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*Research Article*

# A Data-driven Approach to Assess the Need for Priority Treatment of Potentially Contaminated Sites (PCSs) in Slovenia

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**Abstract:** This paper presents a multi-criteria decision-making model for assessing the need for priority treatment of potentially contaminated sites (PCSs) in Slovenia, with the aim of reducing risks to human health and preventing further environmental degradation, and to support the establishment of a national PCS management system. We established and developed a model consisting of four criteria and nine indicators reflecting environmental sensitivity and human-health risk. Application of the model shows that 35 sites (5%) fall into the highest vulnerability class, while additional 196 sites require accelerated investigation or remediation. The largest share of sites (248) exhibits a moderate need for priority treatment. Spatial analysis reveals that many PCSs are located on permeable geological formations, near surface waters, or within water protection zones, underscoring their exposure to contaminant migration. These vulnerabilities are further amplified by increasing climate-related hazards, such as extreme precipitation and flooding. The proposed approach provides an objective basis for identifying the most critical sites where interventions would yield the greatest environmental, social, and economic benefits. It supports more strategic decision making, optimizes resource allocation, and strengthens Slovenia's capacity to implement national and European environmental and climate commitments.

**Keywords:** PCS management; soil protection; sustainable land use; multi-criteria decision-making model (MCDM); decision-support framework; Slovenia

**Highlights:**

- The first geographic method from Slovenia for assessing the need for priority treatment of PCSs.
- Over 60 attributes are monitored for each PCS.
- 5% of PCSs were classified in the 5th class with the highest vulnerability level (need urgent priority treatment).
- PCSs hotspots in Slovenia are found in the wider area of larger towns, in lowlands, plains, along major rivers, along main road and railway connections, and transport nodes.

## 1. Introduction

Environmental pollution poses a significant threat to human health, ecosystems, and natural resources (Bica, 2020; European Commission, 2021a; Yi et al., 2023; Zabeo et al., 2011). The European Green Deal (European Commission, 2019) aims to ensure a healthy environment for all living beings and calls for an improved monitoring, prevention, and mitigation of air, water, and soil pollution. Additionally, the EU Action Plan: Towards Zero Pollution for Air, Water and Soil (European Commission, 2021a; European Union, 2022) sets out a comprehensive vision of zero pollution for 2050, which aims to "reduce air, water and soil pollution to levels no longer considered harmful to health and natural ecosystems and that respect the boundaries our planet can cope with, thus creating a toxic-free environment." The document further describes it's objective as a "cross-cutting objective contributing to the UN 2030 Agenda for Sustainable Development and complementing the 2050 climate-neutrality goal in synergy with the clean and circular economy and restored biodiversity goals" (European Commission, 2021a).

At the EU level, two key policy frameworks address the management of (potentially) contaminated sites: the Thematic Strategy for Soil Protection (European Union, 2006) and the EU Soil Strategy for 2030 (European Commission, 2021b). The former obliges member states to implement measures that prevent soil contamination by hazardous substances. Member states are obligated to compile a list of two types of sites: sites polluted by hazardous substances whose concentration levels pose a significant risk to human health and the environment, and sites where certain potentially polluting activities have been carried out (landfills, airports, ports, military sites, etc.). The Strategy also commits member states to remediate the polluted sites in line with national strategies (European Union, 2006). The latter Strategy outlines detailed measures and goals for polluted sites where the soil has partially or entirely lost its capacity to provide essential ecosystem functions and services due to degradation (e.g., monitoring the remediation progress of contaminated sites by 2030, compiling an EU priority list for contaminants by 2024, etc.) (European Commission, 2021b).

In terms of spatial planning, the remediation of contaminated sites is crucial for ensuring circular land use management (European Commission, 2020; Williams, 2020) and achieving the goal of no net land take by 2050. Both strategic goals are embedded in EU policy frameworks, which recognize that the remediation of contaminated and potentially contaminated sites can contribute to safeguarding agricultural and forest land (European Environment Agency, 2023). Beyond land-use efficiency, remediation also improves public health, ensures natural resource protection (water, soil, land, etc.), preserves cultural landscapes, mitigates the sites' unattractive appearance, etc. (De Sousa, 2001; Gunjyal et al., 2023; Reddy & Kumar, 2018; Sinnett et al., 2022).

Slovenia has yet to adopt a national strategy outlining priority remediation tasks, although the treatment of (potentially) contaminated sites is mentioned in two strategic documents that prioritize soil protection and remediation. The Resolution on the National Environmental Action Program 2020-2030 (Act No. 31/20 and 44/22 – ZVO-2) emphasizes the importance of preserving soil quality by preventing unsustainable soil processes (e.g. soil compaction, pollution, etc.) and by remediating contaminated sites or establishing appropriate new land use on these sites. The Resolution outlines as one of its measures the rehabilitation and revitalization of degraded soil areas. A similar priority is included in the Spatial Development Strategy of Slovenia 2050 (Act No. 72/23), which lists among its priorities the rehabilitation of brownfields that were once waste landfills and other old environmental burdens. It also stresses the need to improve and implement measures in said areas by providing the systematic allocation of funding, personnel, research, and IT support to monitor the state of these sites.

This article outlines a decision-making model for evaluating the need for priority treatment of potentially contaminated sites (hereinafter: PCSs) with the aim of reducing risks to human health and the environment. To provide some background, the establishment of the first PCS inventory in Slovenia is described. The PCS inventory is not yet comprehensive due to the limited amount of data for Slovenia. The modelling results are examined at the level of individual indicators and the spatial distribution of PCSs. These findings will help support the national PCS monitoring system and shape more targeted activities to identify new PCSs that have not been identified yet due to the incomplete records (proximity to water, in areas of old industrial centers, etc.).

The principal challenge in Slovenia is that the management of PCSs significantly lags behind practices established elsewhere in Europe and worldwide. Until recently, no national PCSs database existed. As a result, the absence of systematic and targeted monitoring has left the actual environmental and human-health impacts of PCSs largely unknown, as well as the true extent and urgency of required remediation measures. The overarching aims of this research were to establish an effective framework for PCSs management; to test innovative processes capable of accelerating PCSs monitoring, assessment, and remediation; and to evaluate the scientific value of spatial databases for analyzing and prioritizing PCSs. These aims were operationalized into the following research goals: (1) the establishment and management of a national PCS database, (2) the definition of relevant attributes for systematic PCS monitoring, (3) the identification of appropriate indicators for determining site-specific priorities based on environmental sensitivity and human-health risk, (4) the examination of PCSs using these indicators, and (5) the final prioritization of PCSs for targeted and timely intervention. To achieve these goals, we developed a multi-criteria GIS decision-making model that ranks

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PCSs according to two key dimensions: environmental sensitivity to pollution and potential risk to human health. This framework provides an objective and transparent basis for prioritizing sites for further investigation and remediation. The model was developed through a multidisciplinary process that enabled collaboration and integration across diverse scientific disciplines and institutional sectors. The resulting prioritization enables a more focused, efficient, and innovative approach to PCSs management by ensuring that attention and resources can be directed toward the most critical sites. We anticipate that these contributions will support more strategic decision-making and help reduce Slovenia's current lag in the systematic management of PCSs. This represents a necessary step for the country to implement the many European and national strategic commitments related to sustainable development, a healthy environment, and the protection of land and biodiversity.

Furthermore, PCSs management must increasingly account for the impacts of climate change, which in Slovenia are reflected in the rising frequency, magnitude, and intensity of extreme weather events (Mužina, 2024), including (flash) flooding (Bureau of Meteorology, Hydrology and Oceanography, 2023b; Trobec, 2017). Under such conditions, PCSs are even more exposed to natural hazards—such as floods, landslides, and avalanches—which can significantly amplify the negative environmental and human-health consequences of potential contaminations. This increased vulnerability was clearly demonstrated during the 2023 floods, when numerous PCSs were inundated (Bureau of Meteorology, Hydrology and Oceanography, 2023a), underscoring the urgent need for improved risk assessment, preparedness, and remediation planning.

## 2. Theoretical framework

The definition and use of the term "potentially contaminates sites" varies across European countries. The European Environment Agency (EEA) defines PCSs as "sites where unacceptable soil contamination is suspected but not verified, and detailed investigations need to be carried out to verify whether there is unacceptable risk of adverse impacts on receptors" (Panagos et al., 2013). At the EEA level, which encompasses 38 countries, the Progress in Management of Contaminated Sites in Europe indicator (European Environment Agency, 2022) monitors (potentially) contaminated sites. In Slovenia, PCSs are defined as sites that are suspected of being contaminated from past or present activities (Lampič & Rebernik, 2023). PCSs include various industrial sites, mining sites, waste disposal sites, airports, ports, former military sites, petrol stations, industrial dry-cleaning facilities, agricultural activities, and sites that have been contaminated in the past due to waste disposal (Lampič et al., 2021).

Effective PCSs management involves more than just their identification and monitoring: it requires a comprehensive assessment to ensure a timely identification of actually contaminated sites in the most sensitive areas that constitute the biggest threat to human health and the environment (Laha et al., 2000; Li et al., 2017; Samlani et al., 2024). The European Environment Agency defines a four-step comprehensive management system of contaminated sites (van Liedekerke et al., 2014), that further directly supports both the Thematic Strategy for Soil Protection (European Union, 2006) and the EU Soil Strategy for 2030 (European Commission, 2021b):

1. (Potential) contaminated site identification. Identifying areas with expected soil contamination.
2. Preliminary survey of the identified (potentially) contaminated sites. Detailed description of the site and surrounding area in order to further identify possible pollutants (description, past and present land use, PCS location in relation to various protection regimes – water protection areas, Natura 2000 sites …). The pedological features are determined along with the potential pollutants that could be expected in the soil due to past or present activities. Contaminated sites database with potentially polluted soil and other elements of the environment is compiled based on the collected data.
3. Main site investigations. Selecting the criteria to identify and address the sites that present the greatest risk to human health and the environment. Set priorities based on criteria (characteristics of the pollutants, level of contamination, protection regimes, etc.).
4. Implementation of risk reduction measures. Based on risk assessment and taking into account best practices and effective innovative approaches, the most suitable risk reduction measures or rehabilitation plans are selected (rehabilitation plans and risk reduction measures are tailored to the characteristics of each individual site). This step must include an estimation of the feasibility of the measure implementation, approximate costs, and designate the payer (polluter, state). This phase also includes implementing the rehabilitation measures along with setting up a monitoring system for monitoring the efficacy of the measures.

Most European countries follow this approach (van Liedekerke et al., 2014) and keep regional or national inventories of contaminated sites (Naidu et al., 2015; Panagiotakis et al., 2025; Panagos et al., 2013). Slovenia, however, has

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not yet adopted a legally binding definition of a PCS, which continues to hinder efforts to address contaminated sites in a systematic and comprehensive manner (The National Council of the Republic of Slovenia, 2019). A major step in this field occurred between 2020 and 2022, when the first PCSs inventory was established at the initiative of the Ministry of the Environment, Climate and Energy to follow legally binding regulation on waste and water management (particularly the protection of drinking water resources). The remediation of contaminated sites is carried out pursuant to the applicable Environment Protection Act (Act No. 44/22). The national PCSs inventory was outlined in 2021 (Lampič et al., 2021; Lampič et al., 2022a) and upgraded in 2022 with a completed methodology for pinpointing priority areas for implementing measures, thus establishing the foundations for comprehensive national PCSs management. These efforts correspond to step 3 of comprehensive PCS management and are intended to ensure that priority is assigned to locations within environmentally sensitive areas or areas where potential contamination could pose a threat to human health. At the same time, the associated risk assessment for each site is carried out in relation to other evaluated locations (D'Aprile et al., 2004; Marzocchini et al., 2018; Zabeo et al., 2011).

Numerous authors have used similar approaches in their studies (e.g., Pickford, 2001; Sorvari & Seppälä, 2010; Yi et al., 2023; Zabeo et al., 2011). Since assessing the need for priority PCS treatment entails gathering and analyzing various environmental and other spatial data, the selected criteria used by authors of similar studies were examined in more detail (Table 1). The criteria set differ between studies, as their selection depends on the availability and reliability of the data, the geographical characteristics, the local context of the studied locations, etc. The studies often utilize existing data on previously identified and well-known contaminations and present contaminants, whereas no such database exists for Slovenia yet. By analyzing the range of studies, we were able to make more effective and informed decisions on which criteria are the most relevant for Slovenia. The criteria were selected based on the accessibility, relevance, and expected data quality and reliability for calculation.

**Table 1.** Overview of the criteria used in different studies of (potentially) contaminated sites' assessments.

| **Criteria** | **Reference(s)** |
|---|---|
| Population density | D'Aprile et al., 2004; Jiang et al., 2021a; Jiang et al., 2021b; Marzocchini et al., 2018; Secretariat of the Minamata ..., 2019; Sorvari & Seppälä, 2010; Yi et al., 2023; Zabeo et al., 2011 |
| Land use (current and/or future) | D'Aprile et al., 2004; Lamé, 2011; Marzocchini et al., 2018; Pickford, 2001; Sorvari & Seppälä, 2010; Zabeo et al., 2011 |
| Percentage of vulnerable groups | Marzocchini et al., 2018; Yi et al., 2023; Zabeo et al., 2011 |
| Ground water (e.g. number of bearing layers, quality class, usage class, type of groundwater bodies, protection typology, extension etc.) | Bica, 2020; D'Aprile et al., 2004; Lamé, 2011; Marzocchini et al., 2018; Mishra et al., 2016; Pickford, 2001; Secretariat of the Minamata ..., 2019; Zabeo et al., 2011 |
| Surface water (e.g. quality class, flow rate, usage class etc.) | D'Aprile et al., 2004; Jiang et al., 2021b; Lamé, 2011; Marzocchini et al., 2018; Mishra et al., 2016; Pickford, 2001; Secretariat of the Minamata ..., 2019; Zabeo et al., 2011 |
| Geology and soil (e.g. physical properties, type, porosity, stratigraphy, geochemical properties of the rock, contamination transport etc.) | Bica, 2020; D'Aprile et al., 2004; Jiang et al., 2021b; Lamé, 2011; Marzocchini et al., 2018; Mishra et al., 2016; Pickford, 2001 |
| Climate (e.g. wind speed, temperature, precipitation, humidity - all annual, $PM_{2.5}$ etc.) | Jiang et al., 2021b |
| Protection regimes (typology and extension) | D'Aprile et al., 2004; Pickford, 2001; Secretariat of the Minamata ..., 2019; Sorvari & Seppälä, 2010; Yi et al., 2023; Zabeo et al., 2011 |

| | |
|---|---|
| Status of vegetative cover | Marzocchini et al., 2018 |
| Position and history of the contamination source | Bica, 2020; Jiang et al., 2021a; Jiang et al., 2021b; Lamé, 2011; Mishra et al., 2016 |
| Presence of contamination (type of pollutants and their quantity) | Bica, 2020; D'Aprile et al., 2004; Jailler, 2016; Jiang et al., 2021a; Lamé, 2011; Marzocchini et al., 2018; Mishra et al., 2016; Secretariat of the Minamata …, 2019; Sorvari & Seppälä, 2010; Yi et al., 2023 |
| Other (e.g. remediation costs, ownership, accessibility of the site, land price, image aspects etc.) | D'Aprile et al., 2004; Jiang et al., 2021a; Jiang et al., 2021b; Lamé, 2011; Marzocchini et al., 2018; Pickford, 2001; Sorvari & Seppälä, 2010; Yi et al., 2023 |

Based on a literature review, a variety of methods and approaches that have previously been used, were identified to develop the priority treatment of PCSs. Most of them use the risk-based or the multi-criteria approach that integrate contamination characteristics, exposure potential, vulnerability, and socio-economic factors. Risk- and health-based approaches commonly use human health risk assessment (HHRA), enabling ranking based on risk magnitude, sometimes supported by spatial risk mapping that combines GIS and HHRA to identify areas where remediation yields the highest risk reduction per cost. Groundwater-specific frameworks frequently assess aquifer vulnerability alongside source hazard, while fuzzy rule-based systems have been designed to manage uncertain or imprecise input data on contaminant fate, transport, and exposure, producing continuous priority scores (Carlon et al., 2008; Leal Pacheco et al., 2025; Li et al., 2021; Polat et al., 2014; Wu et al., 2022). Multi-Criteria Decision Analysis (MCDA) methods are widely used to aggregate risk, cost, technical feasibility, ecological effects, and social considerations into structured ranking outputs (Cinelli et al., 2021; Sorvari & Seppälä, 2010; Wu et al., 2022). National and regional screening tools often follow similar principles by scoring sources, pathways, receptors, land use, and population characteristics to generate priority lists for further investigation (e.g., Li et al., 2017; Li et al., 2021). However, despite the wide range of existing tools, a significant research gap remains, as current prioritization frameworks are rarely harmonized, differ considerably in data requirements and transparency, and lack systematic validation across diverse environmental and socio-economic contexts, leaving no universally accepted method for ranking potentially contaminated sites.

## 3. Study area

Slovenia is a small and young post-socialist country of about 20,000 km$^2$ (Krevs et al., 2023). It gained its independence after seceding from the Socialist Federal Republic of Yugoslavia in 1991. Thirteen years later, the country joined the European Union, which included adopting its legal order on environmental protection. Its geographic position at the intersection of four major European macro-regions: the Alps, the Mediterranean, the Dinaric Mountains, and the Pannonian Plain has bestowed upon Slovenia great physical and human geographical diversity. This diversity also contributes to varying degree of environmental sensitivity (Špes et al., 2002), while supporting exceptionally high levels of biodiversity and geodiversity. As a result a substantial share of the country (13%) is designated as a natural protected area and an even greater share is covered by Natura 2000 sites (37%) (Institute of the Republic of Slovenia for Nature Conservation, 2024).

The country has a population of about 2 million with an average population density of about 100 people/km$^2$. About half the population lives in cities, only the capital of Ljubljana has about 288,000 inhabitants (Statistical Office of the Republic of Slovenia, 2024). Industrial development was most present along the railway corridor and on the outskirts of towns, while the regional development was designed based on the concept of polycentrism (Act No. 72/23; Drozg, 2005). After Slovenia's independence, the loss of the Yugoslav market, the transition to a market economy, and an uncompetitive industry caused many plants to fail, leaving behind brownfields and old environmental burdens as remnants of past activities (Cotič & Ažman Momirski, 2020; Lorenčič & Prinčič, 2018).

Urbanized areas are predominantly concentrated in lowlands, particularly on water-permeable fluvioglacial gravel and sand deposits along major rivers such as the Sava, Drava, Savinja, and Mura. These deposits form important aquifers with substantial groundwater reserves, which serve as key regional drinking-water sources and are highly susceptible

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to pollution. On the other hand, almost half of the country's territory is made up of sparsely settled and less economically developed karst areas (Gostinčar & Stepišnik, 2023) where the shallow soil and vertical drainage into the underground have only modest neutralization and regenerative capabilities, making these areas even more susceptible to pollution. Soils in Slovenia are quite specific due to numerous natural and pedogenetic factors, resulting in abundant diversity and variety (over 600 types and subtypes have been categorized) (Ministry of Agriculture, Forestry and Food & CPVO, 2001); their physical and chemical characteristics are quite favorable compared to other European soils (Vrščaj et al., 2017).

Slovenian soils are young and at early development stages, so the main limiting factor of its agricultural use is the shallow depth of the soils and rocky terrain in many areas. Due to this shallow depth, the soil's regenerative capabilities are moderate, and the frequency and presence of primary carbonates increases the buffering capacities for acidic compounds (Repe, 2010). Due to the diverse terrain and limited flat areas, the country has only 25% of utilized agricultural areas, a majority of which are permanent grassland (56%) and 38% arable land (Ministry of Agriculture, Forestry and Food, 2024). Larger areas of arable land are located predominantly in the bottoms of basins and valleys, where soils suitable for agriculture have developed on the alluvial deposits of major rivers. Despite the large proportion of karst surface, which is characterized by the absence of a river network, the rest of the country has a relatively dense river network of about 1.3 km/km$^2$, owing to the high precipitation (Kolbezen & Pristov, 1998). The headwater character of the majority of Slovenia means that many watercourses are small and have low discharge, making them particularly vulnerable to pollution, especially during extended drought periods.. Approximately 12% of the country lies within flood-prone areas (Komac et al., 2008), including potentially contaminated sites, partly as a consequence of inappropriate spatial planning decisions.

## 4. Materials and Methods

The Potential Contaminated Sites Inventory was compiled in 2021,comprising 532 units, and expanded a year later to a totaling of 671 units. The primary source for establishing a PCSs inventory for Slovenia was the Functionally Derelict Areas (FDA) Database (Department of Geography, Faculty of Arts, University of Ljubljana, 2020). This is a national database of the Ministry of Natural Resources and Spatial Planning, which contains underutilized or abandoned areas with visible effects of previous use and a decreased usability (Lampič et al., 2017; Rebernik et al., 2023). The FDAs spatial layer was originally created in 2017 and is updated every three years at the national level (Rebernik et al., 2023). FDAs must not be equated with PCSs, although many abandoned sites could be included in the PCS inventory due to their previous activities and old environmental burdens (Frantál et al., 2013), as their impact on soil and/or water pollution can be assumed. In identifying the PCSs, we focused on those FDAs that used to have (and in some instances continue to have) activities that cause soil and water pollution:

1. industrial and commercial activities – e.g., industrial and commercial services, mining;
2. military activities;
3. warehousing – e.g., storage of petroleum, chemicals, manure;
4. agricultural areas;
5. treatment plants.

Based on the past use and field inspections 411 areas from the database were defined as PCSs, which constitutes over a third of all FDAs in Slovenia (Lampič et al., 2020). The inventory was then amended based on existing databases, including the Database of Closed Industrial Landfills, the Database of Closed Municipal Landfills, the SEVESO Site Registry (includes sites posing smaller or larger environmental risks due to activities relating to the manufacturing, use, and storing of hazardous substances), the IED Operator Registry (includes data on subjects with Environmental permit pursuant to the Regulation on the Types of Activities and Devices Causing Industrial Emissions), and additional individual critical locations documented by the Ministry of the Environment, Climate and Energy (Lampič et al., 2020; Lampič et al., 2021; Lampič et al., 2022b). The PCSs spatial data layer currently has 671 sites and is a tool for gathering, editing, amending, and analyzing the data. The data set for PCSs monitoring includes over 60 attributes. Each area was bordered and drawn as a polygon (using the ArcGIS Pro software) based on the real estate cadaster, as a precise plan enables us access to other parcel-related data (e.g., ownership) (Lampič et al., 2020; Lampič et al., 2021; Lampič et al., 2022b). PCSs are also a spatial problem, so spatial analysis is an even more important element for priority treatment and the foundation of PCS management (Pizzol et al., 2011).

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The design of the inventory followed the guidelines of the European Environment Agency and its PCS-related indicator (van Liedekerke et al., 2014; European Environment Agency, 2022). The key element was to define the activities that have the potential to pollute the environment, as this allows for the identification of truly contaminated areas within the most environmentally sensitive locations. While at the same time they pose the greatest threat to human health (e.g. Rai et al., 2025).

The need for priority treatment of an individual PCS was than assessed using a multi-criteria decision-making model based on the environmental sensitivity and the threat posed to the health of the local population in the event of contamination (Figure 1).

Environmental sensitivity and the risk to the local population in the event of a contamination depend on a number of factors on the PCS impact area, such as soil and bedrock characteristics, the proximity to sources of water and population, land use, etc. (e.g., Ali et al., 2023; Barthrellos et al., 2024; Jiang et al., 2021a; Jiang et al., 2021b; Sorvari & Seppälä, 2010; 2010; Stoyanova et al., 2019; Tcherkezova et al., 2019; Tchorbadjieff et al., 2019; Yi et al., 2023; Zabeo et al., 2011). To determine which PCSs require priority treatment, nine indicators were used to assess the need for priority treatment:

- the population in the wider area of the PCS (STAT.si portal STAGE, 2019);
- % of agricultural areas in the wider area of the PCS (Ministry of Agriculture, Forestry and Food, 2021);
- the possibility of pollutants entering the food chain within the area of the PCS (Ministry of Agriculture, Forestry and Food, 2019);
- the possibility of pollutants entering the groundwater within the area of the PCS (Ministry of Agriculture, Forestry and Food, 2019);
- rock permeability within the area of the PCS (Geological Survey of Slovenia, 1967–1998; 2008);
- proximity of the PCS to surface waters (Slovenian Water Agency, 2022a; 2022b);
- flood risk in the (wider) area of the PCS (Slovenian Water Agency, 2020, 2022c);
- water protection areas in the (wider) area of the PCS (Slovenian Water Agency, 2021a; 2021b);
- nature protection regime in the (wider) area of the PCS (Slovenian Environment Agency, 2021a; 2021b).

In selecting the indicators, we drew on insights from previous studies (e.g., Bica, 2020; Lamé, 2011; Pickford, 2001; Yi et al., 2023; Zabeo et al., 2011); however, the final selection was a compromise, as it was also constrained by the availability of spatial data layers at the national level. The selection of individual indicators has been further refined to account for the availability of primary data published at regular intervals. In this context, we consider indicators that meet the following criteria: statistical quantifiability, scientific validity, and reliability. Thus, we employed a broad range of spatial layers that differ in scale, quality, and reliability, as well derived datasets generated from them. Consequently, it was necessary to harmonize all datasets appropriately prior to use (e.g., georeferencing, rescaling, etc.).

Since PCSs pose a potential threat to the health of the local population we determined how many people live in their proximity. The larger the population in a PCS area of influence (1 km radius), the greater the risk posed to human health. The share of agricultural areas in the wider PCS area also indicates the potential risk posed to human health. Hazardous substances can enter the food chain through farming products growing on contaminated soil. A greater share of agricultural areas therefore constitutes a higher chance for their transmission. Pollutants enter the food chain and the groundwater by being accessible to organisms and by entering through the soil. Both mechanisms are contingent upon specific mechanical and chemical characteristics that are typical for different soil types, so their assessment took this into account. Rock and sediment permeability determines their ability to transfer water, which affects the speed of rainwater and flood water and with it any potential contaminants percolating as they are washed from the soils or carried along towards the groundwater. Aquifers composed of more permeable rock and sediments are therefore more at risk for groundwater contamination. The proximity of the PCS to water and their location in flood areas and water protection areas is relevant because different water bodies are interconnected (rivers, lakes, groundwater, losing streams, marshes …), which poses a direct threat to watercourses, groundwater, and drinking water. The proximity of surface waters is considered in the model mainly because of the risk of water bodies becoming contaminated in the event of spills of hazardous substances, pollutant leeching, runoff from firefighting, etc. The presence of PCSs on flood areas is especially troublesome because this can lead to the contamination of river water, sediments, and groundwater in the event of floods. Flood waters can transport hazardous substances downstream, threatening the quality of the river water, sediments, where the contaminants may concentrate and linger for longer periods of time, as well as the

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groundwater (Foulds et al., 2014). The contaminated water containing fine sediments may spill onto lower-lying floodplains, contaminating the soil and percolating into aquifers, potentially threatening drinking water sources (Andrade et al., 2018). The presence of PCSs in a water protection area or in its immediate vicinity constitutes a threat to drinking water quality and can affect human health. If a PCS is situated within or in the immediate vicinity of a protected area, it may pose a potentially larger threat to the species or natural environments designated for protection and conservation. Two types of nature protection regimes were considered: protected areas and Natura 2000 sites.

The selected indicators were categorized into five classes (the 1st class indicates the lowest priority, and the 5th class the highest priority for PCS treatment) and then grouped into four sets of criteria that represent population, soil, water, and the nature protection aspect (Table 2). The definition of threshold values for assigning individual indicators to specific classes was based on expert judgement, as no sufficiently detailed sources or literature were available to guide a data driven classification. To enhance the objectivity and robustness of the process, we engaged experts from multiple disciplines (including agronomy, geography, soil science, hydrology, ecology, environmental protection, spatial planning, and medicine) thus ensuring that the classification reflects a broad spectrum of professional perspectives relevant to environmental and human health considerations. In addition, the classification framework was adapted to the environmental specificities of Slovenia. For this purpose, we relied on the key national reference study on environmental vulnerability (Špes et al., 2002), which provided the conceptual and empirical basis for incorporating regional characteristics into the evaluation procedure. This ensured that the thresholds and indicator classes appropriately reflect the spatial heterogeneity and ecological sensitivity of the Slovenian environment.

**Table 2.** Criteria, indicators with classes, and criteria weights.

| Criterion | Indicator | Class | Weight |
|---|---|---|---|
| **Population** | Population in a 1 km radius from the PCS perimeter | 1: up to 100 people<br>2: between 101 and 500 people<br>3: between 501 and 1000 people<br>4: between 1001 and 5000 people<br>5: over 5000 people | **0.15** |
| | % of agricultural areas in a 1 km radius from the PCS perimeter | 1: up to 10.00% of agricultural areas<br>2: between 10.01% and 25.00% of agricultural areas<br>3: between 25.01% and 50.00% of agricultural areas<br>4: between 50.01% and 75.00% of agricultural areas<br>5: over 75.00% of agricultural areas | |
| **Soil** | Risk of pollutants entering the food chain in the area of the PCS | 1: negligible<br>2: low<br>3: moderate<br>4: high<br>5: very high | **0.31** |
| | Risk of pollutants entering the groundwater in the area of the PCS | 1: negligible<br>2: low<br>3: moderate<br>4: high<br>5: very high | |
| | Rock permeability in the area of the PCS | 1: very poor permeability<br>2: poor permeability<br>3: moderate permeability<br>4: good permeability<br>5: very good permeability | |
| **Water** | Proximity of the PCS to surface waters | 1: more than 1000 m<br>2: 501 m to 1000 m<br>3: 51 m to 500 m<br>4: 1 m to 50 m | **0.44** |

| | | | |
|---|---|---|---|
| | | 5: 0 m | |
| | Flood risk in the area of the PCS or proximity of flood areas in a radius of 1 km from the PCS perimeter | 1: PCS over 1 km from the flood area<br>2: PCS under 1 km from the flood area<br>3: PCS in an area of very rare floods<br>4: PCS in an area of rare floods<br>5: PCS in an area of frequent floods | |
| | PCS presence in different water protection areas or the presence of water protection areas in a radius of 1 km from the PCS perimeter | 1: PCS over 1 km from the water protection area<br>2: PCS under 1 km from the water protection area<br>3: PCS in a wider water protection area<br>4: PCS in a narrow water protection area<br>5: PCS in the narrowest water protection area | |
| **Nature protection** | PCS presence in protected areas and/or Natura 2000 sites or the presence of protected areas and/or Natura 2000 sites in a radius of 1 km from the PCS perimeter | 1: PCS over 1 km from Natura 2000 or protected areas<br>2: PCS under 1 km from Natura 2000 or protected areas<br>3: PCS under 1 km from Natura 2000 and protected areas<br>4: PCS in Natura 2000 or protected area<br>5: PCS in Natura 2000 and protected area | **0.10** |

The criteria were then weighted to reflect their relative importance regarding environmental sensitivity and health risk posed to population in the event of contamination. We applied the Analytical Hierarchy Process (AHP) method (Saaty, 1977), comparing each criterion with the others based on its perceived importance, which enables the calculation of corresponding weights. A panel of eight experts from the fields of soil science, agronomy, hydrology, geography, spatial planning, and ecology assessed the importance of each criterion using on a 9-point scale, with each judgement translated into a numerical preference score (Coyle, 2004). The AHP method is well established and has been widely used in comparable studies (e.g., Nardo et al., 2005; 2008; Slabe Erker et al., 2016; Vecchione, 2010). Indicators within each criterion were not weighted prior to aggregation, as we assumed their individual influence to be equal.

Using the Weighted Linear Combination (WLC) method (Eastman, 2006), the individual indicators were first aggregated within the criteria (except the nature protection criterion, which has only one indicator):

$$S=\sum y_i$$

where:
S = sum
$y_i$ = i-th indicator value

then, the criteria were merged according to the same principle:

$$S=\sum w_i x_i$$

where:
S = sum
$w_i$ = i-th criterion weight
$x_i$ = i-th criterion value

By applying the multi-criteria decision-making model (MCDM) (Figure 1) the total environmental sensitivity and risk to human health in the event of a contamination was calculated for each PCS, ranging from 1.75 to 4.44, wherein the lower values designated a lower and the higher values a higher environmental sensitivity and potential threat to human health in the event of a contamination. The obtained values were subsequently linearly rescaled to the interval between 0 and 5 and were then arbitrarily partitioned into five classes, according to the need for the priority treatment of PCSs. Values with a linearly rescaled magnitude below 0.75 were assigned to Class 1. Class 2 comprised values ranging from 0.75 to 1.74, whereas Class 3 included those between 1.75 and 2.4. Values between 2.5 and 3.4 were categorized into Class 4, while all values exceeding 3.5 were assigned to Class 5.

The ArcGIS Pro 3.1.0 software tool was used for the (final) spatial modelling and to visualize the spatial distribution of the results and the spatial density of PCSs. The spatial distribution was analyzed based on their density of occurrence,

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wherein the influence of each PCS was additionally weighted with a class determining its need for priority treatment. The PCSs that were classified in the highest 5th class had 5 times the influence than the PCSs in the lowest 1st class in the density calculation. The density was calculated for 500 m greed cells using a 5 km search radius, enabling the identification of clusters and spatial patterns of PCSs with respect to their weighted influence.

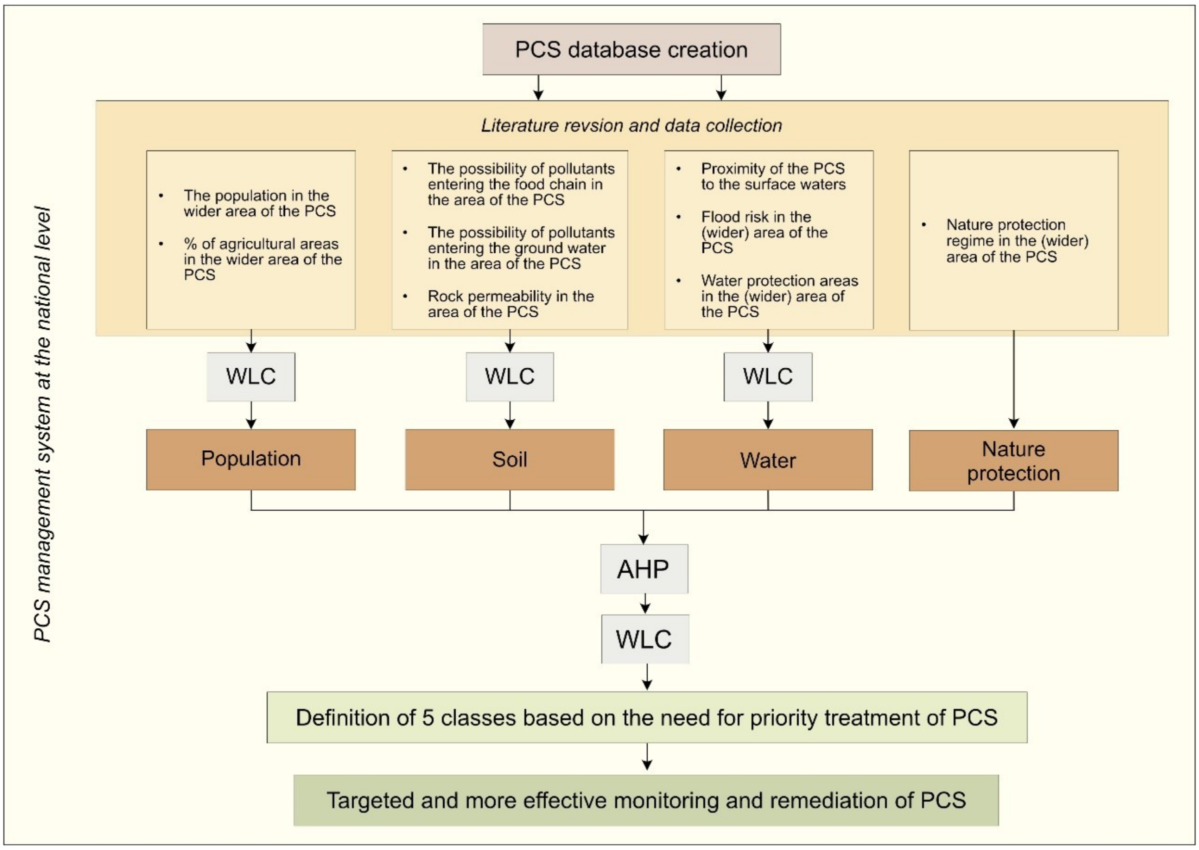


**Figure 1.** Research diagram of the methodological framework.

## 5. Results

### *5.1. PCSs characteristics according to applied indicators*

For a better presentation of the utilized data, the first section of the results presents PCSs characteristics according to the values of each indicator used to evaluate environmental sensitivity and risk to human health in the event of a contamination (Figure 2). The descriptions of each class are presented in detail in Table 2.

Based on population size in a 1 km radius of a PCS, the 4th class was the most common (1001 to 5000 people) with 35%. PCSs most commonly (45%) had between 25.01% and 50.00% of agricultural areas (3rd class) in the wider area.

The soils in PCS areas provide mostly low (2nd class, 50%) or negligible (1st class, 24%) accessibility of the pollutants to organisms. In contrast, the risk of potentially hazardous substances entering the groundwater through the soil is very high (5th class, 35%) and high (4th class, 17%) on over a half of PCSs. These are mostly shallow and skeletal eutric or dystric brown soils on gravels and sands as well as undeveloped and developed sandy alluvial soils. Over 2/3 (66%) of the PCSs are located on areas of highly permeable rocks (5th class), as many are present in areas of permeable gravel-sand deposits or highly karstified carbonate rocks (mostly limestones and partially dolomites).

The largest share of PCSs (69%) is less than 50 m away from the nearest water body (4th and 5th class), while only 14% are over 500 m away from the nearest water body (1st and 2nd class). Particularly concerning is the fact that 43% of PCSs lie directly adjacent to, or are traversed by, a watercourse (5th class). This spatial pattern reflects the past industrial development when industrial facilities were traditionally located near water sources to meet various water demands. According to flood hazard maps, over a third of PCSs (37%) are located on flood areas. Most of those (14% of all PCS) are located in areas of frequent floods (5th class) and the least (10% of all PCS) in areas of very rare floods (3rd

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class). Nearly one quarter of the PCSs (24%) at least partially lie in water protection areas (3rd, 4th, and 5th class). A significant share of these (15% of all PCSs) are located in a wider water protection area (3rd class), where restrictions on activities that affect the physical environment are least stringent. On the other hand, 2% of the PCSs are present in the strictest water protection area (5th class).

It turned out that over ¾ of PCSs (82%) are located outside protected areas (1st, 2nd, and 3rd class), although over half of them (55%) are located within one kilometer away, highlighting their potential indirect environmental impact.

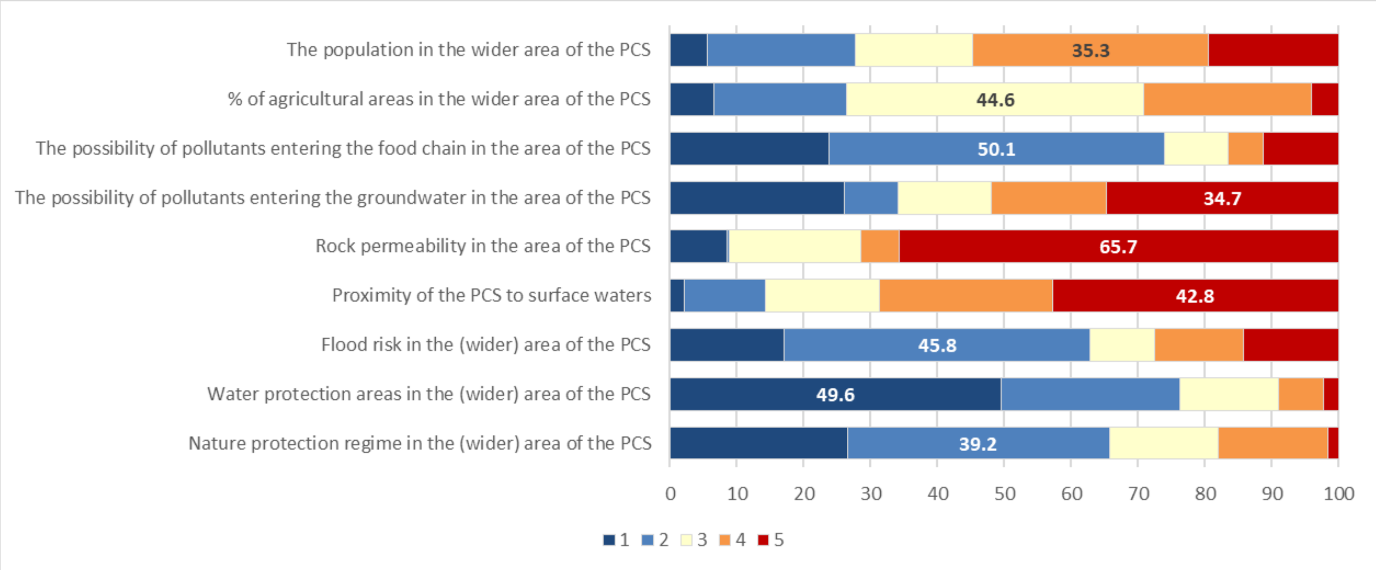


**Figure 2.** Indicators according to the proportion of each class represented, with values attributed to the dominant class.

### *5.2. PCS classification and their spatial distribution*

The second section of the results presents the PCSs characteristics per calculated level of environmental sensitivity and potential threat to human health in the event of a contamination (Figure 3) as well as their spatial distribution. Following the AHP process (Saaty, 1977) the calculated weights (Table 2) illustrate that environmental sensitivity and risk to human health in the event of a contamination are most affected by criteria relating to water (0.44) and soil (0.31). The remaining quarter of the influence is composed of the criteria relating to population (0.15) and nature protection (0.10). The consistency of the calculated weights was confirmed with the consistency ratio (CR < 0.1).

35 PCSs (5 %) were classified in the 5th class with the highest level of environmental sensitivity and threat to human health in the event of a contamination and corresponding priority treatment. These mostly have a combination of a proximity to surface waters and the presence of a PCS in a water protection area or a floodplain on one hand and/or a great mobility of contaminants in the soil profile, their accessibility to plants or a high permeability of the bedrock. A total of 196 PCSs were grouped into 4th class, the "highly needed priority treatment" category. The 3rd class has the most PCSs (248) with a moderate need for priority treatment (Figure 3 and Table 3).

**Table 3.** Number and share of PCSs per individual class of priority treatment.

| PCS priority treatment class | Number of PCS | Share of PCS |
|---|---|---|
| No priority treatment required (1) | 19 | 3 |
| Less needed priority treatment (2) | 173 | 26 |
| Moderately needed priority treatment (3) | 248 | 37 |
| Highly needed priority treatment (4) | 196 | 29 |
| Urgent priority treatment (5) | 35 | 5 |
| **Total** | **671** | **100** |

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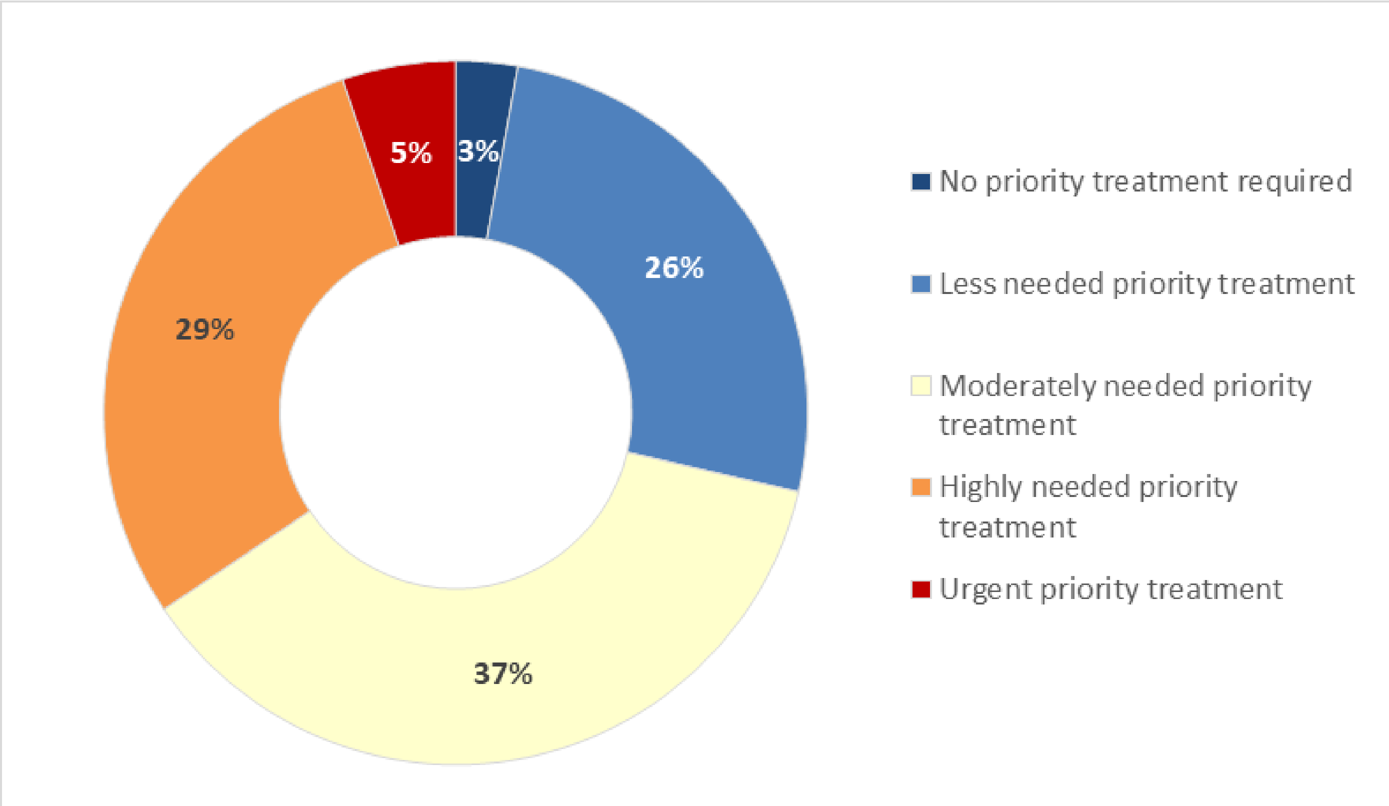


**Figure 3.** PCSs per need for priority treatment based on the assessment of environmental sensitivity and threat to human health in the event of a contamination.

The spatial distribution of PCSs (Figure 4) is a reflection of various physical and human geographic factors and policies that have affected the more or less successful economic and spatial development of Slovenia to date, of which PCSs are a by-product.

The density depicts the synergistic effect of PCSs being concentrated in certain areas and their potentially negative impact on the environment and human health as hotspots (Figure 4). In general, these hotspots are grouped across the wider area of larger towns (Ljubljana, Maribor, Celje, Trbovlje, etc.), in lowlands, plains, along major rivers, along main road and railway connections, and transport nodes. The most effective decrease of the potentially negative effects that PCSs have on the environment and human health could be achieved by placing priority treatment on the PCSs in the worst, 5th class, that are also located in said hotspots. This kind of increased PCSs density constitutes an even greater possibility for contamination and threat to human health due to the potential multiplication effects.

## 6. Discussion

The first Slovenian inventory of 671 PCSs is a solid starting point for further work, but it is far from comprehensive. It needs to be upgraded with other potential sources that have not been included in the PCSs database due to a lack of suitable data and information, data reliability level, etc., but should be verified and included in the future, such as:

- Closed and abandoned underground and surface mines and mining waste sites in Slovenia (Gosar et al., 2020);
- Polluted karst caves (Tičar, 2021);
- Exploitation sites (with or without valid concession (Geological Survey of Slovenia, 2023));
- Register of illegal waste dumps (Ecologists without borders, 2022), and
- Data on interventions involving hazardous substances from the Administration for Civil Protection and Disaster Relief.

The PCS inventory data will most likely need to be updated in the future. Currently, over 60 attributes are monitored for each site, describing its characteristics, contamination, measures, etc., although the actual data remains sparse and often underdefined. Many more sites will be included once further research and analysis is concluded providing answers to whether a site is actually contaminated or not. The data will be coalesced with the databases from the

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Slovenian Environment Agency, which has been monitoring pollution at the state level using soil monitoring, tracking ground water and surface water quality, etc. Linking these spatial data layers could expand the existing database and offer more insight into the actual state of PCSs. Any further database development will have to include monitoring the conditions on the PCSs themselves, which will require a collaboration of different agents and experts following an inter-sectoral and transdisciplinary approach (e.g., spatial planners, pedologists, hydrologists, etc.), so that this data is included in the spatial planning systems at all levels.

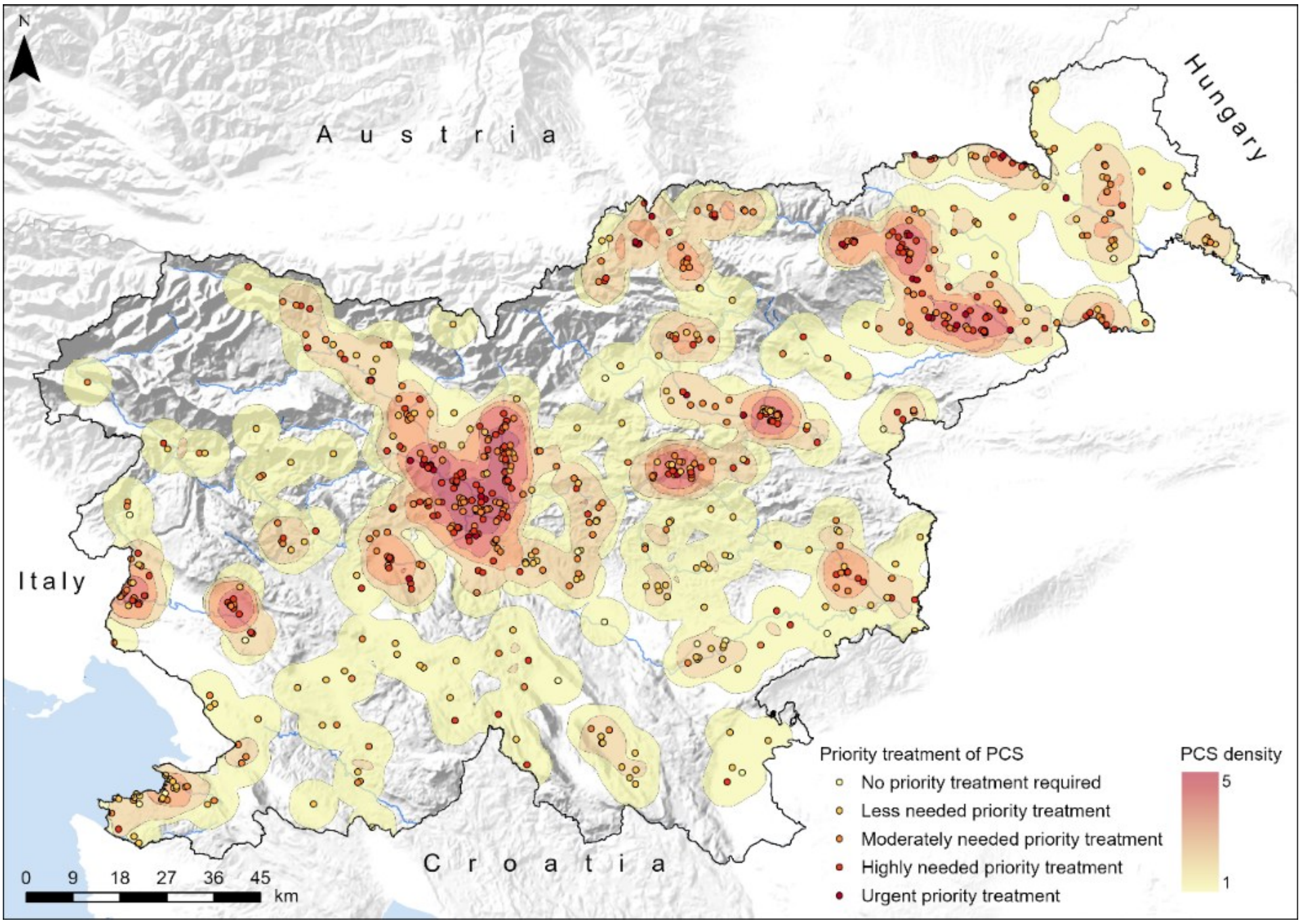


**Figure 4.** PCSs density hotspots based on their potentially negative impact on the environment and human health.

The presented results of the study reveal a complex interplay between natural environmental characteristics, historical industrial development, and contemporary spatial patterns that shape the environmental sensitivity of potential contaminated sites (PCSs) in Slovenia. The analysis of individual indicators demonstrates that water related and soil related criteria exert the strongest influence on the overall environmental sensitivity and potential risk to human health, as confirmed by their high AHP derived weights. The dominance of these criteria aligns with findings from similar assessments, where hydrological conditions and soil permeability frequently determine the extent and mobility of contaminants (D'Aprile et al., 2004; Marzocchini et al., 2018; Mishra et al., 2016).

The high share of PCSs located on shallow, skeletal soils, permeable gravel-sand deposits and carbonate rocks indicates an inherent vulnerability of these areas. More than half of all PCSs fall within classes associated with high or very high risk of contaminant migration into groundwater. Rapid infiltration and limited soil retention capacity of such terrains facilitate the downward movement of pollutants eventually entering groundwater (Bica, 2020; Zabeo et al., 2011). The sensitivity of water environments is further amplified by the proximity of many PCSs to surface waters. Almost 70% of evaluated sites lie within 50 m of water bodies of which 43% are located directly adjacent to or intersected by a watercourse. This spatial pattern reflects historic industrial practices in which facilities were sited near rivers to secure water for technological processes, cooling, waste disposal etc. While such spatial arrangements were once seemingly advantageous, they now represent a major environmental burden, as accidental or historical contamination can readily enter hydrological systems and cause downstream impacts. The presence of nearly one quarter of PCSs within designated water protection areas further underscores the systemic vulnerability of certain regions. Although most are located within wider protection zones where restrictions are less stringent, even a small number of sites within the strictest zones present disproportionate risks to water resources. These findings highlight tensions between historical land use patterns and modern water protection policies and will have to be addressed in the future. The classification of PCSs showed that 34% fall into categories requiring high or urgent priority treatment. However, this proportion cannot be reliably compared with national assessments in other European countries, as methodologies, classification criteria, and monitoring practices differ substantially (D'Aprile et al., 2004; Jiang et al., 2021a; Zabeo et al., 2011).

The spatial distribution of PCSs mirrors long standing socio-economic and infrastructural development patterns in Slovenia. High density clusters (hotspots) are concentrated around major urban centers, transportation corridors, and river valleys, representing the areas historically associated with industrial production, logistical activities, agricultural activities etc. The clustering of PCSs is particularly important because it increases the probability of combined or synergistic impacts, thus intensifying environmental pressures and amplifying health risks for nearby populations.

The most effective mitigation strategy would involve targeted interventions in areas where high environmental sensitivity coincides with high spatial density of PCSs. Prioritizing remediation or risk reduction measures in these hotspots would maximize environmental and public health benefits while ensuring an efficient allocation of financial and institutional resources. The identified patterns also underscore the importance of integrating environmental sensitivity assessments into future spatial planning, followed by the reduction of long-term legacy of contamination and prevention of new risks from emerging.

The robustness of the model is ensured by its use of a large and diverse dataset that draws both on the geographical specificities of the analyzed area and on insights from previous research and established good practices (e.g., Bica, 2020; Lamé, 2011; Pickford, 2001; Yi et al., 2023; Zabeo et al., 2011, etc.). The model exceeds a simple one-dimensional analysis and is designed to be replicable and adjustable to be applied to other areas (countries/regions). It can also be adapted to the needs of individual sectors addressing specific issues (e.g., water, soil, human health, etc.). If new, high-quality, reliable data is acquired, it can be included to improve the results, helping decision-makers with the area management and strategic spatial planning and use.

In assessing environmental sensitivity and risks to human health in the event of contamination, we relied on a set of various spatial data layers. With certain adjustments, their usefulness proved to be adequate. But the study is not without limitations. The utilization of data of varying quality for the model was inevitable, which may, to a certain extent, diminish the reliability of the results. The data layer used for evaluating bedrock permeability was only available at a scale of 1:250,000, preventing us from making a detailed permeability estimate for each individual PCS. It forced us to conduct additional examinations for many of the locations by complementing data with information from the basic geological map at a scale of 1:100,000, as well as with field verification. The flood maps are also incomplete, as they do not exist for some areas in Slovenia. In such cases, we had to use older, generalized, and less reliable flood maps that do not necessarily reflect the actual situation to estimate the flood risk at the PCS. For the analysis of contaminants possibly leeching into the groundwater or entering the food chain, the absence of data on anthropogenously induced soil changes on PCSs meant our only option was to rely on an expert assessment according to the presumed natural soil type. Due to personal data protection regulations, population data were provided only at a one-hectare resolution. Recently the Geological Survey of Slovenia has produced and released a national landslide susceptibility map, which should certainly be considered in any future assessments of environmental sensitivity and potential threats to human health posed by PCS sites.

The modelling results indicate that every third PCS in Slovenia lies in a flood area. This number is most likely even higher in reality, as was seen during the last major flooding that hit Slovenia in August 2023 (Bureau of Meteorology, Hydrology and Oceanography, 2023a), when flooding affected many areas (Figure 5) that are not even included on existing flood maps. In light of the current trends and future projections (Vertačnik & Bertalanič, 2017), Slovenia can expect an increase in the frequency, scope, and intensity of extreme weather events and flooding (Bureau of Meteorology, Hydrology and Oceanography, 2023b; Trobec, 2017), which is precisely why future PCSs management must pay even more attention to PCSs in flood areas. Finally, spatial planning is a crucial factor for successful flood risk management and potentially contaminated site management falls under its scope.

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**Figure 5.** Example of a flooded PCS in Mislinja in the August 2023 floods in Slovenia (photo: Archive of the Department of Geography, Faculty of Arts, University of Ljubljana).

## 7. Conclusions

The existing data and spatial layer highlight an urgent need for a systematic approach addressing potential soil and water contamination in Slovenia. The data enables the relevant authorities to make more targeted and evidence-based decisions when selecting areas for further investigations, taking into account both the primary sources of contamination and the degree of site abandonment. Through intensive work conducted over a three-year period (2020-2022), we were able to make the PCSs inventory official and (to a limited extent) publicly accessible through the Environmental Atlas of Slovenia portal of the Slovenian Environment Agency. The PCSs inventory supports a system for the identification of (actual) contaminated sites, and the monitoring of activities carried out on them - something that does not currently exist in Slovenia. The system also includes executing remediations, measures etc. and ensures a comprehensive PCSs management system as set out by the European Environment Agency (2021).

In accordance with the Directive (EU) 2025/2360 (Soil Monitoring Law), our research and its outcomes directly contribute to addressing the issue of contaminated sites through a risk-based and stepwise approach. This framework requires that Member States ensure that the risks to human health and the environment posed by potentially contaminated and contaminated sites are identified, managed, and maintained at acceptable levels, taking into account the environmental, social, and economic impacts of soil contamination. Moreover, the directive stipulates Member States to systematically identify potentially contaminated sites within their territory and ensure appropriate investigations are carried out.

Effective management of potentially contaminated sites is essential for promoting sustainable land use, reducing environmental risks, and coordinating with policies and strategies at the national and European level (e.g., circular land use management, no net land take, etc.). The study emphasizes the importance of using reliable data and methods, and especially the transdisciplinary work across scientific fields (soil geography, hydrogeography, spatial planning, environmental protection, etc.) with actual inventory users (Ministry of the Environment, Climate and Energy, Waste Management Division). Our approach combines expert knowledge with the user experience and need to identify priority PCSs to remediate and rehabilitate. Integrating a diverse set of data and criteria into a systematic classification framework enables stakeholders to identify high priority areas where the intervention will have the greatest environmental, social, and economic impact. This not only accelerates the remediation of the contaminated sites but also supports strategic spatial planning and ensures optimal allocation of resources. The methodology contributes to wider sustainability goals to improve soil conditions, reduce the number of degraded areas, and promote effective land use. Any further efforts should be focused on improving and upgrading the criteria, ensuring constant and dynamic data updates, and strengthening stakeholder cooperation to ensure the framework's adaptability and applicability across different regional and sectoral contexts. Appropriate dissemination and education of the relevant users about the inventory and its contents is crucial to ensure that it is considered by potential investors and landowners before launching a new investment, while holding polluters accountable.

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