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# Site selection for Croatian low and intermediate level radioactive waste repository

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**ABSTRACT**
Radioactive waste disposal and management presents a unique problem at the Krško nuclear power plant as it is built and co-owned by the Republic of Croatia and the Republic of Slovenia. Each country is responsible for the management of half of the low- and intermediate-level radioactive waste (LILW) and spent nuclear fuel (SNF). So far, Slovenia has officially selected the site for LILW disposal and the Croatian programme has a single location left (since 1999), not officially approved as acceptable. This paper contains a new approach to site selection related to the implementation of GIS technology and presents a map of potential areas for LILW disposal including only the remaining Croatian location. It was constructed based on eleven layers that include natural characteristics and anthropogenic pressures. For the construction of the main map, detailed topological checks and spatial analysis of polygons have been made, reducing potential areas to be further evaluated.

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Radioactive waste; programme; LILW; disposal; repository; Republic of Croatia

## 1. Introduction

Krško Nuclear Power Plant (KNPP), located in Vrbina in the Municipality of Krško, Slovenia, is co-owned by the Republic of Slovenia and the Republic of Croatia. It was built as a joint venture by both countries while they were still a part of the former Socialist Federative Republic of Yugoslavia (SFRY). The Croatian national energy company (Hrvatska elektroprivreda – HEP) now owns 50% of the KNPP. Therefore, HEP and (indirectly) the Republic of Croatia are co-responsible for the decommissioning of Krško NPP and for the disposal of half of the radioactive waste (RW) which has been and will continue to be generated in the operation and decommissioning of KNPP (Council of the European Union, 2011).

The Republic of Slovenia selected Vrbina as a site for the repository for the Slovenian portion of the low- and intermediate-level radioactive waste (LILW) from the KNPP. The site was selected after the initial volunteer-based screening process (Mele & Železnik, 1998) and is accepted by the local community, as well as by the regulatory body, Slovenian Nuclear Safety Administration (SNSA) and was included in the Slovenian National Spatial Plan for LILW Repository (Official Gazette, 2009a; Official Gazette, 2012). The deadline for the start of waste disposal site trial operation is 2021 (National Assembly of the Republic of Slovenia, 2016), and if the repository is not finished within that time, all of the currently available waste storage space at the KNPP will be filled and the power plant may not be able to continue operations.

After almost 40 years since the Croatian programme for radioactive waste disposal has started, there still is no clear solution for the disposal of the institutional waste (Non-Power Radioactive Waste – NPRW, and Disused Sealed Sources – DSS) and the Croatian half of the waste from the KNPP in Croatia. The Government of the Republic of Croatia held its 124th Session on 9 November 2018 (Official Gazette, 2018a), and accepted the National programme for implementation of strategy of radioactive waste, disused sources and spent nuclear fuel management (Government of the Republic of Croatia, 2018). This National Programme includes an affirmation of the Čerkezovac site as the Radioactive Waste Management Centre (RWMC) with the Central National Storage Facility (CNSF) for institutional radioactive waste originated in Croatia, as well as the location for long-term storage of LILW from the KNPP.

Considering the spent nuclear fuel (SNF) from KNPP, the dry storage facility at the KNPP site is planned for 2023. In addition, the Republic of Slovenia and the Republic of Croatia issued the 'Reference Scenario for Geological Disposal Facility in Hard Rock with Cost Estimation for its Implementation, 2018' (ARAO, 2019), in the framework of the Third revision of the common KNPP RW and SNF Disposal Programme under the obligation from the Intergovernmental

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Agreement. Long-term dry storage is only a temporary solution, and the basic premise is that in order to select the site for the disposal of the entire quantity of SNF, the territory of both countries will be considered.

The Croatian half of the operational radioactive waste (LILW), currently stored at the KNPP site, is planned to be stored at the RWMC in Croatia. The RWMC is not yet established, but the possible disposal site, Čerkezovac, is known and confirmed by the Government of the Republic of Croatia. The RWMC is anticipated to receive the NPRW and DSS as well. Currently, most of the NPRW is stored at two closed temporary storage facilities within the Institute for Medical Research and Occupational Health and the Ruđer Bošković Institute which are located in the Croatian capital, Zagreb. DSS are stored at the two mentioned temporary storage facilities as well. The disposal of the decommissioning waste will probably be performed at the repository for the LILW, as well as the operational LILW form KNPP, NPRW and DSS.

The last official Croatian programme for the LILW repository site selection began in 1991 and in 1999, Trgovska gora was the single region left and selected for disposal out of four preferred sites (APO, 2000). The most likely location to be selected on Trgovska gora was Majdan, already considered in an earlier site selection programme (INA-PROJEKT, 1987). Trgovska gora was included in Spatial Planning Programme of the Republic of Croatia (Official Gazette, 1999) as a location reserved for LILW repository. Although Trgovska gora has been well selected considering all relevant criteria, it has not yet been accepted by the local community, or officially approved by the Croatian regulatory body. In 2013, the site of a military logistic complex Čerkezovac, also located at Trgovska gora, not too far from Majdan, was proposed as a potential location for the Central National Storage Facility (CNSF) of institutional radioactive waste and disused sealed sources. The benefits of the Čerkezovac site are that it has a developed infrastructure and storage capacity and is declared as unusable for Croatian military on a long-term basis. In 2014, during the development of strategic national documents for radioactive waste management, Čerkezovac was proposed as the preferred site for the Radioactive Waste Management Centre (RWMC). The Radioactive Waste, Disused Sources and Spent Nuclear Fuel Management Strategy (Official Gazette, 2014) describes that the RWMC should include all facilities for the processing, conditioning, manipulation, long-term storage and disposal of radioactive waste and disused sources originating from the territory of the Republic of Croatia, including a central storage facility, as well as radioactive waste and spent nuclear fuel not generated on the territory of the Republic of Croatia, whose obligation arises from an international treaty. In the National Programme, the capacity of the RWM Centre has been reduced to radioactive waste storage facilities with auxiliary buildings and infrastructure only, while the spent nuclear fuel will be managed as a common solution of both countries on a site which has to be confirmed in the future.

It must be noted that the Čerkezovac site has all the attributes of the appropriate location for the long-term storage and is the likely location for the disposal of the LILW, being part of the Trgovska gora, which has already been approved as a potential location for the disposal of the LILW (Schaller & Lokner, 1998). Even if the disposal is to be considered, the choice of disposal system must be properly selected and approved, according to the best practices (Dermol & Kontić, 2011; Poškas, Kilda, Šimonis, Jouhara, & Poškas, 2019).

Acceptance of Čerkezovac as the RWMC might speed up the process of acceptance of the same location for the construction of the near-surface disposal site, which would mean lower transportation costs and reduction of other expenses. Disposal at a different location after long-term storage at the Čerkezovac site, would allow a modern and acceptable way for the disposal site selection, as has been performed in other countries (Metlay, 2016; Yun, 2008). Certainly, more than just one potential location can be identified, and, after the voluntaristic approach is applied (Chapman & Hooper, 2012; Kojo & Richardson, 2014; Ramana, 2013; Stefanelli, Seidl, & Siegrist, 2017), there is a higher likelihood of acceptance of the possible location by the local community and the Croatian people in general.

This paper contains a description of the work done on the project that relates to GIS technology and its specific use in the site selection activities (Carver & Openshaw, 1996; Wilson, Matthews, Pulsipher, & Wang, 2016), as well as visibility actions within the stakeholder engagement, which is of significant importance for radioactive waste disposal programmes (Zuidema, 2015). Informatically speaking, a GIS project is a catalogue or collection of all the available geospatial data, and maps are the product of our visualization, and something to aid in decision making.

The massive progress of the information technology has enabled the development of GIS technology and a wide range of applications of geographic information systems for scientific, technical and educational purposes. Using GIS for site selection is a common practice in the world because it provides a systematic insight into complex issues and GIS is most often applied in processes involving wider environmental and socioeconomic issues such as disposal site selection (Carver, 1991; Rezaeimahmoudi, Esmaeli, Gharegozlu, Shabanian, & Rokni, 2014). In the context of radioactive waste management, GIS is a tool that enables the development of an integral platform that can contain all key information for radioactive waste disposal site selection (Carver & Openshaw, 1996; Silva, Heilbron, & Heilbron, 2015; Xinglai & Sheng, 2006).

## 2. Site selection criteria

Prior to implementing the GIS process, 1991–1999 Programme's criteria (Croatian Institute of Urbanism, 1991) has been studied in order to redefine why potential areas were chosen and which conditions they have met. Site selection criteria were given as two groups: (1) exclusion criteria – for segregation of unfavourable areas of territory, and (2) comparison criteria – used for the assessment of selected potential areas in order to select the best. Consideration is given to all the exclusion criteria used in the 1991–1999 Programme by some of the old geospatial layers being refreshed with new data and some of the criteria supplemented with new additional layers. Since this paper is not a part of an official site selection process, comparison criteria are not applied to all potential sites, however, they are applied for additional assessment of the Čerkezovac site.

The basis for data selection for exclusion maps and additional comparison criteria were Croatian legislation and the IAEA (International Atomic Energy Agency) recommendations: (a) Conclusion on setting criteria for site selection for thermal power plants and nuclear facilities (Official Gazette, 1992), (b) Ordinance on the disposal of radioactive waste and used sources (Official Gazette, 2018b), (c) Regulation on conditions and methods of disposal of radioactive waste, spent closed radioactive sources and sources of ionizing radiation not intended to be further used (Official Gazette, 2008), (d) Ordinance on Evaluation of a Location for a Nuclear Facility (Official Gazette, 2017), (e) Spatial-planning bases, research and assessment of suitability of locations for thermal power plants and nuclear facilities in Croatia (Croatian Institute of Urbanism, 1994), (f) Siting of Near Surface Disposal Facilities IAEA Safety Series No. 111-G-3.1 (IAEA, 1994), (g) Near Surface Disposal Facilities for Radioactive Waste: Specific Safety Guide, IAEA Safety Standards Series No. SSG-29 (IAEA, 2014), (h) Near Surface Disposal of Radioactive Waste: Safety Requirements, IAEA Safety Standards Series No. WS-R-1 (IAEA, 1999) and (i) Disposal of Radioactive Waste: Specific Safety Requirements, IAEA Safety Standards Series No. SSR-5 (IAEA, 2011). Regulation on conditions and methods of disposal of radioactive waste spent closed radioactive sources and sources of ionizing radiation not intended to be further used (Official Gazette, 2008) was suspended with the Ordinance on Evaluation of a Location for a Nuclear Facility (Official Gazette, 2017). Since no proper placement document was issued, this research can only partially refer to this regulation.

Renewed and accepted exclusion site selection criteria are shown in Table 1. Comparison criteria for additional assessment of the Čerkezovac site are given in four basic aspects with several detailed parameters (see Table 2).

## 3. Data and methods

Since the last time the search for the location was performed, some criteria have been modified, as well as regulations and legislation, changes to the density of population, and GIS layers have been updated, modified, or added. Significant development of personal computers, remote sensing and GPS technology made the use of powerful GIS built-in methods possible. The site selection procedure in GIS software has included a few stages: initial selection of layers, topology check, spatial analysis, additional analysis of areas on geological maps and finally a cartographic preview of suitable areas for the LILW disposal site.

### 3.1. Data collection and preparation for GIS

For the exclusion of inappropriate areas, the following geospatial layers were used:

- Flooding safety (Mini Map 1) – according to the Waters Act (Official Gazette, 2009b) and European

**Table 1.** Renewed and accepted exclusion site selection criteria.

| Criteria | Explanation |
|---|---|
| Flooding safety | All natural floodplains are excluded regardless of whether they are protected or not (a floodline of probability of flooding at 1000 years or less) |
| Seismotectonics and seismology | (a) Seismotectonics – areas with maximum possible earthquake intensity of IX° and a higher degree of MCS scale are excluded<br>(b) Neotectonics – areas in the zone of nominated active faults are excluded |
| Lithological and geomorphological characteristics | Areas with increased erosion caused by the lithological composition or dynamic relief are excluded; those built of rocks unstable in natural conditions and during construction activities. Areas with landslides and terrains prone to rockslides, if they endanger facilities (depending on its geometry), are excluded as well |
| Hydrogeology (protection of aquifers) | Areas for the protection of drinking water sources are excluded according to the Ordinance on protective measures and conditions for determining the sanitary protection area of drinking water sources. In order to protect the water, location of the disposal site should not be in areas with significant water bodies of any type |
| Population density | Areas where cumulative population density in a radius of 20 km is greater than 78.1 inhabitants per km$^2$ are excluded |
| Protection of natural heritage | Areas of national parks, nominated nature parks and other important nature reserves are eliminated |
| Mining and mineral exploitation | Areas in the zone of current or future exploitation of ores, minerals, gas, coal, etc. are eliminated |
| Protection of cultural heritage | Areas of cultural goods listed in the World Cultural and Natural Heritage List are eliminated; spaces of cultural goods which, by the totality of their values, are of great and great importance to the social community |
| Special purpose | Areas of special purpose and their protective zones are excluded |

**Table 2.** Comparison criteria for additional assessment of the Cerkezovac site.

| Aspect | Parameter | Detailed parameter |
|---|---|---|
| Technical-technological aspects | Geology and seismology | Seismotectonics and seismic activity – locations in the areas of lower maximum expected earthquake intensity are preferred |
| | | Engineering geology (soil mechanics and foundation) – the worse the natural conditions at the site (the higher the ground slope, the surface layer of the soil with the lower geomechanical characteristics with the lower permissible load), the location is worse |
| Safety of installation | Meteorological and hydrological aspects | Meteorological aspects (extreme occurrences) – locations with lower intensity and precipitation are preferred |
| | | Hydrological aspects (security from flooding) – locations that are out of the reach of mountain streams, and areas without or with a lesser risk of erosion processes are preferred |
| | Geology and seismology | Seismotectonics and seismic (neotectonic) activity – the sites in neotectonic less active zones are preferred |
| | | Lithology and geomorphology – preferably, the sites are made of clay, marl or sediments that represent a mixture of clay and silt, provided that they are not susceptible to landslide and erosion, then those from compact magmatics and metamorphites (granites, gneisses) |
| | Environmental protection | Soil condition (chemical aggressivity) – locations in areas with low chemical aggressiveness of soil prevails are preferred |
| Safety and acceptance of locations | Transport | Transport of radioactive waste – locations whose position in relation to the position of nuclear power plants and for which the existing traffic system provide the greatest possible security are preferable. For the transport of waste, the best quality roads and shortest routes are not used, but those where the danger (likelihood) of the accident is the smallest |
| | Meteorological and hydrological aspects | Meteorological aspects (dispersion) – locations for which the dispersion of the ground layer of the atmosphere is higher are preferred |
| | Areas of cultural goods listed in the World Cultural and Natural Heritage List are eliminated; spaces of cultural goods which, by the totality of their values, are of great and great importance to the social community. | Hydrological aspects (distance of surface flows) – preferably, the locations are further away from constant and intermittent surface flows or accumulations |
| | Geology and seismology | Hydrogeology – locations with smaller reservoirs of groundwater, and where conditions of infiltration and underground flow are such that reduce the possibility of transporting radionuclides, are preferable |
| | Demography | Demographic aspects – locations with lower population density and poorer demographic conditions in settlements in the radius 5 km from the site are preferred |
| | Purpose and use of space | Settlements – locations with a smaller number of settlements and fewer settlements with pronounced central and working functions in a radius of 5 km are preferred |
| | | Tourism – locations with a smaller number of tourist centres and a smaller number of existing and planned tourist accommodation facilities in a radius of 5 km are preferred |
| | | Agriculture - locations with a lower plant-production potential of soil, greater suitability for livestock production and greater distance from highly productive crops in a radius of 5 km are preferred |
| | | Forestry – sites for which lower secondary forest products are available (edible mushrooms and medicinal herbs) in a radius of 5 km are preferred |
| | | Industry and Mining – locations with smaller industrial centres of less sensitive industries in a radius of up to 5 km are preferred |
| | | Infrastructure – locations where the connection to infrastructure installations (water supply, power grid) is better are preferred |
| | | Special purpose – sites that, from the aspect of defense; have no restrictions or special requirements are preferred |
| | Environmental protection | Protection of natural heritage – locations with a smaller number of protected and recorded sites and are of lesser significance in a radius of 5 km are preferred |
| | | Protection of cultural heritage – locations where the number of protected and recorded sites and facilities is lesser in a 5 km radius are preferred |
| | | Soil status (plant production) – locations with a lesser amount of high-yielding soils for biological production in a radius of 5 km are preferred |
| | | Biological-ecological values – sites that are biologically less valuable or less sensitive are preferred |
| | | Radiological aspects of the existing state – locations with lower migration of groundwater into soils and bioaccumulation of radionuclides in organisms in a radius of 5 km are preferred |
| Acceptability of wider area | Purpose and use of space | Settlements – locations with a smaller number of settlements with more pronounced central and working functions and a |

(*Continued*)

**Table 2.** Continued.

| Aspect | Parameter | Detailed parameter |
|---|---|---|
| | | smaller number of larger settlements in a radius of 5–20 km are preferred |
| | Environmental protection | Tourism – locations with a smaller number of tourist centres, a smaller number of existing and planned touristic accommodation facilities (and if these capacities have shorter use during the year) of up to 20 km radius are preferred<br>Protection of natural heritage – locations with a smaller number of protected and recorded natural heritage sites in a radius of up to 20 km are preferred<br>Protection of cultural heritage – locations with the lesser representation of particularly valuable protected and recorded entities and objects of cultural heritage are preferred |

directive 2007/60/EU (European Union, 2007) zones of a floodline of probability of flooding at 1 000 years or less were used for the exclusion (Croatian Waters, 2019).

- Seismotectonics and seismology (Mini Map 2 – Seismotectonics and Neotectonics) – (Schaller, 1997).
- Lithological and geomorphological characteristics (Mini Map 3) – since there were no changes in data, this layer is taken from 1991 to 1999 Programme (Croatian Institute of Urbanism, 1991).
- Hydrogeology (protection of aquifers) (Mini Map 4) – these exclusion criteria consist of two layers: (a) a hydrogeological layer with two important water-bearing environments and (b) a layer with sanitary protection zones of springs and pumping sites (Official Gazette, 2002).
- Population density (Mini Map 5) – this map is created according to the data of the Central Bureau of Statistics 'Population Census 2011' (Croatian Bureau of Statistics, 2019).
- Protection of natural heritage (Mini Map 6) – new layers were adapted according to the Nature Protection Act of 2013 (Official Gazette, 2013a) and the Ecological Network Regulation of the same year (Official Gazette, 2013b) which includes areas incorporated in Natura 2000 (Croatian Environmental and Nature Agency, 2019)
- Mining and mineral exploitation (Mini Map 7) – there was no old map, and the production of the viable new map would take a far too long time. Therefore, all existing data considering mineral resources and their exploitation (Faculty of Mining, Geology and Petroleum Engineering, 2008) known and available to the authors, were compiled into one layer and used as a workable exclusion map.

Certain exclusion criteria maps could not be produced. 'Protection of cultural heritage' was included in 1991–1999 Programme (Croatian Institute of Urbanism, 1991) map titled 'Protection of natural heritage'. In order to comprise this criterion, several areas (from the list of national heritage sites (Register of Cultural Goods, 2016)) have been considered and excluded from the resulting map: Diocletian's Palace in Split and the old city centre of Dubrovnik (under UNESCO protection), as well as the areas of cities where important monuments of cultural heritage are located; archaeologically valuable sites, historical urban and rural settlements and memorial areas; places with a concentration of cultural goods and specific landscape features (Mošćenićka Draga-Rijeka-Novi Vinodolski, Trogir-Split-Omiš, the Makarska Riviera with massive Biokovo, the islands of Krk, Brač, the western part of Hvar with the Pakleni otoci, Biševo, the eastern part of the island Korčula, the western part of Pelješac, Lastovo and the Dubrovnik Riviera between Split and Cavtat with the nearby hinterland and the Elaphite Islands).

Exclusion criteria's SPECIAL PURPOSE would include areas of strategic importance for the Republic of Croatia (military objects, special industrial sites, etc.). In the unlikely event of a collision of these sites with the selected sites, the Government will decide what purpose it is more important for.

### 3.2. Čerkezovac and Majdan sites

The decision on the adoption of the Spatial Planning Programme of the Republic of Croatia (Official Gazette, 1999) by the Croatian Parliament on 7 May 1999 (Croatian Parliament, 1999) included potential sites for LILW disposal at Trgovska gora in the Majdan region, which in turn is a part of the Gvozdansko area. The three locations considered for the site selection (INA-PROJEKT, 1987) were: Veliko brdo, Milinkovac i Pavlovo brdo. Although all other potential sites were excluded from further consideration for the disposal site, Majdan did fall into preferable areas when considering comparison criteria. Detailed field research in the wider area of Majdan, performed by the INA-PROJECT geologists for the purpose of evaluating possible micro-locations, resulted in the geological map M 1:25000 (INA-PROJEKT, 1987; Schaller, 1997). However, by the mid-2010s, the affirmation of Čerkezovac site as the Radioactive Waste Management centre (RWMC), the location for long-term storage of LILW from the KNPP and institutional RW, originated in Croatia, began. It was adopted and affirmed by the Decision of the Government of the Republic of Croatia on its 124th Session, held on 9 November 2018

(acceptance of the National Programme for the Implementation of the Radioactive Waste and Spent Nuclear Fuel Management Strategy (Government of the Republic of Croatia, 2018)). The Čerkezovac site is a small military logistic complex with developed infrastructure and storage capacity, appraised by the Croatian military as 'non-perspective' and otherwise would be useless after the Croatian military abandons it.

Considering the Čerkezovac site through comparison criteria (see Table 2), it fits the criteria in all aspects. It effectively has same properties as the three Majdan sites considering Seismotectonics and Seismic Seismic Activity in all features, Meteorological aspects (extreme occurrences and dispersion) and Hydrological aspects (security from flooding and distance of surface flows). In view of Engineering geology (soil mechanics and foundation) aspects, the location is agreeable, also considering Lithology and geomorphology and Soil condition (chemical aggressivity). Considering Transport aspects, Čerkezovac has well-kept roads and the existing traffic system provides considerable security and a small likelihood of an accident. Considering the acceptability of a wider area, the Čerkezovac site meets the criteria.

### 3.3. Map design

The two main GIS techniques used to produce the final map were: merge layers and symmetrical difference layers.

The merge layers process copies all the features from two or more existing layers into a new combined layer. In this paper, 7 groups of vector polygon layers (a total of 11 layers) shown on small maps (Mini Map 1–Mini Map 7) were combined into one polygon layer. It must be noted that some polygon vector layers originated from raster layers, due to a lack of better backgrounds. In addition, the flooding safety layer is too complex (almost three million features) for a merge and symmetrical difference process, so it had to be divided into several sublayers. The country polygon is also very complex, as a multipart feature, because it has more than 40 thousands vertices.

The symmetrical difference is an analytical process in which two polygon layers are used to create one new layer with the overlapped areas of the original layers. Simply, this analysis process creates a new polygon layer with the features of either one of the original layers, but the new layer does not include the areas where both of the layers existed.

Specifically for this research, the two abovementioned techniques were very time-consuming. The complexity of 2 layers – state border and combined layer (merged 11 input layers), overburdened the software several times. After that, extensive manual work had to be done with the resulting layer that excluded some topological errors, gaps and overlaps, and also an analysis of each potential area with recent topographic and ortophoto maps. Also, the Multipart to Singlepart tool split some odd polygons into smaller ones. Insufficiently large polygons (areas less than 1 km$^2$) were deleted, and then the preliminary map of potential LILW sites was created, with 64 polygons (Mini Map 8).

Afterwards, a topological check and spatial analysis of the preliminary map were performed, and the number of potential areas was reduced from 64 to 50. A topological check included a very detailed analysis of each polygon in relation to all the individual exclusion layers, especially because of several very important facts. Initially, it was topologically impossible to correctly connect features in the hydrogeological layer because the layer consists of two parts, a group of groundwater bodies for the Adriatic and a separate group for the Black Sea basin. That is why only a detailed preview (with a higher zoom level) of the map could see which type of aquifer belongs to the gaps between the two basins. After that, four polygons have been excluded. In the second step, for the layer with islands (Croatia has over a thousand islands and they cover a total area of about 3300 km$^2$) it was decided that this area is not appropriate considering tourism and the preservation of nature and marine ecosystems (eight polygons have been excluded). In the third step, small areas along the state border were also considered as inappropriate and therefore an additional two polygons were excluded.

New spatial analysis reduced the number of PA from 50 to 23. It was performed underlying four layers, which cover the entire state territory. The first of them was a layer of sheets of SFRY basic geological map at scale 1:100,000 as a more detailed examination of the existing old lithological layer, due to the area of the recent alluvium, the proximity of the new layer of floods and the lithostratigraphy. The second imported layer was a new layer of topographic maps of the Republic of Croatia at a scale of 1:25,000 (Geoportal of State Geodetic Administration, 2019), due to significant changes since 1992 in topography, hydrography and population in the area and also due to small settlements that are not part of the Settlement database in the Croatian Bureau of Statistics (parts of villages). The third considered layer was a new demographic layer consisting of settlements with a population density higher than the population density of Croatia, 78.1 pop./km$^2$.

PA were also analysed according to possible transport and distances from roads, proximity to the state border, sea, river, etc. Finally, the shape of the area but also the location should create a circle, square or rectangle and that criteria also excluded a few PA.

The complete results of the topological check and all spatial analyses of PA on the preliminary map are shown in Mini Map 9. The rejected PA are indicated by red markings and the remaining PA by green markings.

The Main Map shows only 23 potential areas with prominently displayed Čerkezovac and Majdan Sites, also shown on a large scale in Mini Map 10.

The total area of these LSGU located on PA for the LILW disposal site is 2.348,78 $km^2$ and that area is 4.15% of area of the entire state territory.

## 4. Discussion and conclusions

Past studies dealing with LILW site selection in Croatia (period 1979–1991) did not utilize computers but manual GIS, which tried to utilize and combine all the relevant maps which were published at that time. Cartographers would create maps on clear plastic sheets and overlay these sheets on a 'light table' to create a new map of the overlaid data. Even in that preliminary stage of site selection, this process was not sufficient, and extensive long-term fieldwork was needed. In the 1990s, the PROMETHEE (Preference Ranking Organisation Method for Enrichment Evaluations) method was used. After those two stages of investigation, there was a long gap in research and decision making considering the site selection process. In 20 years, potential areas and locations for the disposal of LILW were known, but not officially confirmed until recently.

In the era of GIS technology and with the presence of recently developed thematic maps, the logical step was to use modern knowledge, data and software to verify previous work and to obtain some new information. This research is the first Croatian GIS-based site selection process for LILW disposal. Although it utilizes a similar methodology as the older site selection process, GIS software represents a powerful tool, which makes a significant difference.

Both old and modern (this research) approaches for site selection do include a large part of Trgovska gora as the potential site for disposal of the LILW. The new approach, utilizing GIS technology, new data sets, and fresh information, helped to obtain more detailed, accurate and precise areas with the required properties for LILW site selection. Compared to the old site selection method, the approach shown in this paper gives more reliable results and possible alternatives to the selected site. It also proves that the selected site has met the required criteria and that Trgovska gora, and more specifically the Čerkezovac site is a possible location for the LILW disposal site. This new approach discarded certain areas included in the old siting process, since certain data has changed since then, or was not available.

The Čerkezovac site, a Croatian soon to be ex-military base, does have all the infrastructure and storage capacity and is within the acceptable terrain/area, according to site selection criteria. Considering that the interim solution, according to Croatian National Programme for the Implementation of the Radioactive Waste, Disused Sourced and Spent Nuclear Fuel Management Strategy (Government of the Republic of Croatia, 2018), is that Čerkezovac is being considered for long-term storage, a scientifically easier claim, and not a disposal site, it can be concluded that the site is convenient. However, the location for the final disposal is yet to be decided upon.

Although properly performed, the site selection process for the low and intermediate-level radioactive waste (LILW) disposal site in Croatia did not include a voluntaristic approach. The only remaining area for the LILW disposal site, Trgovska gora, fits in site selection criteria and is acceptable concerning preliminary research. Site-specific research, on location, has not yet been performed.

Future research should include more detailed validation of old layers, and the weight of each data group (weighting criteria) would be included in the research if this were the official site selection. In that case, several other criteria would be crucial, i.e. ease and safety of transport (selection of optimal transport route), possible routes for first responders (in case of an accident), political and societal impact, infrastructure of potential sites, as well as the development of infrastructure on site, etc.

## Software

All maps were made using ESRI ArcGIS 10.1 for Desktop. The final map was made in Adobe Illustrator CC 2019.

## Disclosure statement

No potential conflict of interest was reported by the authors.

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