THE SPATIAL AND PLANNING ASPECT OF SOLVING THE ISSUE OF RADIOACTIVE WASTE DISPOSAL IN THE REPUBLIC OF SERBIA

by

Nebojša D. STEFANOVIĆ* *, Nikola M. KRUNIĆ, and Nataša M. DANILOVIĆ HRISTIĆ

Institute of Architecture and Urban & Spatial Planning of Serbia, Belgrade, Serbia

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In the Republic of Serbia, radioactive waste has been stored for many years at the Vinča location near Belgrade. However, the location is not suitable for this purpose. It is necessary to define a location for radioactive waste disposal in Serbia in accordance with international criteria, strict spatial conditions, and planning solutions of national interest. The need to conduct research that will define potential zones for radioactive waste disposal is the basic starting point in this paper. The framework of the research is the development of the Spatial Plan of the Republic of Serbia from 2021 to 2035, on the basis of which it is possible to determine potential zones for the construction of a radioactive waste disposal. In this paper, the authors present the results of research on spatial constraints from the aspects of geological and hydrological conditions, spatial protection, and distribution of the population, settlements and buildings, *etc*. A special contribution it makes is the additional analysis of conditionality in relation to the planned purposes and activities of national and priority importance in Serbia. The collection, processing, and presentation of spatial data is the result of analyses conducted with the support of geographic information systems. The research contributes to a definition of potential zones, within the scope of which it is necessary to conduct further research and select the optimal location for a radioactive waste disposal. The paper provides methodological guidelines for further scientific research into the spatial aspects of radioactive waste disposal in Serbia, at the same time pointing out possible directions for further resolution of this issue in practice.

Key words: radioactive waste disposal, spatial plan, constraints, zone, analysis, spatial data

INTRODUCTION

In recent years, spatial and urban planning has placed increasing emphasis on issues of environmental protection and assessing the impact of planning solutions on the future environmental quality [1]. In that sense, nuclear facilities have a special weight in planning, both because of certain conditions necessary for determining their location, design, construction, commissioning, operation, closure and decommissioning, and because of the impact they have, or can have, on the environment [2].

Most nuclear facilities in Serbia are situated at the Vinča location, which covers the entire area of the former Vinča Institute of Nuclear Sciences, with an area of 48 ha near Belgrade, today divided into the institute zone and the zone under the jurisdiction of the public company Nuclear Facilities of Serbia. In accordance with the Law on Radiation and Nuclear Safety and Security [3], which defines a nuclear facility as one or several functionally connected facilities located on the same site and operated by the same person, for the processing or enrichment of nuclear material, a facility for the production of nuclear fuel for a research nuclear reactor, a research nuclear reactor, a facility for managing used nuclear fuel from a research nuclear reactor and a facility for managing radioactive waste, in this study, the existing facilities for storing low and medium radioactive waste at Vinča are understood as nuclear facilities. Radioactive waste is understood as radioactive material in a gaseous, liquid or solid state, whose further use is not planned or foreseen [3], *i. e*., material that contains or is contaminated with radioisotopes with activity levels higher than the limit levels determined by regulations, and which is not planned for further use [4, 5].

At the Vinča site, there are nuclear facilities of great importance in terms of their environmental impact and the implementation of the necessary measures of protection [6, 7], which, in addition to the research reactors RA, which has permanently ceased operation, and RB, which is currently out of operation, also include stor-

* Corresponding author; e-mail: nebojsa@iaus.ac.rs

age facilities for low and intermediate level radioactive waste and spent radiation sources. This waste originates from the previous activities of reactors and other sources, such as research activities at the institute, medical and military institutions, commercial organizations, university laboratories, and the Institute for Technology of Nuclear and Other Mineral Raw Materials, *etc*. It consists of three hangars in which the waste is mostly in barrels, but it is also present in various bulky forms that could not be adequately processed and packed at the time of collection. Liquid radioactive waste is located in four underground reservoirs. Waste from the entire territory of the former Yugoslavia is also stored at the site (except for waste from NPP Krško).

Research, so far concerning the spatial conditions with regard to the Vinča site, has shown that the general conditions related to spatial restrictions and the formation of protection zones around the nuclear facilities, have not been complied with at the site and in its immediate surroundings [8)]. The existing state on the ground, first and foremost, is that the scope of illegal construction and the position of existing and planned frequently used roads, is unfavourable and has caused such restrictions, that in the coming period it is not realistic to expect it is possible to fulfil them. Therefore, in spatial and urban plans, the land use in the part of the area next to the Vinča site has not been determined and it is treated as a potential source of danger, indicating the need to develop a new planning document for the Vinča site.

Due to the relocation of particular buildings and activities of regional, national and international importance, to areas that are a relatively short distance from the nuclear facilities at the Vinča site (Vinča municipal waste landfill, Belo Brdo archaeological site, international infrastructure corridors VII and X) and the national significance of the Vinča location itself, the question of the permanent disposal of radioactive waste in Serbia has been raised.

The spatial plan of the Republic of Serbia determines the long-term basis for the organization, arrangement, use and protection of space in the Republic of Serbia [9], and it is one of the development planning documents with which all public policy documents must be harmonized [10]. The spatial plan of the Republic of Serbia is further elaborated through a system of spatial and urban plans, from which, for the purposes of planning activities of national interest, spatial plans for special purpose areas are developed.

In practice so far, two spatial plans of the Republic of Serbia have been developed and implemented. The first, in 1996 [11], defined the obligation for preparing a plan for the special purpose area of the Vinča nuclear complex and raised the open question of resolving the issue of finding a location for disposing of radioactive waste [12], and the second, from 2010 [13], did not mention this theme at all. The new Spatial Plan of the Republic of Serbia from 2021 to 2035 is currently being prepared [14], which the authors are using as a research framework, and in this study, they determine potential zones for constructing a disposal for radioactive waste in Serbia.

GENERAL SPATIAL CONDITIONS FOR PLANNING THE LOCATION OF RADIOACTIVE WASTE DISPOSAL

The International Atomic Energy Agency (IAEA) in Vienna defines several levels of documents that represent standards for the peaceful use of nuclear energy and reduction of the risk of ionizing radiation in the world, such as safety fundamentals, safety requirements and safety guides, which are further elaborated through national legislative systems. In accordance with the law [3], disposal is the storage of radioactive waste, spent sources or spent nuclear fuel in a disposal facility without the intention of its removal. The IAEA defines the disposal of radioactive waste as its storage in a conditioned state in a place from which it will no longer return to the human environment or to reprocessing [4, 5].

Currently, there are about 100 low and medium activity radioactive waste disposals in operation in the world. These disposals are of various types, from shallow buried engineered concrete trenches, to deep geological disposals [15]. The disposal of radioactive waste is carried out in such a way that it ensures the long-term stability of the disposal, *i. e*., it prevents the radioactive isotopes, present in the waste, from having any contact with the biosphere, especially with groundwater [16]. The basic principle of preserving the stability of waste material is its immobility in an appropriate material or construction, which isolates it in relation to its surroundings.

In the Republic of Serbia, as in the rest of the world, no unique detailed criteria have been defined for the purpose of determining suitable locations for constructing disposals for nuclear waste, particularly with the regard to spatial conditions. After the construction of the nuclear facilities at the Vinča site in the 1950′s and 1960′s, there was no need to plan new facilities at any other location. Regulations were based primarily on the research character of the nuclear facilities, and the protection and reduction of risk from ionizing radiation, while low and intermediate level radioactive waste was stored at the site itself.

In recent years, the issue of constructing a radioactive waste disposal in Serbia has been raised again, with accompanying research on the state of the radioactive waste at the Vinča complex, as well as the consideration of future needs and ways to solve this issue worldwide [17]. With this in mind, the basic phases of the lifespan of a radioactive waste disposal that it needs to go through are: determining the location, design, trial operation, operation and closure, as well as institutional supervision

(control) after closure over the following 100-250 years and unhindered access (without radiological restriction).

Selecting a location for a radioactive waste disposal, the first of these phases, is a priority in the coming period in the Republic of Serbia, and finding a solution for this requires methods and techniques used in spatial and urban planning. As the first step in this phase, it is necessary to analyzeanalyse all available data on the spatial conditions and constraints at the national level (an area of 88848 km^2), and to perform macro-zoning and select zones where there are no spatial constraints to the construction of radioactive waste disposals, using data processing in a geographical information system. Such potential zones for the construction of radioactive waste disposals are then further analyzedanalysed and micro-located.

Through comparative analysis of a number of documents, studies and conditions [18-21] relating to the location of nuclear facilities, it is possible to single out the following general spatial conditions that can be applied to the location of a radioactive waste disposal:

Geological conditions [22]

- the proximity of potentially active fissures and landslides must not be less than 500 m,
- there must be no possibility of ground subsidence resulting from the formation of cavities by pumping water or oil, or due to mining works,
- there must be no possibility of soil collapse due to dissolution and removal of soluble material (karst erosion or other types of erosion), and
- seismically active areas are eliminated (maximum expected earthquake intensity cannot exceed 8 degrees on the Mercalli scale, permitted ground movements must not exceed 0.15 of the acceleration of the earth's gravity).

Hydrological and meteorological conditions

- the use of water for various purposes, especially for drinking and irrigation must not be near the location (especially not downstream),
- there must be no possibility of torrents occurring at the location, or the possibility of flooding due to river overflows or embankment breaches, and
- locations with extreme meteorological conditions are eliminated.

Conditions related to spatial protection

- exploitation areas for natural resources are eliminated (mining of ores, minerals, coal, oil),
- areas within the scope of protected natural assets (national parks, nature parks, special nature reserves, *etc*.) are eliminated, and
- areas of immovable cultural property (UNESCO heritage list, all cultural property of national importance) are eliminated.

Conditions related to the population, settlements and buildings [23, 24]

- larger settlements (25000 or more inhabitants) must not be closer than 2.5 km.
- the proximity to installations with potential emissions of chemicals (particularly gaseous) must not be less than 2 km.
- the proximity to existing civilian and military airports must not be less than 8 km.
- locations downstream of water dams are eliminated, and
- the proximity of frequently used roads must not be less than 1.5 km.

Special conditions [25-27]

- pay attention to the proximity of the state border and other factors important from the military and security standpoint (areas of interest for the country's defence are rejected).

ANALYSIS OF THE GENERAL SPATIAL CONDITIONS FOR PLANNING THE LOCATION OF RADIOACTIVE WASTE DISPOSAL FOR THE TERRITORY OF THE REPUBLIC OF SERBIA

The collection, analysis and processing of data related to these spatial conditions is a complex and time-consuming process, because the data are partially available, they are of different ages and levels of processing, and they are often unsuitable for digital processing, which is especially true for larger areas. Also, preparing a spatial plan is the only process that is of a synthesized character, whereby such data for different areas are collected and processed in a single geographic information system. Therefore, it is essential for research into the spatial conditions for planning the location of a radioactive waste disposal to be linked with the development of a new Spatial Plan of the Republic of Serbia, and this should be done in the first step of the data relating to the existing state, fig. 1.

In terms of geological conditions, the greatest spatial limitations in Serbia (26.58 % of the surface) are in areas where the maximum expected earthquake intensity is over VIII degrees (MCS scale). The highest intensity of VIII degree is related to high basic hazard zones and unfavourable local soil conditions. These are the plains of northeasternnorth-eastern Banat, central Serbia with the valleys of the Velika and Zapadna Morava Rrivers, the wider area of Kopaonik Mountain, the area of the valley and mountainous parts of Kosovo and Metohija, the downstream part of the Timok River Valley with its confluence with the Danube and others. According to the number of inhabitants and level of

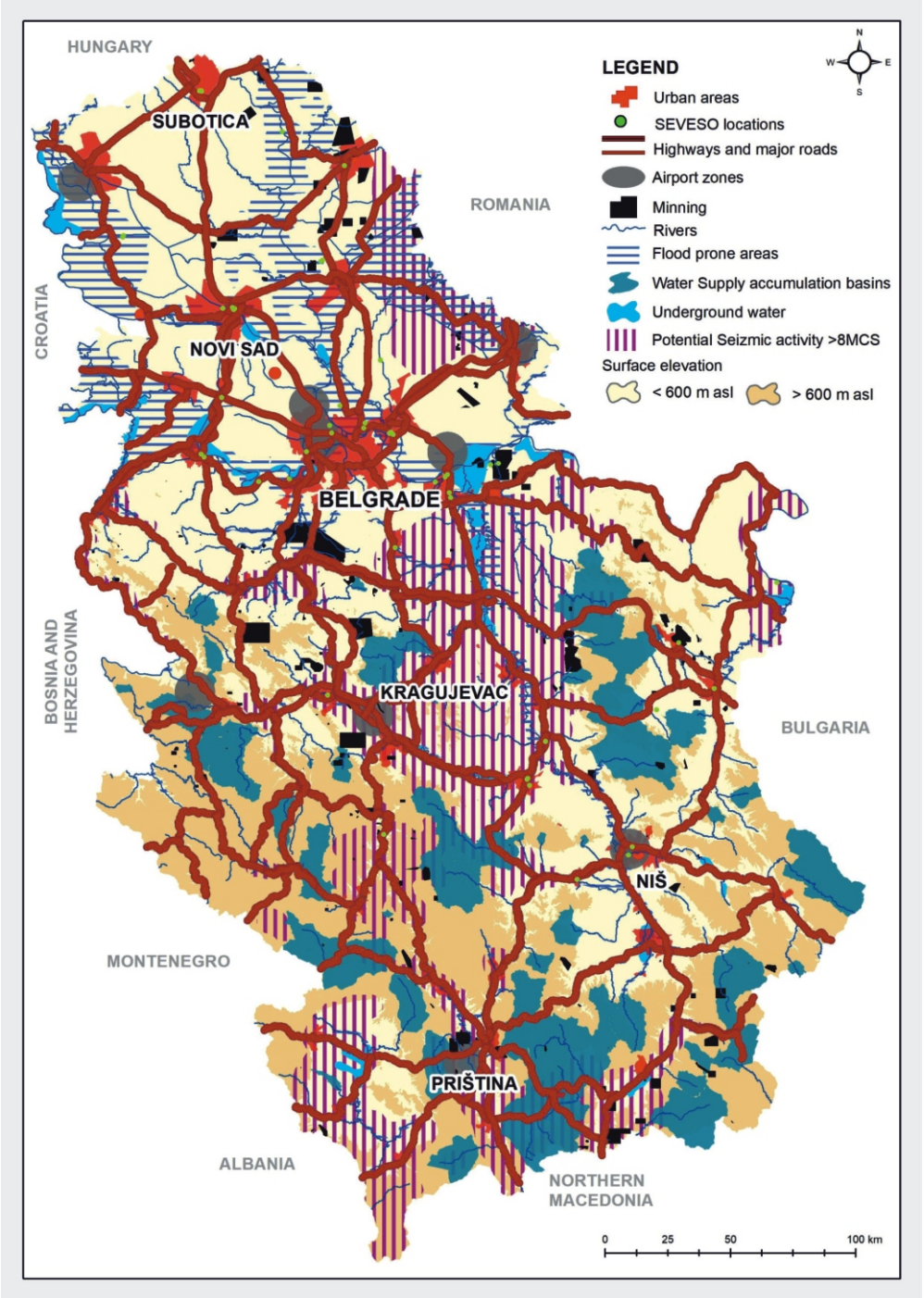

Figure 1. Zones and areas in the Republic of Serbia with unfavourable general spatial conditions for planning the location of a radioactive waste disposal

seismic hazard, the most endangered cities are Jagodina, Kragujevac, Kraljevo, Čačak, Novi Pazar, and Loznica. In the wider area of these cities, there are around 700000 inhabitants.

Areas of mining activities, which limit the possibility of locating a radioactive waste disposal, are represented by significant areas of surface coal mines in three large basins (Kolubara, Kostolac and Kosovo-Metohija), and by the surface mining of metallic raw materials in Bor and Majdanpek, as well as in a small way by several dozen mines for mineral, metallic and non-metallic raw materials at different locations.

All categories of soil erosion are represented on the territory of the Republic of Serbia, with the most pronounced of these being karst erosion. The middle category of erosion is manifested on an area of 9518 km^2, or 10.76 % of the territory of the Republic of Serbia, which is a potential erosion area (production of erosion material in the range of 10 to 20 t/ha per year). Within the framework of areas that have an explicit natural hazard, *i.*

e., predictive erosion areas of strong and excessive erosion (land losses of over 20 t/ha per year) is 13.32 % of the territory, *i. e*., 11776 km^2. This mostly includes terrain at altitudes over 600 m (asl), where there are also restrictions due to the danger of torrents, unstable soil and often protected natural features, made up of the mountainous areas of south-western and southeasternsouth-eastern Serbia. There are no detailed data relating to potentially active faults and landslides for this level of analysis.

Potential areas of flooding that are unfavourable for locating a disposal for radioacticeradioactive waste in Serbia cover 16 % of the total territory, that is, an area of 14146 km^2. Floods have affected the Central Banat and South Bačka areas the most, followed by the South Banat and Belgrade areas. Observed by catchment areas, after Vojvodina, the right bank of the Sava River is most endangered, followed by areas in the Velika Morava Basin, along the right bank of the Drina, in the Beli Drim Basin, Kolubara, Sitnica, Timok, Binačka Morava and Lepenac.

About 11500 watercourses with torrents have been registered in Serbia, in basins ranging in size from several hectares to several hundred square kilometres. This means that practically the whole of Serbia south of the Sava and Danube (the hilly and mountainous part of Serbia) is endangered. Besides Kragujevac, Obrenovac, Jagodina, Ljubovije, Pirot, Grdelica and Vlasotince, the most endangered areas are Grdelica Gorge and Vranje Valley, Kolubara Basin, Nišava River Basin, Ibar Gorge, Upper Timok Basin, Jadar River Basin, Drina Basin upstream of Loznica, the Mlava and Peka basins, the Binačka Morava Basin, *etc.* Areas of very high susceptibility to torrents are represented on 4.2 % of the surface of Serbia, and high susceptibility on 24.2 %, meaning that about 28 % of the territory of Serbia is very susceptible to torrents.

Other significant restrictions for the construction of a radioactive waste disposal are the sanitary protection regimes in the catchments of existing and planned accumulations intended for water supply. Such areas are within the regional systems for water supply to the population, which are located in Central and Southern Serbia. The basins of 36 newly-planned accumulations, in addition to the existing ones, occupy about 8000 km^2, *i. e*., 9 % of the territory of Serbia, from which the possibility of locating a radioactive waste disposal is excluded.

Areas with unfavourable spatial conditions and restrictions in terms of the distribution of the population, settlements and facilities in Serbia are smaller in size than the previously mentioned limitations, but due to their diversity in space, they cause significant limitations. These are settlements and cities with more than 25000 inhabitants and a zone that surrounds them with a radius of 2.5 km (from the edge of the construction area), and airports of different ranks (international, regional, military) with a surrounding zone (radius 8 km), in which the construction of radioactive waste disposals is not permitted. In addition, the spatial limitations relate to the network of frequent roads which in Serbia covers 30000 km of modern roads (most state roads are I or II class), and about 3700 km of railways (international, regional and local), with zones that are unfavourable for constructing a disposal covering a distance of 1.5 km from the transport corridor.

The system of reducing the risk of catastrophe and managing emergency situations is part of the national security system and is of particular importance in the analysis of the spatial constraints in the construction of a radioactive waste disposal. The territory of Serbia is exposed to the dangers of technical and technological accidents, which can cause significant consequences and thus endanger the health and lives of people, the environment and cause a large-scale damage. In this regard, the greatest risk is at the locations where there are industrial facilities and production zones, *i. e*., SEVESO facilities/complexes. These are facilities and locations where there is a danger of serious accidents caused by industrial activity. It was determined that there are 103 such complexes on the territory of the Republic of Serbia, of which 49 are *higher order* complexes and 54 *lower order.* In the protection zones, with a radius of 1 km around the SEVESO facility, construction is prohibited, especially of facilities that may be endangered by the consequences of a technical-technological accident, which includes radioactive waste disposals.

The processing of spatial data on the existing state and conditions of a geological and hydrological nature, as well as conditions related to the population, settlements and facilities (only basic data relating to larger areas are listed), indicates that on an area of about 52900 km^2, which is 60 % of the territory of Serbia, there are significant restrictions with regard to the location and construction of radioactive waste disposals.

ANALYSIS OF PLANNING RESTRICTIONS WITH THE REGARD TO A RADIOACTIVE WASTE DISPOSAL – SPATIAL PLAN OF THE REPUBLIC OF SERBIA FROM 2021 TO 2035

In addition to the previously mentioned data related to the current situation, as a second step in researching the spatial conditions for planning the location of a radioactive waste disposal, it is necessary to analyzeanalyse the concept of the future spatial development of the Republic of Serbia and individual planning solutions of national importance. The aim of such research is to record important planned purposes and activities in space, as well as planning constraints for defining a suitable location for constructing of a radioactive waste disposal. In this paper, the authors use newly-formed spatial databases and preliminary solutions from the Spatial Plan of the Republic of Serbia from 2021 to 2035, fig. 2. The most important aspects to analyzeanalyse are ur-

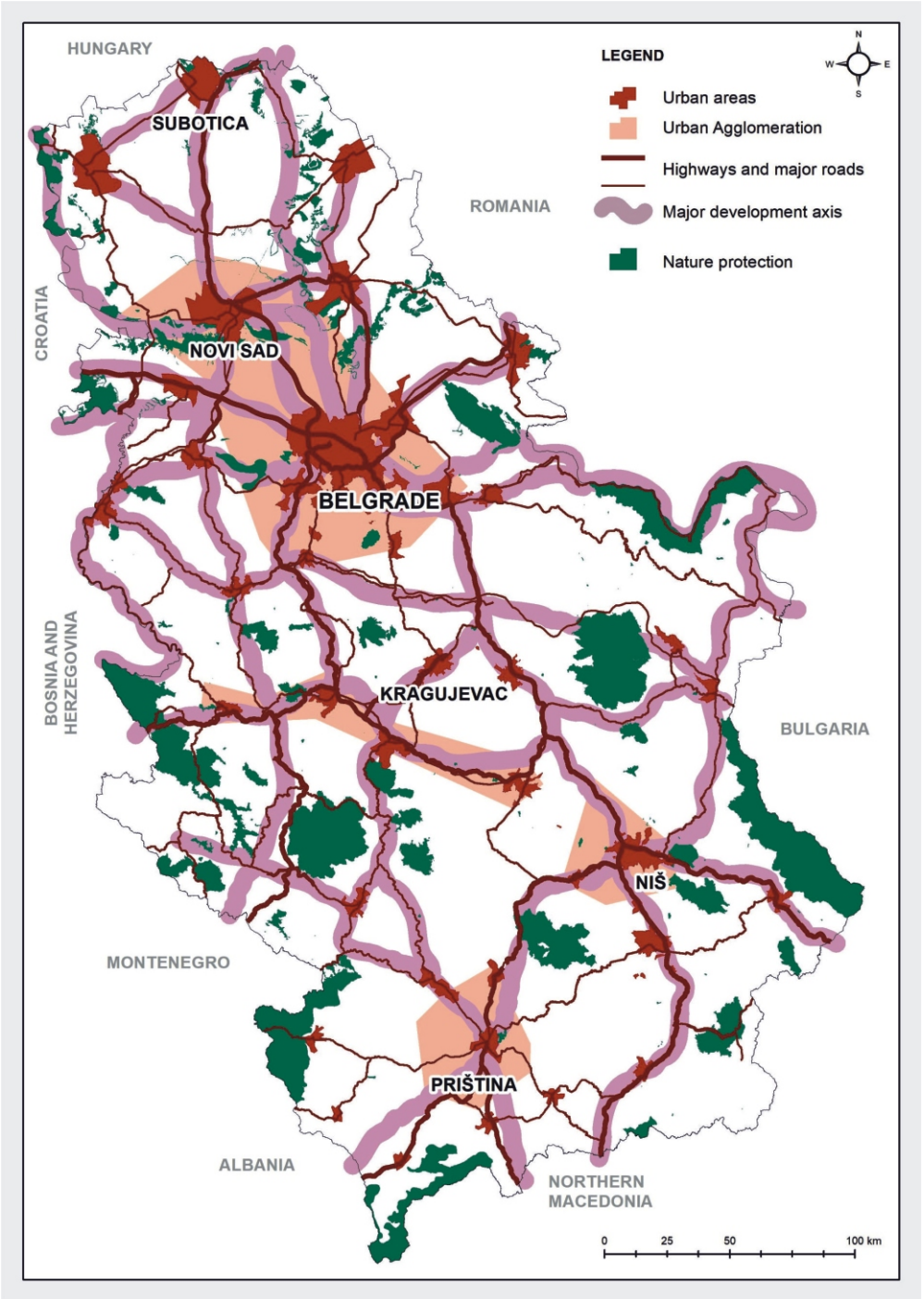

Figure 2. Overview of zones and areas in the Republic of Serbia with planning restrictions for planning the location of a radioactive waste disposal

ban and traffic systems (frequently used roads), development zones, protected areas and natural values.

The structure of basic land use in the Republic of Serbia (88848 km^2) is dominated by agricultural land covering 43113 km^2 (48.7 %), and forest and unwooded forest land covering 38,240 km^2 (43.1 %), while unfavourable areas from the standpoint of locating a disposal are wetlands and water surfaces covering 2377 km^2 (2.63 %) and other areas (construction land, artificial surfaces) covering 4757 km^2 (5.4 %). Planned changes in the basic land use that may be important for the analysis of spatial constraints will be directed towards: – Stopping the process of land degradation, misuse of agricultural land and irrational expansion of construction areas of urban and peri-urban zones. – Adjustment of purposes to natural conditions (afforestation) at the expense of agricultural land of lower quality, around infrastructural corridors, sources of accumulations, industrial zones, suburban forests and degraded areas. – Certain restructuring in the land use due to the construction of priority traffic infrastructure corridors.

The spatial plan establishes the protection of space on a total area of about 27115 km^2 or 30 % of the territory. These are areas where the possibility of locating radioactive waste disposals is excluded. The protection of space is mostly planned for protected natural assets or those that are planned for protection (about 15442 km^2) and immovable cultural goods (about 11 km^2), as well as for catchment areas of the sources of regional water supply systems (about 11662 km^2). Parts of these spaces overlap. In addition, space has been reserved for systems of transport infrastructure corridors (I class state roads, railways, product pipelines, main and distribution gas pipelines). In addition, the reservation of space for corridors that are part of transport infrastructure systems (state roads of the first order, railways, product pipelines, main and distribution gas pipelines) and for exploitation fields is determined, whereby these spaces are balanced at the lower levels of planning.

Important for spatial analysis, in this paper, is planning in relation to the completion and development of the planned road and railway infrastructure in Corridor 10, and the branches of that corridor on the territory of the Republic of Serbia, along the primary and secondary development belts, as well as the completion and reconstruction of the existing state road network (so-called fast highways). The most important traffic routes, which limit the possibility of building radioactive waste disposals in their vicinity, are the first level routes on Corridor 10 state roads: IA rank number 1 (Horgoš – Novi Sad – Belgrade – Niš – Vranje – Preševo), IA rank number 3 (Batrovci – Belgrade) and IA rank number 4 (Niš – Pirot – Gradina). Routes that mostly belong to the second level are roads IA rank number 2 (Belgrade – Čačak – Požega), IA rank number 5 (Pojate – Kruševac – Kraljevo – Čačak), the Požega – Kotroman extension (border with Bosnia and Herzegovina) and the Požega – Boljare extension (border with Montenegro), as well as the IB rank network of state roads.

In the protection of natural and cultural values and the effort to improve the quality of life, the special focus of the spatial plan is on the improvement and protection of the environment, whose degree of endangerment and degradation is disproportionately higher in relation to the level of economic and social development achieved. In the planning period, the declared protected areas of natural assets and those recommended for protection, will cover a total area of 909530 ha (10.28 % of the territory of Serbia) under strict protection regimes, of which 40880 ha (4.49 %) are under the level I protection regime and 229975 ha (25.28 %) under the level II protection regime. It is reasonable to assume that on the space planned for research and protection, with a total area of 440,000 ha in the planning period, 220000 ha (2.48 % of the territory of RS) will be declared protected areas, so that the total protected area will be about 1129530 ha (12.76 % of the territory of Serbia).

Metropolitan areas also stand out as a planning category that excludes the possibility of locating a disposal for radioactive waste. The metropolitan area of Belgrade and Novi Sad, with numerous sub-centers of different ranks, is the most developmentally promising, starting from the highest functional capacity and demographic potential, excellent traffic connections and solidly equipped infrastructure. It is a complex and dynamic system of urban settlements with a high degree of functional and spatial/morphological connection, a multi-layered hierarchy, with the potential to become the centercentre of a metropolitan region in this part of Europe. Conditionally, the centers of Bačka Palanka to Smederevo, and from Pančevo to Lazarevac also belong to it. In the coming period, the concentration of functions, the population, users of space and the economy in this urban area will continue to grow. The metropolitan area will also become the dominant tourist destination in Serbia. The metropolitan area of Niš, with its numerous subregional regional and local urban centres is promising in terms of development, starting from its geostrategic and transport position, high functional capacity and human capital, its excellent traffic connections and solid infrastructure. It is a complex and dynamic system of urban settlements that is the centre of the region of Eastern and Southern Serbia. In the coming period, the concentration of functions, the population, users of space and the economy in this urban area will continue. To to grow. This metropolitan area will become the second-most dominant tourist destination in Serbia. The metropolitan area of Priština, with its subregional regional and local urban centerscentres and development potential (traffic, functional and demographic), is the centre of Kosovo and Metohija. In the coming period, within its range, the concentration of functions, construction of traffic corridors and the development of secondary development zones towards other urban areas will intensify. In addition to these areas, the West Moravian agglomeration stands out in Serbia, in which there are morphologically and spatially/functionally connected urban centerscentres with significant functional capacity and good traffic connections, namely, the cities of Užice, Čačak, Kraljevo and Kruševac, which need better infrastructure, with planned and more dynamic economic development.

Further development of Serbia's urban system is based on transformation, according to the characteristics of its fundamentally different areas, from the metropolitan areas and agglomerations mentioned, to medium and small urban centres in underdeveloped rural, hilly/mountainous or border areas with latent potential.

The spatial integration and functional connection of urban centres and regional units, essential for territorial cohesion, economic stimulation and competitiveness of all parts of the Republic of Serbia, will intensify and achieve connections and integration through development axes/belts and transport corridors, which are already formed or expected in the future.

In this regard, of particular importance are: – Primary development belts, which stretch through areas with the highest concentration of population and economic activities, as well as international and national transport infrastructure corridors: the Danube-Sava belt, which has key development importance, both for Serbia and for the integration of the economy with European Union countries, including urban and industrial centerscentres, and the international ports of Belgrade, Novi Sad, Smederevo and Pančevo; Corridor Belt X; the West Moravian Belt, along the West Morava, from Užice to Čačak, Kraljevo, Kruševac and Corridor X, which also provides the possibility of spatial integration in the direction of Bosnia and Herzegovina in the west, and Bulgaria and Corridor IV in the east; the Kolubara belt, in the direction from Belgrade to Obrenovac, Valjevo, Gornji Milanovac and Čačak, which provides the possibility of spatial integration in the direction of the West Moravian belt and further along the Golja-Pešter direction to Montenegro in the south; the Toplica-Kosovo-Metohija belt, in the direction from Niš towards Prokuplje, Kuršumlija, Priština, Prizren and Albania (Durres). – Secondary development belts, which stretch through insufficiently developed areas with significant natural and created potential, whose transport position, accessibility, infrastructure and superstructure, as well as the demographic processes, should be improved, namely, the Bačka, Tisa, Fruška Gora-Mačva, Drina-Šumadija-Homolj, Šumadija, Podrinje, Braničevo-Podunavlje, Zlatibor, Golija -Pešter, Timok, Ibar, Pešter-Lim, Kosovo-South Morava and Metohija development belts.

Processing of the spatial data on all the above limitations, caused by the planned spatial development of the Republic of Serbia and planning solutions that mostly relate to urban and transport systems, development zones, protected areas and natural values, indicates that on an area of about 45300 km^2, which is 51 % of Serbia, there are significant planning constraints for locating and building a radioactive waste disposal.

RESULTS OF THE ANALYSIS

The analysis and processing of two important groups of spatial data, the first on the existing constraints and the second on the planning conditions and restrictions, have led to the basic result that on a the total area of about 69300 km^2, which makes up 78 % of the total area of Serbia, there are restrictions that make this area unfavourable for locating a radioactive waste disposal, fig. 3. This research has analyze and commented on data available at the level of the entire territory of the Republic of Serbia, and the areas that were assessed as unfavourable according to individual constraints overlap to a great extent. This means that such areas are unfavourable because of at least two, and often more spatial constraints, making further detailed research necessary.

This analysis established that there are no restrictions on an area of about 19060 km^2, which makes up 22 % of the surface of Serbia, indicating that this area is potentially favourable for locating a radioactive waste disposal. This includes certain areas that are located at over 600 m above sea level (asl) but which have no other restrictions, and they are considered conditional in this category of surfaces.

In general, besides the fact that these potentially favourable areas for locating a radioactive waste disposal are different and significantly dispersed throughout Serbia, it is possible to distinguish four zones in which they are recognized, namely:

– *the zone of Northern Vojvodina* – which is mainly made up of the area of Central Bačka between the course of the Danube and Tisa rivers, with the smaller areas of northern and Southern Banat. This zone should be accepted conditionally, because in the opinion of the authors it is possible to notice some constraints that are not the subject of analysis in this paper, primarily high-quality agricultural land (I to IV quality class) and the flow of surface and groundwater is towards high population density zones;
– *the zone of Western Serbia* – which consists of a wider area around the city of Valjevo (mostly northwest) and the upper course of the Kolubara River. This zone also needs to be accepted conditionally, because significant additional restrictions are possible in it, such as the direction of surface flows and groundwater towards zones of high population density, and significant areas of potential tourist areas and regions (Valjevo Mountains, Divčibare);
– *the zone of Eastern Serbia* – which for the most part consists of the area around the town of Negotin, the lower course of the river Timok (Negotin region) and the eastern slopes and hills of the Homolje mountains. No additional restrictions are observed for this zone, and at this stage of the analysis it can be considered favorable for locating radioactive waste disposals, especially having in mind that it is a distinctly depopulated area, away from agglomeration zones and higher population densities, as well as in a very peripheral area isolated by many natural factors (hydrological, meteorological, geomorphological, *etc*.);
– *the zone of Southern Serbia* – which consists of a wider radial area around the city of Niš. At this stage, no additional limitations can be observed in this zone either. The Toplica district of the Toplica River Basin and the surroundings of the towns of Prokuplje and Kuršumlija stand out as the largest in terms of surface area. They are depopulated areas that are mostly geomorphologically isolated at the foot of mountains or higher terrain, but with somewhat unfavourable conditions related to surface flows towards the city of Niš.

The spatial and planning aspect of finding an initial resolution to the issue of locating a radioactive waste disposal in Serbia is in some way completed by the results of

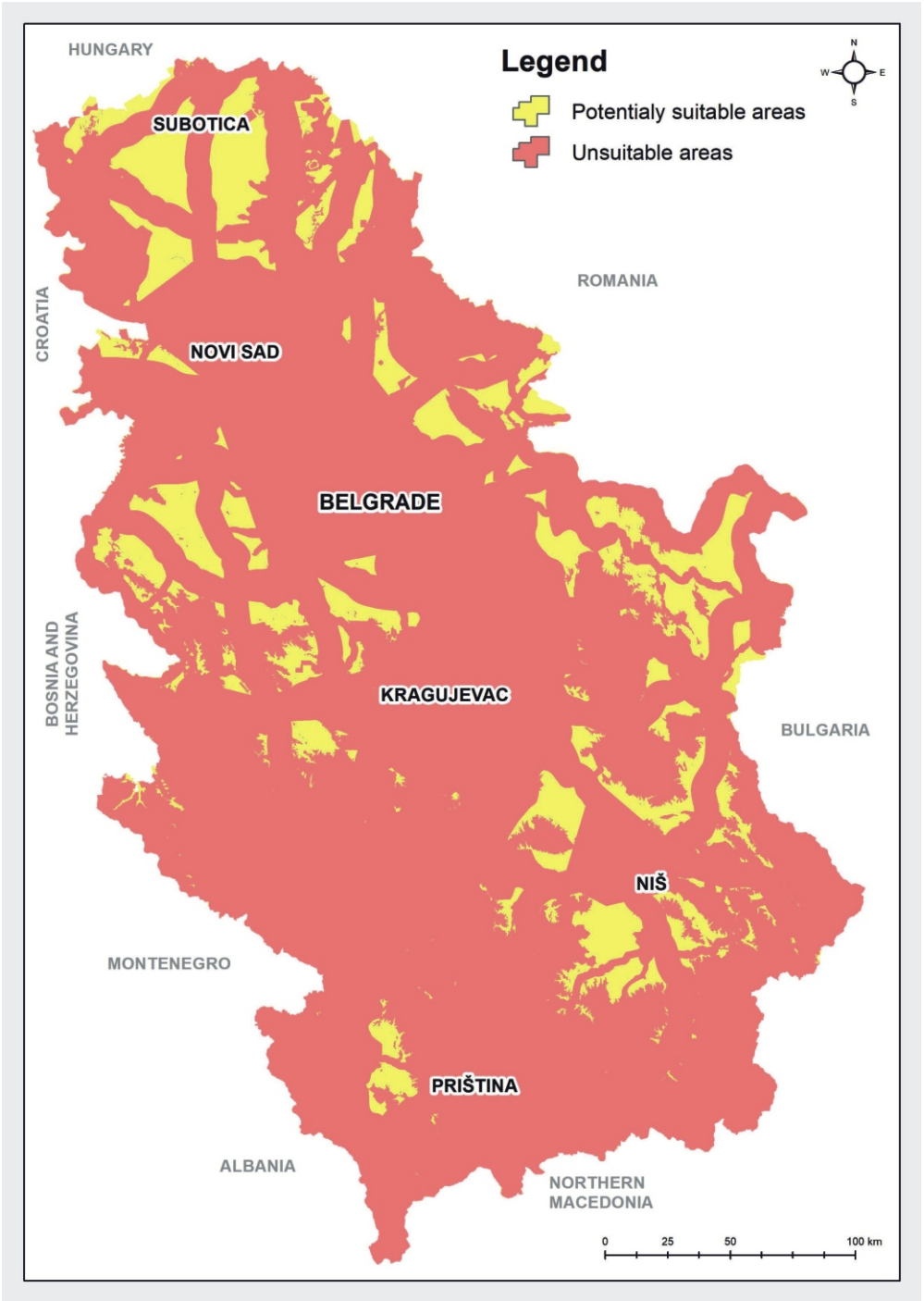

Figure 3. Overview of zones and areas in the Republic of Serbia that are favourable for further planning with regard to the location of a radioactive waste disposal

this analysis. In addition to the fact that it is necessary to start with comprehensive and detailed research of this type, this analysis indicates what conclusions we can expect in the future. In the field of spatial research, according to the authors of this paper, it is important to know that only 22 % of Serbian territory has been assessed as being favourable for locating a radioactive waste disposal, *i*. *e*., that it is necessary for more attention to be directed towards the previously mentioned zones (with an emphasis on Eastern and Southern Serbia).

CONCLUSIONS AND RECOMMENDATIONS

Through the research and the presentation of its results in this paper, the authors have tried to contribute to initiating and solving the issue of the permanent disposal of radioactive waste in Serbia. Based on previous research and knowledge of the technical and radiation properties of the radioactive waste stores at Vinča, as well as a proposal for the concept of a single disposal

[17], it seems that it is the right moment to approach systematic research to determine the location for a radioactive waste disposal. This is supported by the fact that the new Spatial Plan of the Republic of Serbia from 2021 to 2035 is currently under preparation, which brings the problem of radioactive waste storage into a spatial context and provides an opportunity for the timely direction of further research, as well as making necessary decisions.

Over recent years, spatial analyses and data processing with the use of geographic information systems have represented a common methodological procedure in spatial development planning [28-32]. However, such a procedure has not yet been applied in Serbia to those data that are of significance and have a direct influence on the possibility of determining the zones and locations for a radioactive waste disposal. Therefore, this research aimed to first systematize the general spatial conditions and criteria for selecting the location for a radioactive waste disposal and to later collect and process such data for the territory of Serbia. A special contribution of the research is that it was conducted simultaneously with the preparation of the Spatial Plan of the Republic of Serbia, which made it possible to use newly-collected data from 2020. In addition, the new category of planning restrictions was also considered, which further prevent the location of a radioactive waste disposal on significant areas.

The results of the research, which indicate that 78 % of the surface of Serbia, due to one or more constraints, is unfavourable for locating a radioactive waste disposal, have great applicative significance. Thus, scientific and professional attention can be focused in a relevant way on those zones in which limiting factors have not been identified and which should be the subject of further, more detailed research. In addition, with previous knowledge of the problems at the site of the Vinča Nuclear Complex [8], this research has been able to give feedback during the preparation of the Spatial Plan of the Republic of Serbia [33] in such a way that the implementation measures in the plan envisage the priority development of a spatial plan for the special purpose area of the Vinča location and the development of a study for determining the location of a radioactive waste disposal in Serbia.

For further phases of research into the issue of a radioactive waste disposal in Serbia, the limitations of this research should be taken into account, in terms of two important aspects. The first refers to the general spatial conditions used in this paper, which are of a general type and refer generally to nuclear facilities in the broadest sense. As such, they have conditioned stricter restrictions, which in the coming period can be reviewed and moderated depending on the nature and technical characteristics of the radioactive waste disposal. The second aspect relates to the availability and nature of the data used in the spatial analysis. For further research, it would be necessary to obtain the missing data and innovate that which is not in a usable digital format.

The research presented in this paper is of initial and scientific character. Beginning to solve the issue of the permanent disposal of radioactive waste in Serbia requires a systematic approach, which in terms of the spatial aspect, implies at least two methodological phases. The first phase is a study (preparation of a study) that includes macro-zoning of space, with additional research and coordination of numerous institutions, and later micro-zoning of space, with detailed analysis, multi-criteria evaluation and site selection. The second phase is the planning and design phase (preparation of a spatial plan for the special purpose area), through which the location is checked and confirmed, the rules of arrangement, construction, use and protection of the space are defined, and later the design for the future radioactive waste disposal is made. It is in this direction that it is possible and necessary to conduct further scientific research, in order to give full support to permanently resolving the issue of radioactive waste disposal in Serbia.

AUTHORS' CONTRIBUTIONS

Conceptualization: N. Stefanović and N. Krunić, methodology: N. Stefanović and N. Danilović -Hristović, formal analysis: N. Stefanović, investigation and sources. Nataša Danilović-Hristović, data curation: N. Stefanović and N. Krunić, writing-original draft preparation: N. Stefanović, writing-review and editing: N. Stefanović, and N. Danilović-Hristić, visualization: N. Krunić, supervision: N. Krunić.

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Небојша Д. СТЕФАНОВИЋ, Никола М. КРУНИЋ, Наташа М. ДАНИЛОВИЋ ХРИСТИЋ

ПРОСТРОРНИ И ПЛАНСКИ АСПЕКТ РЕШАВАЊА ПИТАЊА ОДЛАГАЊА РАДИОАКТИВНОГ ОТПАДА У РЕПУБЛИЦИ СРБИЈИ

У Републици Србији се радиоактивни отпад дужи низ година складишти на локацији Винча код Београда. Постојећа локација складишта није погодна за одлагање радиоактивног отпада. Потребно је дефинисати локацију за одлагање радиоактивног отпада у Србији ускладу са међународним критеријумима, строгим просторним условљеностима и планским решењима од националног интереса. Потреба спровођења истраживања у циљу дефинисања потенцијалних зона за одлагање радиоактивног отпада је основно полазиште у овом раду. Оквир спроведеног истраживања представља израду Просторног плана Републике Србије од 2021. до 2035. године, као активности на основу које је могуће утврдити потенцијалне зоне за изградњу одлагалишта радиоактивног отпада. У овом раду аутори презентују резултате истраживања о просторним ограничењима са аспекта геолошких и хидролошких услова, заштите простора, распореда становништва, насеља и објеката и др. Посебан допринос јесте додатна анализа условљености у односу на планиране намене и активности од националног и приоритетног значаја у Србији. Прикупљање, обрада и презентација просторних података је резултат анализа спроведених уз подршку географских информационих система. Допринос споведеног истраживања се огледа у дефинисању потенцијалних зона, у обухвату којих је потребно спроводити даља истраживања и одабир оптималне локације за одлагалиште радиоактивног отпада. У раду су дате методолошке смернице за даља научна истраживања просторних аспеката одлагања радиоактивног отпада у Србији, уз истовремено указивање на могуће правце даљег решавања тог питања у пракси.

Кључне речи: радиоактивни отпад, одлагалиште, просторни план, ограничење, зона, анализа, просторни податак