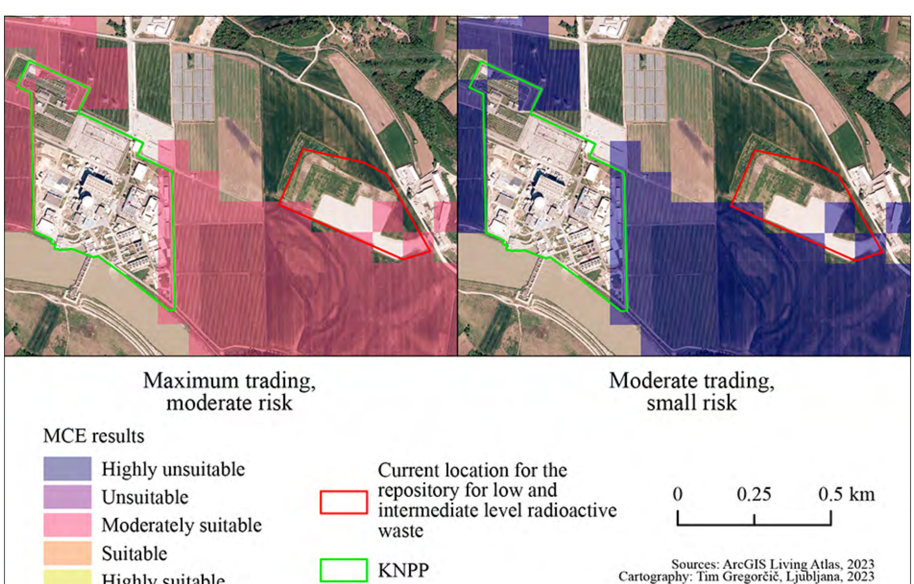


**Figure 9.** Evaluation of the current site selection

sessment variant with a moderate compromise and a low siting risk, the site of the facility would be classified as very unsuitable. The proposed landfill site has a soil cultivation potential score of 73 and the rock permeability falls into class 5, which is the highest permeability and consequently the least suitable. The peak ground acceleration value was 0.275, placing the site in the second class of the most seismically hazardous areas. In terms of landslide potential, the site falls into class 1, which represents the highest suitability. The average annual rainfall is 1200 mm, the distance to the KNPP is between 1 and 2 km and the average distance to the agglomerations is 483.99 m.

## Discussion

The aim of this study was to identify the most suitable sites for the construction of a repository for low and intermediate level radioactive waste in Slovenia, taking into account certain criteria and constraints. The assessment was carried out using a GIS-based MCE approach and the TOPSIS method. The currently selected site is mostly located within the 500 metre agglomeration buffer and is therefore unsuitable. Apart from the constraints, the site is not located in a highly suitable or suitable zone, which justifies doubts about the current spatial planning decision. We have also proposed alternatives whose realisation poses a lower risk compared to the current site selection. The highest OWA values for both decision alternatives were observed in the north-eastern part of Slovenia.

As the Republic of Croatia is jointly responsible for the disposal of half of the radioactive waste produced in the KNPP, it is currently in the process of selecting a site for the construction of a repository for low- and intermediate-level radioactive waste. In contrast to the situation in Slovenia, the study by Perković et al. (2020), which considered a similar combination of constraints and criteria, showed that the results obtained with modern GIS research approaches are consistent with the assessment results of the old approaches and confirm that a large part of Trgovska gora (more precisely Čerkezovac) is suitable for the construction of the disposal site as originally planned. This suggests that the Croatian approach to site selection may have considered relevant constraints and criteria in a more meaningful or transparent way in previous decades, when advanced GIS evaluation capabilities were still limited. Nevertheless, Perković et al. (2020) used a simplified GIS-based multi-criteria methodology that is not directly comparable to the one used in our study. Their results also do not allow a comparison of suitability between alternative sites.

Compared to the studies by Bilgilioğlu (2018) and Lim & Afifah Basri (2022), the methodology used in this study provided the opportunity to assess the current site selection and propose alternative sites at a local spatial scale, while their methods only resulted in a regional overview. However, the alternatives proposed in this study require further assessment of environmental and social factors at the local level that have not yet been considered, such as water table, site accessibility, municipal spatial plans, public opinion, stakeholder consideration, etc. Public (non-) approval of site selection has already proven to be an important factor in the final decision on the site selection in Slovenia (Mele & Zeleznik, 1998). The weighting of the AHP criteria in this study was determined by the authors, while Bilgilioğlu (2018) conducted interdisciplinary expert interviews with nuclear safety experts to define them, making them more credible. No other study has attempted to assess the areas suitable for the construction of a repository for low and intermediate level radioactive waste in Slovenia using modern GIS methods. Therefore, it was not possible to compare the results directly. However, if we compare the results of this study with those of other countries, we can conclude that the alternative sites proposed in this study are generally consistent with the trend that the most suitable areas are located in flood-safe areas with low seismic intensity, low rock permeability, low annual precipitation rates and low landslide potential (Bilgilioğlu, 2022; Harun et al., 2016; Lim & Afifah Basri, 2022; Perković et al., 2020). In addition, our study has taken a step forward by using the OWA method instead of the WLC or other symmetric difference method, which leads to more complex alternative solutions to the identified problem based on a precautionary principle.

With possible methodological extensions, even higher quality results can be achieved. The OWA method offers even more risk and trade-off options than the two selected ones. This would make it possible to identify even more alternatives that would be even more useful from the decision-maker's point of view. The need for a better spatial resolution of some factor layers, such as seismic intensity and the very general 1:250,000 spatial scale rock permeability dataset, has already been mentioned. For the removal of agglomerations, the agglomeration layer representing the larger settlements of the country was used, but it would have been better for the quality of the results if it had also included data on smaller settlements that were not considered. The 2020 layer of functionally degraded areas is now partially outdated and an updated layer, which is not yet available, should be used for more up-to-date results. Figure 7 shows that many of the resulting areas are still covered by built-up areas. This is due to the relatively large size of the grid cells compared to the width of the polygons representing streets or individual buildings when these are scattered.

## Conclusion

Slovenia's only nuclear power plant is the main source of low and intermediate level radioactive waste. Due to the accumulation of this waste, a new repository is needed. The aim of this study was to determine which sites in Slovenia as a whole are best suited for construction when selected criteria are taken into account. For this purpose, the GIS-based MCE method called OWA was used in combination with the TOPSIS method. The evaluation was based on eight criteria and five constraints. The weighting of the criteria was determined by the AHP. A total of 40.08% of the land area was divided into five suitability classes of two decision alternatives: maximised compromise between criteria with a moderate risk of a wrong decision and moderate compromise between criteria with a low risk of a wrong decision. In the first alternative, 1.37% of the evaluated areas were categorised as very suitable and 14.35% as suitable. The largest proportion was categorised as moderately suitable. In the second alternative, no areas were categorised as very suitable. Only 0.003% was classified as suitable, with an area smaller than 9.47 ha, i.e. insufficient. The largest proportion was categorised as unsuitable. Based on the criteria and constraints applied, the majority of the current development area is unsuitable, mainly due to its location within the 500 m agglomeration buffer. From this we can conclude that the current site selection is not an optimal choice in terms of human and environmental safety. Using the TOPSIS method, several sites with better characteristics were identified. They are located in the north-eastern part of Slovenia (in the northern foothills of Haloze and in the vicinity of Slovenska Bistrica, Slovenj Gradec and Ormož).

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