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RESEARCH PAPER

Municipal Solid Waste Management and Health Risks: Application of Solid Waste Safety Plan in Novi Sad, Serbia

Giovanni Vinti[1,2] · Bojan Batinić[3] · Valerie Bauza[4] · Thomas Clasen[4] · Terry Tudor[5] · Christian Zurbrügg[6] · Mentore Vaccari[2]

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Abstract

Inadequate solid waste management (SWM) can cause environmental contamination and health risks. Minimizing the health risks from SWM practices requires the identification of linkages between potential sources of exposure, environmental transport pathways, and adverse health outcomes. A safety planning approach can represent an innovative tool for reducing such risks. In previous research, we introduced the solid waste safety plan (SWSP) concept, only focusing on the health risk ranking assessment matrix. Here, we demonstrate the application of the SWSP framework in a case study of the municipal landfill of Novi Sad, Serbia. We identify potential hazards and assessed the likelihood and severity for them, using a combination of quantitative and semi-quantitative approaches to estimate risk levels for each identified hazard. Hazards deemed high and very high risks for the community and workers include groundwater contamination from leachate, airborne contaminants from combustion and non-combustion processes, and worker injuries associated with waste combustion. Control measures for each are identified, together with a corresponding cost analysis. Adding a final top cover to the landfill and introducing a collection, transport, and treatment system for the biogas would address hazards presenting high health risks but are also among the highest costs. While we demonstrate the approach and utility of an SWSP in a research context, future work is needed to assess the use of the SWSP by local communities or SWM utilities.

Highlights

- The structure and development of a solid waste safety plan (SWSP) are discussed.
- The SWSP is applicable both in developing and industrialized countries.
- The SWSP was applied to the municipal landfill of Novi Sad, Serbia as a case study.
- Highest risks resulted from worker injuries and groundwater and air contamination.
- Control measures and associated cost estimates were identified.

✉ Giovanni Vinti
giovanni.vinti@unipa.it

✉ Mentore Vaccari
mentore.vaccari@unibs.it

[1] Department of Engineering, University of Palermo, 90128 Palermo, Italy

[2] Research Center for Appropriate Technologies for Environmental Management in Resource-Limited Countries (CeTAmb), University of Brescia, 25123 Brescia, Italy

[3] Department of Environmental Engineering and Occupational Safety and Health, Faculty of Technical Sciences, University of Novi Sad, Trg Dositeja Obradovica 6, 21000 Novi Sad, Serbia

[4] Gangarosa Department of Environmental Health, Rollins School of Public Health, Emory University, Atlanta, GA, USA

[5] The Connected Places Catapult, The Pinnacle, 170 Midsummer Blvd, Milton Keynes MK9 1BP, UK

[6] Department of Sanitation, Water and Solid Waste for Development (Sandec), Eawag, Swiss Federal Institute of Aquatic Science and Technology, Überlandstrasse 133, 8600 Dübendorf, Switzerland

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Introduction

In 2023, 2.1 billion tonnes of municipal solid waste (MSW) was generated, and a further increase is projected in the following years (UNEP 2024). However, inappropriate solid waste management (SWM) can cause environmental contamination and health risks. Furthermore, SWM influences greenhouse gas (GHG) emissions globally; for example, open waste burning produces GHGs, and the decomposition of organic matter in landfills and dumpsites releases methane (Gómez-Sanabria et al. 2022; Trapani et al. 2018). Thus, an adequate SWM, based on the circular economy approach, can have benefits in reducing the need for raw materials, waste generation, health risks and GHG emissions. For example, composting is a biomass valorisation technique (Cosenza et al. 2018) that, compared to landfilling, lowers GHG emissions (Ye et al. 2023). Concurrently, other authors have suggested using waste biomass as biofuels with good potential for reducing GHG emissions (Emmanouilidou et al. 2023). Nevertheless, solid waste is often not adequately managed, especially in low- and middle-income settlings (Villa et al. 2022; Benhamdoun et al. 2023). Over the years, many studies have assessed the possible health risks associated with the SWM practices regarding soil, water, air pollution for exposed populations (WHO 2016; Vinti et al. 2021). Indeed, several contaminants that represent a threat to human health are contained in solid waste or generated from SWM practices such as open burning. Heavy metals, PCBs, dioxins/furans (PCDD/F), and particulate matter are examples of contaminants with potential carcinogenic or toxic effects (Velis and Cook 2021). Additionally, waste disposal on land can lead to long-term contamination of groundwater and surface water resources (Alao et al. 2023).

Minimizing the health risks from SWM practices requires identification of the linkage between potential sources of exposure, possible environmental transport pathways, and possible adverse health outcomes (Agbotui et al. 2022). Typical routes of exposure include direct dermal contact with waste, inhalation of contaminants, and direct or indirect ingestion of contaminants via pollution of water, soil, or plants, and accumulation in the food chain (Hines et al. 2019). Vectors, such as insects, can also spread infectious pathogens. For example, inadequate solid waste accumulation is often assumed as a risk factor for infectious and vector-borne diseases because it may provide breeding and feeding sites for animals and insects (Krystosik et al. 2020). Thus, inappropriate SWM can negatively affect the exposome (Gao 2021).

An approach successfully implemented for assessing the risk posed by potentially contaminated sites consists of the source-pathway-receptor (SPR) model (Cairney et al. 1997). It is also known as human health risk assessment (HHRA) (Zhang et al. 2023), and it is based on the following steps: hazard identification, dose–response assessment, exposure examination, and risk characterization. Based on that, guidelines and standards have been enforced in many countries worldwide, such as the USA, Italy, the UK, Australia, and China (Zhang et al. 2023; Gibellini and Vaccari 2021). However, it is a tool that, when confirming contamination, anticipates site-specific interventions aimed at remediating the area or applying interim measures to prevent the spread of contaminants.

Hazard and operability (HAZOP) is another helpful methodology. It is usually used for examining a processing facility to mitigate and control risks. This methodology's success is rooted in its rigorous adherence to process flow diagrams and piping and instrumentation diagrams. Segmenting the design into manageable sections with defined boundaries, referred to as nodes, ensures a thorough analysis of each piece of equipment within the process (Dunjó et al. 2010). Furthermore, authors (Fattor and Vieira 2019) have implemented a modified HAZOP to contribute to mitigate solid waste-related risks in three waste pickers cooperatives in Brazil. Thus, when it comes to SWM, HAZOP can also be effective in identify weak points of the system and then implement control measures.

Over the years, further approaches have been proposed to evaluate the risk level associated to solid waste. For example, Kumar and Alappat (Kumar and Alappat 2005) have introduced the Leachate Pollution Index (LPI). It is a quantitative tool for reporting uniformly the leachate pollution data of landfills and dumpsites to quantify the leachate contamination potential.

Additionally, the World Health Organization (WHO) has promoted the utilization of a safety planning approach for environmental risks using a hazard analysis and critical control points (HACCP) framework originally developed for food safety (WHO 1997). The WHO safety plan is a ground-breaking approach that in the area of water and sanitation has been implemented over the last two decades through its Water Safety Plan (WSP) (Davison et al. 2005) and Sanitation Safety Planning (SSP) (WHO 2015, 2022). In particular, the WSP approach combines risk assessment and management practices into a drinking-water supply system, guaranteeing water quality from the catchment to the consumer (Pérez-Vidal et al. 2020). Likewise, the SSP is a risk-based approach aimed at supporting operators in assessing and minimising health risks related to sanitation systems (Domini et al. 2017). Notably, the Water Safety Plan was introduced in the European Union through Directive (EU) 2020/2184 on the quality of water intended for human consumption (European Union Council 2020).

However, a safety plan approach has yet to be developed in the field of solid waste. It represents the objective of this research. Indeed, we have recently proposed a safety plan approach for SWM and developed a framework for a SWSP (Vinti 2021; Vinti et al. 2023). Here, we present the entire structure of the SWSP, aiming to foster an open discussion within the scientific community, demonstrating its application using a case study from Novi Sad, Serbia.

Thus, after setting up a team of experts, the first objective consisted of collecting information necessary for describing the case study. This allowed the conceptualization of the health risk matrix specific to the case study. Then, further details needed for the matrix were searched. Based on the information that was collected, the matrix was filled out. The link between health risks and the number of people affected represented the next step. Such activities were fundamental for identifying appropriate control measures to mitigate the risks. Finally, a cost analysis was carried out. Limitations were also discussed.

Materials and Methods

Data Collection

The steps utilised for the development of the SWSP are shown in Fig. 1. More details are available in Supplementary Material (Annex 1). Data were collected for the municipal landfill of Novi Sad between May 2020 and January 2021. The location was selected after a consultation among the authors taking into account the available information about solid waste in the city and the period of the research, which was during the Covid-19 pandemic (UN 2021). In that period, the situation in Serbia was less dangerous than in other countries, and the restrictions on movement were not excessive. Unfortunately, the Covid-19 situation became more complex during the last research period in Serbia. Data were primarily collected through interviews with local stakeholders, observations of the local situation and maps and technical documents shared by local experts. These field data were supplemented by analysis of scientific publications, analysis of technical reports, and news on local events related to solid waste. Data from observations, interviews, scientific literature, and reports were initially used to describe the case study and SWM practices.

Risk Assessment and Hazard Identification

We developed a risk assessment matrix specific to the municipal landfill of Novi Sad, with an approach similar to that used in the WSP and the SSP (see Table S2 (Supplementary Material, Annex 1)). We used the definitions adopted by Davison et al. (2005) in the WSP, where the hazard was defined as any chemical, biological or physical agent having the potential to cause harm, and a hazardous event described as a circumstance that can lead to the presence of a hazard. Finally, the risk was expressed as the likelihood that determined hazards can cause harm of a certain magnitude in exposed populations.

We then employed the parameters used in the SSP (WHO 2015) for the severity, likelihood, and risk level measurement scales as summarized in Table S3 (Supplementary Material, Annex 1). However, considering that exposure pathways and risks related to SWM are different from wastewater

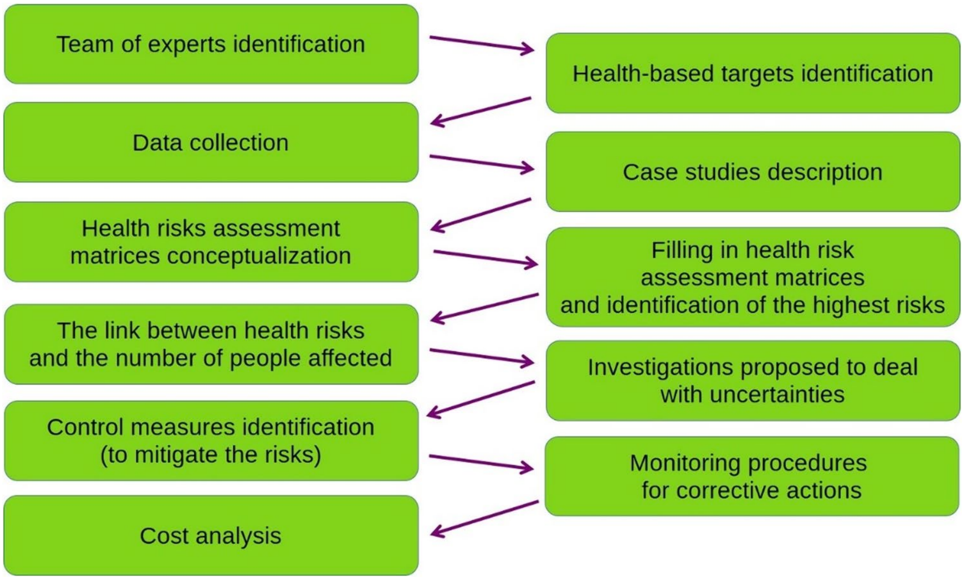


Fig. 1 Steps illustrating the development of the SWSP

and drinking water, as done in Vinti et al. (2023), we adapted the definitions from the SSP to make distinct meanings for the SWM semi-quantitative risk assessment parameters, summarized in Table S4 (Supplementary Material, Annex 1). Using a semi-quantitative health risk assessment approach, the team calculated a priority score for each hazard. The methodology followed in weighing each hazardous event included in the matrix regarding likelihood and severity was based on the search for the information presented in Table S5 (Supplementary Material, Annex 2). For example, in the case of leachate leaking in groundwater, the likelihood was based on the presence of groundwater, hydrogeological characteristics, the absence of a waterproof layer at the bottom of the landfill, etc. The severity was based on leachate characteristics, proximity to inhabited areas, the kind of use of groundwater, etc. The general structure of the risk matrix used for this study is available in Table S2 (Supplementary Material, Annex 1). Only the hazardous events resulting in high and very high risk were focused upon.

Furthermore, although data about physiochemical characteristics in the groundwater in the landfill correspondence were available, the parameters measured were not very useful in conducting a health risk assessment. However, the concentration of three inorganic compounds measured by Djogo et al. (2017) in the groundwater below the Novi Sad municipal landfill was studied. The compounds were considered indicators because they exceeded the Serbian hygienic drinking water standards (Serbian Gazette 2019). The compounds considered were Boron (B), Magnesium (Mg), and Potassium (K). Thus, as discussed in the results section, we studied the flow and the decrease in the concentration of these contaminants up to 600m away from the contamination source (i.e., the landfill of Novi Sad). The objective was to understand if the concentration of the chemicals was above the national legislation limits for drinking water at the point of exposure. The following conditions were considered based on a previous study (Vaccari et al. 2018): Diffusion and dispersion phenomena but not degradation of contaminants; Continuous release of leachate from the landfill toward the groundwater; Homogeneous aquifer properties; and One dimensional groundwater flow. However, since the groundwater parameters from Djogo et al. (2017) were not very useful in conducting a health risk assessment, values from a review on the characteristics of leachate from landfills and dumpsite (Vaccari et al. 2019) was also taken as a reference.

Contaminant Modelling

Furthermore, the absence of a waterproof layer at the bottom of the landfill, the proximity of the water table with the bottom, and the groundwater thickness (i.e. 30–35 m) were considered. Therefore, it was assumed that the aquifer's entire thickness was affected by contamination below the landfill, in line with results from a previous study (Vaccari et al. 2018). Using that study as a reference, the Leaching Factor was first calculated. It represents the ratio between the concentration of contaminants in the landfill bottom and the groundwater. Then, Eq. (1) for the Dilution Attenuation Factor (DAF) was used (APAT 2008):

$$\frac{1}{DAF} = exp\left[\frac{x}{2\alpha_x} \times \left(1 - \sqrt{1 + \frac{4\lambda_i \alpha_i R_i}{v_e}}\right)\right] \times \left[erf\left(\frac{S_w}{4\sqrt{\alpha_y x}}\right)\right] \quad (1)$$

where: DAF: Dilution Attenuation Factor; x: the distance between the source of release and the point of exposure = 600 m; α_x = longitudinal dispersivity (calculated as $\alpha_x = 0.1$ x) (m); α_y = transverse dispersivity (calculated as $\alpha_y = 0.33\ \alpha_x$) (m); λ = first order degradation rate constant (1/d); R_t = time delay coefficient (-); v_e = pore velocity (m/s); S_W = source width perpendicular to groundwater flow direction (m) = 800 m.

Equation (1) takes as a reference the Domenico analytical model (Domenico 1987), where advection, dispersion, diffusion and decaying of a contaminant plume in the groundwater are considered. Precautionarily, it was assumed that the entire thickness of the aquifer is affected by contamination. Consequently, the equation considers dispersion only along the x and y axes. Furthermore, the absence of tests to assess site-specific biodegradation is frequent. In such cases, λ can be conservatively assumed equal to 0 (APAT 2008).

The following equation was used to obtain the concentration of contaminants at the point of exposure:

$$C_x = C_0/DAF$$

where: C_X = concentration of the contaminant at the point of exposure considered; C_0 = initial concentration of the pollutant in the groundwater.

Study Area

The Serbian municipality of Novi Sad was selected as a case study to implement the SWSP. Novi Sad is the second-largest city of Serbia and the capital of the province of Vojvodina, in the northern part of the country. Figure 2 shows satellite images of Serbia, Novi Sad and its municipal landfill. Novi Sad municipality occupies an area of 699 km^2. The total population in the municipality in 2017 was estimated at 404,118 inhabitants (GIZ 2019). At the time of the study, there were no sanitary landfills in the Novi Sad municipality, thus a landfill that does not meet the EU Landfill Directive minimum criteria was selected. It did not have a base protective layer and a system for collecting and treating leachate

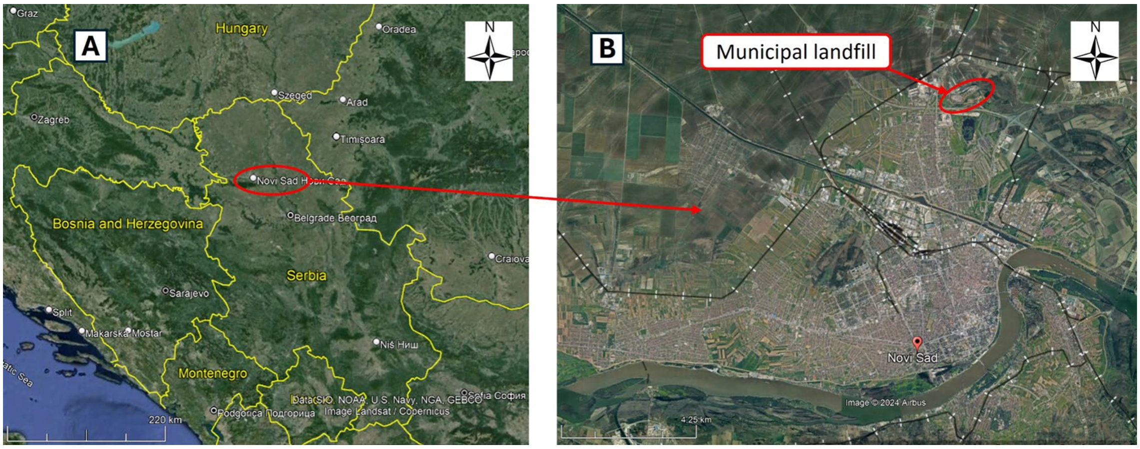


Fig. 2 Satellite images of Serbia (**A**) and Novi Sad (**B**) (from Google Earth Pro). **A** Imagery date: 10 April 2013 (accessed on 20 May 2024). The scale legend is on the bottom left corner of the figure. **B** Imagery date: 17 February 2024 (accessed on 20 May 2024). The scale legend is on the bottom left corner of the figure

Table 1 Waste composition in Novi Sad [from GIZ (2019)]

Waste component	[%]
Food and green	49.5
Paper and cardboard	10.7
Metal	1.1
Plastic	14.2
Glass	3.5
Rubber and leather	> 0.4
Wood	Not Available
Other	20.6

(Vinti 2021; Djogo et al. 2017). At the time of the study, most of the waste collected in Novi Sad was landfilled in the municipal landfill. It was the largest in the region, and is located approximately 6 km north of the city centre.

In addition to the municipal landfill, there were about 19 illegal dumpsites. In Novi Sad, a Public Utility Company (PUC) was in charge of waste management at the time of the study (Vinti 2021). In 2017, the total municipal solid waste (MSW) generation in Novi Sad municipality was 135,700 tons (GIZ 2019). Data on waste composition in Novi Sad municipality are summarised in Table 1.

Compared to most Serbian municipalities, officially, the waste collection rate in the Novi Sad region was very high. In particular, Novi Sad municipality had a coverage of about 100% (GIZ 2019).The landfill is located in the northern part of the city (Fig. 2), about 600 m from the closest houses. However, a supermarket and some factories were close to the landfill, as shown in Fig. 3, where point 1 is the supermarket, and points 2–6 represent other shops and factories (Vinti 2021).

Fig. 3 Satellite image of the landfill of Novi Sad and the closest buildings (from Google Earth Pro). Imagery date: 5 September 2020 (accessed on 20 May 2024). The scale legend is on the bottom left corner of the figure

The distances of the landfill from the highway and the city centre were 180 m and approximately 6 km, respectively. The landfill is constructed in a flat part of the city, on sand pits, and surrounded by agricultural lands. It was estimated that, over the years, more than 2.8 million m^3 of municipal and non-hazardous industrial waste had been landfilled in it (Vinti 2021). There are no accurate data on when the landfill started to operate; however, it was estimated around 1980 (Vinti 2021). It covered about 28 ha, of which 24 ha were used for waste disposal. The average waste depth was between 12 and 14 m, and the average height of waste above the ground level was 5–7 m (Vinti 2021). The site was fully fenced and monitored by security guards.

People living in the unofficial settlement north of the landfill (about 100 houses) complained about bad smells (Vinti 2021). Furthermore, Stojanović (Stojanović 2017) highlighted bad smells in the city having official dwellings close to the landfill, i.e. Klisa suburb; people avoided spending time outdoors in the suburb because they found it difficult to breathe.

Air quality in the municipal landfill, in terms of PAHs and POPs, was analysed based on Petrovic et al. (2018). The authors measured air concentrations of 16 PAHs. The carcinogenic risk was always below the limit value defined by US EPA (Petrovic et al. 2018). However, only the gaseous phase of ambient air was analysed, excluding particulate matter, thus affecting the overall risk calculation.

Gas extraction from the landfill body was only partially performed with 96 passive gas wells. The gas wells were only drilled, and none of them were connected to a gas collection and treatment system. In addition, many wells had pipe perforations near or above the ground level, or were damaged and covered with waste during landfill operations. Some monitoring of biogas emissions was periodically conducted. Fires that sometimes occurred could be considered a consequence of biogas mismanagement. In addition to small fires, about 1–2 times per year, a big fire that lasts for some days occurred. Fires took place in the active part of the landfill, where waste had been disposed of in the previous 20–30 years, causing high methane production (Vinti 2021). Additionally, onsite systems to adequately prevent and manage fires were limited.

When the land was prepared for the landfill, no geomembranes were used as a waterproof layer at the bottom (Vujic et al. 2012). Consequently, as typical in dumpsites, the spread of leachate to groundwater can be very high (Vaccari et al. 2018). Furthermore, there was no leachate treatment system at the landfill, and the drainage channels, including those around the landfill, were dug into the ground (Vujic et al. 2012).

In Novi Sad, three aquifers were in the area of the municipal landfill (Vujic et al. 2012):

- Aquifer I, the shallowest one, with a free water table.
- Aquifer II, a shallow sub-artesian aquifer;
- Aquifer III, a deep sub-artesian aquifer.

The entire location lies on the alluvial plain of the Danube. Aquifer I is at a depth from 5 (water table) to 30–35 m (bottom of the aquifer) below the ground level (Vinti 2021). It is a sub-artesian aquifer in a wide investigation area because of clayey sediments in the roof. Hydrogeological study on numerous wells in the area defined the filtration coefficient of 5×10^{-4}–6.8×10^{-4} m/s and transmissibility coefficient of 1.0×10^{-2}–1.2×10^{-2} m^2/s (Vinti 2021). Clayey sediments at the bottom of the first aquifer represent a hydraulic barrier against groundwater mixing from the first and the deeper aquifers. The depth of the landfill in some points reaches about 5 m under the ground level, thus it is almost at direct contact with Aquifer I (Vinti 2021). In Aquifer I, the general direction of groundwater flow is north–south, and the groundwater flow gradient was 1.2%. Given the proximity with the first aquifer, the absence of a waterproof layer at the bottom, weather conditions, waste characteristics, and following a precautionary approach, a continuous leachate flow towards the first aquifer was assumed in our study. Most houses were connected to the piped water supply, and officially nobody used water from the first aquifer. However, there was no official prohibition of using the first aquifer. Consequently, some households had their own well from which they extracted and used water from the first aquifer free of charge (Vinti 2021).

At the time of the study, there were no technologies for treating MSW in the region, such as waste incineration or composting plants. The only exception was recycling, but only in individual municipalities and at low percentages. In particular, in Novi Sad small amounts of recyclable materials were separated at the waste sorting facility adjacent to the landfill. The capacity of the sorting facility was low. Indeed, only about 10% of the total MSW generated in Novi Sad could be processed. Furthermore, since the input was the mixed MSW stream, the percentage of sorted materials was less than 10% of the input material. Consequently, less than 2% of the total waste collected in Novi Sad was effectively recycled (Vinti 2021).

The Novi Sad landfill is more similar to a dumpsite. The concentration of pollutants in the leachate from the landfill's peripheral canals was the same magnitude as the concentration of the same substances in the groundwater near the landfill downstream (Djogo et al. 2017). For example, the average NH_4 concentration in leachate was 28.1 mg/l, while the groundwater concentration was 12.45 mg/l. The average BOD_5 concentration in leachate was 82.2 mg/l, while the groundwater concentration was 68.2 mg/l. The average $KMnO_4$ concentration of leachate was 26.6 mg/l, while the groundwater concentration was 17.7 mg/l.

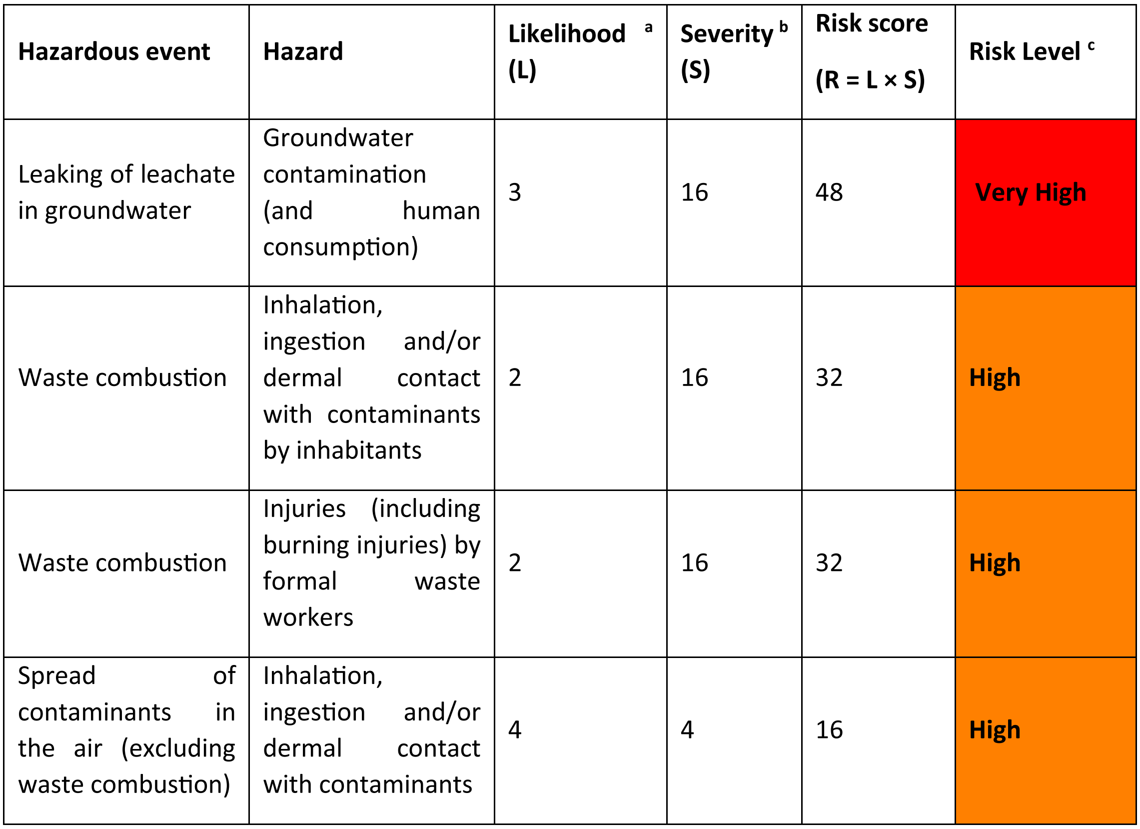
Results

Health Risk Assessment Matrix

Table 2 presents the risk assessment matrix developed for the municipal landfill of Novi Sad. More details are available in Supplementary Materials (Annex 1).

Three hazardous events resulted in high risk and one in very high risk. They are introduced below and are discussed in detail in Section "Discussion".

Table 2 Disposal of solid waste in the municipal landfill of Novi Sad – risk assessment matrix



Hazardous event	Hazard	Likelihood [a] (L)	Severity [b] (S)	Risk score (R = L × S)	Risk Level [c]
Leaking of leachate in groundwater	Groundwater contamination (and human consumption)	3	16	48	Very High
Waste combustion	Inhalation, ingestion and/or dermal contact with contaminants by inhabitants	2	16	32	High
Waste combustion	Injuries (including burning injuries) by formal waste workers	2	16	32	High
Spread of contaminants in the air (excluding waste combustion)	Inhalation, ingestion and/or dermal contact with contaminants	4	4	16	High

[a] Likelihood: Very unlikely {1}, Unlikely {2}, Possible {3}, Likely {4}, Almost certain {5}

[b] Severity: Insignificant {1}, Minor {2}, Moderate {4}, Major {8}, Catastrophic {16}

[c] Risk Level: L [Low], M [Medium], H [High], VH [Very High]

The event "leaking of leachate in groundwater" associated to the hazard "groundwater contamination (and human consumption)" refers to leachate that can reach groundwater if it is not adequately managed. It can pose significant health risks to human receptors. Following a conservative approach, the information collected allowed defining the event, in terms of likelihood, as possible. The risk refers to people living in the closest zone and in the direction of the groundwater flow (i.e., from north to south). Although those living in the closest zones to the landfill were aware of the contamination of the first aquifer and the related risks in case of human consumption, many of them owned wells, and there were no official restrictions in terms of the use of groundwater. Officially, people had to ask for permission from the local administration to dig a well. However, no official restrictions limited the aquifer's use. As explained in detail in Section "Discussion", the average concentrations of Cd, Cr and Pb at the point of exposure resulted above the WHO (2017) guidelines for drinking water quality, even more than an order of magnitude. It is important to consider that, in the health risk analysis, we referred to Aquifer I, i.e. the shallowest aquifer with a free water table.

The hazard "inhalation, ingestion and/or dermal contact with contaminants by inhabitants" related to the event "(uncontrolled) waste combustion" takes into consideration that during waste combustion the people of Novi Sad can absorb contaminants. For instance, pollutants can be directly inhaled or can be ingested because of bioaccumulation in the food chain (Velis and Cook 2021). Additionally, authors have found that uncontrolled waste combustion in landfills resulted in adverse pregnancy outcomes in women living nearby (Mazzucco et al. 2019).

The other event in Table 2 associated with waste combustion was "injuries (including burning injuries) by formal waste workers". It is a risk that can affect waste workers. Indeed, as already mentioned, many fires broke out in the Novi Sad landfill. Additionally, as general information, according to Tot et al. (2019), in Serbia, no landfill is covered daily. This fact increases the risk of waste burning.

The last event considered that individuals in the surrounding community can absorb hazardous substances from the landfill. For instance, if the waste disposal site is not adequately managed, solid particles can be transported by the wind; additionally, gaseous emissions represent a frequent issue in such areas (Salami and Popoola 2023).

Link Between Health Risks and the Number of People Affected

The hazard "groundwater contamination (and human consumption)" can involve residents downstream of the groundwater flow that passes through the landfill. Although further investigations are needed, the potentially contaminated groundwater could reach people from the Klisa and Veliki Rit suburbs, as shown in Fig. 4.

The groundwater flow from Aquifer I mainly reaches Veliki Rit, but the diffusion and dispersion of contaminants in the aquifer (Domenico 1987) could potentially reach a wider area. This assertion led conservatively to consider also the Klisa suburb. About 16,000 people lived in Klisa. In addition, 5,000 residents were assumed in the Veliki Rit suburb. Conservatively, it was assumed that between 10 and 50% of those people use groundwater from the first aquifer through private wells, i.e., between 2,100 and 10,500 residents. The assumption is conservative because, in reality, most people usually use the water network instead of groundwater wells (Vinti 2021). Further investigations will be necessary to understand the actual situation. Additionally, it is essential to consider that the contaminated plume will spread to a broader area due to the dispersion and dilution phenomena (Domenico 1987). However, the same effect allows for a significant reduction in the concentration of leachate pollutants in directions external to those of the plume, which follows the direction of the groundwater (Gibellini and Vaccari 2021; Vaccari et al. 2018).

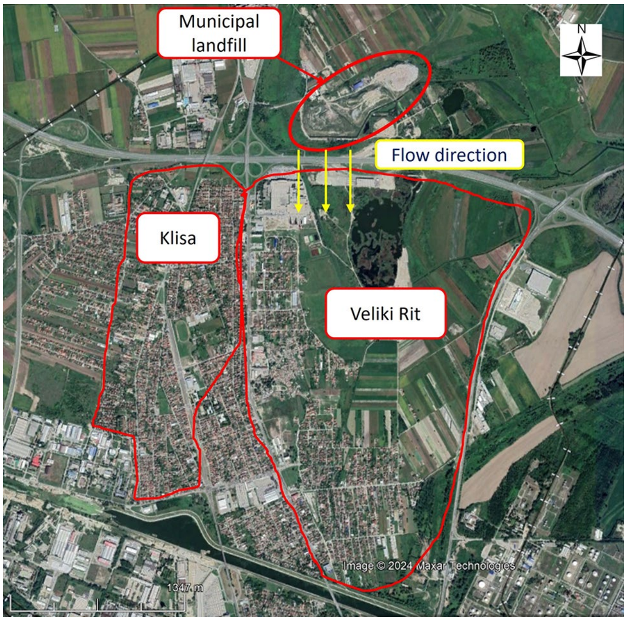


Fig. 4 Novi Sad landfill, Klisa suburb and Veliki Rit suburb (from Google Earth Pro). Imagery date: 5 September 2020 (accessed on 20 May 2024). The scale legend is on the bottom left corner of the figure

"Waste combustion" and the related hazard "injuries (including burning injuries) by formal waste workers" relates to the personnel of the landfill. Unfortunately, receiving detailed information about the workers was impossible. However, considering both landfill workers and administrative staff in the landfill building, between 50 and 100 people were employed (Vinti 2021).

The other hazard related to "waste combustion" involved the residents in Novi Sad. It was "inhalation, ingestion and/or dermal contact with contaminants by inhabitants". On average, the big fires in the landfill were assumed to happen 1–2 times per year. In this case, the wind direction will affect human receptors. However, most people potentially involved lived south and southwest of the landfill. And a few hundred more who lived in the north must be added. Consequently, the most exposed group would be those living in the areas of Fig. 4 and a few thousand more. However, when waste combustion occurs, human receptors in the area can mainly absorb contaminants by inhaling the air and ingesting contaminated food through the food chain. According to WHO (2019), most general population exposure to dioxins related to waste combustion is ingesting contaminated foods of animal origin. Such a health risk could affect even more than 100,000 residents in Novi Sad.

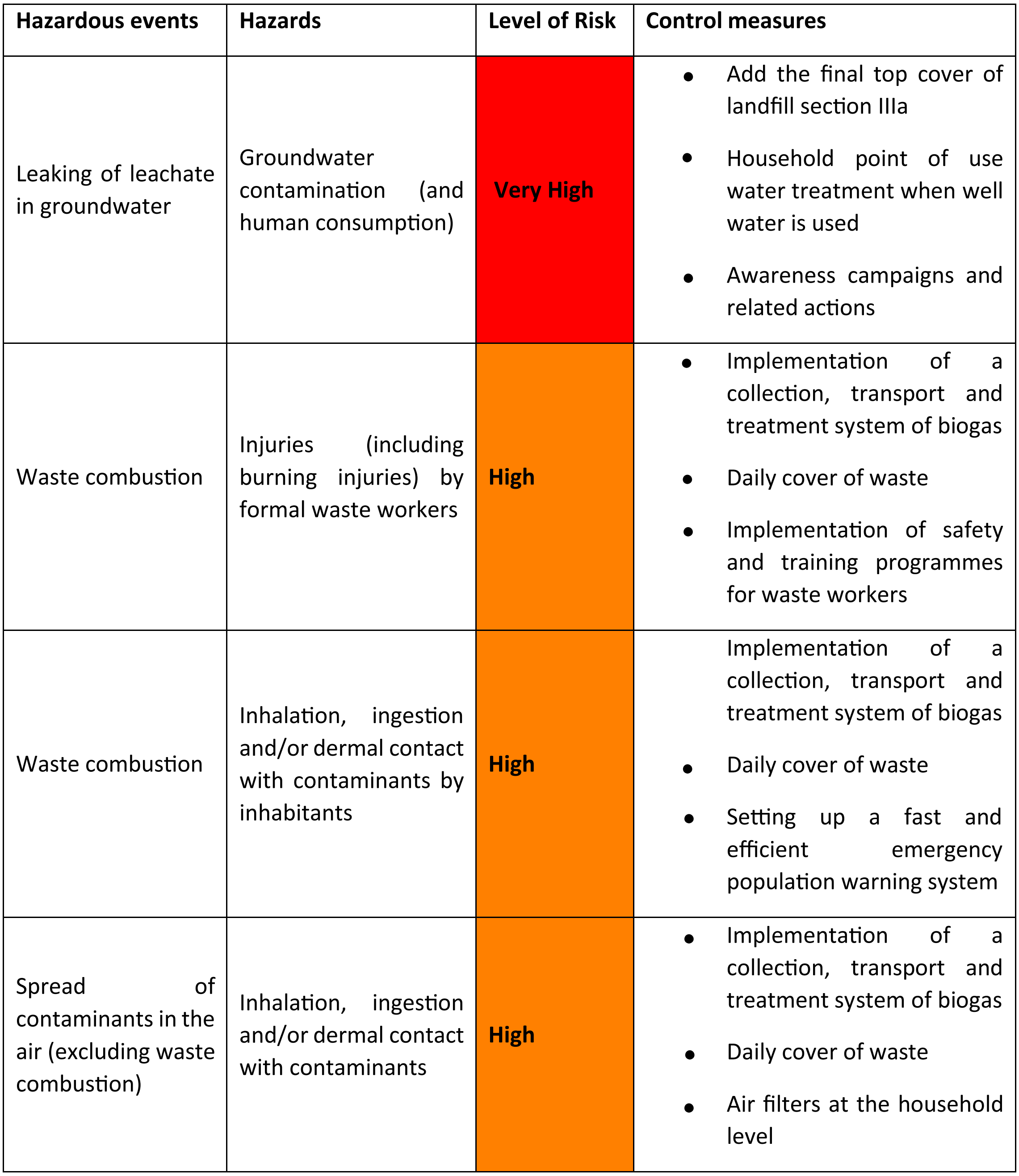
The last hazardous event with high risk consisted of the "spread of contaminants in the air (excluding waste combustion)", associated with the hazard "inhalation, ingestion and/or dermal contact with contaminants". People most affected were assumed as those in Fig. 4, the closest to the landfill, and some other thousand. Conservatively, a total of about 25,000 people were taken. However, further investigations will be needed.

Control Measures and Priorities

Control measures are actions, activities and processes having the scope to prevent or minimise hazards identified (Davison et al. 2005). The control measures that were identified to reduce the highest risks associated with the municipal landfill of Novi Sad are summarised in the last column of Table 3.

As can be seen, the identified actions include capital works (such as implementing a biogas treatment system), operational interventions and behavioural measures. The Supplementary Material (Annex 3) provides more details about the proposed control measures.

Table 3 Risk matrix with the control measures identified



Hazardous events	Hazards	Level of Risk	Control measures
Leaking of leachate in groundwater	Groundwater contamination (and human consumption)	Very High	• Add the final top cover of landfill section IIIa • Household point of use water treatment when well water is used • Awareness campaigns and related actions
Waste combustion	Injuries (including burning injuries) by formal waste workers	High	• Implementation of a collection, transport and treatment system of biogas • Daily cover of waste • Implementation of safety and training programmes for waste workers
Waste combustion	Inhalation, ingestion and/or dermal contact with contaminants by inhabitants	High	Implementation of a collection, transport and treatment system of biogas • Daily cover of waste • Setting up a fast and efficient emergency population warning system
Spread of contaminants in the air (excluding waste combustion)	Inhalation, ingestion and/or dermal contact with contaminants	High	• Implementation of a collection, transport and treatment system of biogas • Daily cover of waste • Air filters at the household level

Cost analysis of the Control Measures

A cost analysis was completed for the proposed control measures. The costs associated with all the control measures discussed in the previous section are summarised in the last column of Table 4. More details are available in Supplementary Material (Annex 4).

The most expensive interventions are for the implementation of a collection, transport and treatment system of biogas and the cover of the landfill. However, enforcing awareness campaigns and safety programmes would be essential to reduce environmental health risks in the short-term using fewer economic resources.

Discussion

Using our proposed SWSP approach, we identified four events at the landfill in Novi Sad which could cause very high and high risks for people and workers, based on a risk assessment (Table 2) estimating the likelihood and severity of each event. A list of control measures was identified

Table 4 Matrix of health risk including the cost for the control measures

Hazardous events	Hazards	Control measures	Cost
Leaking of leachate in groundwater	Groundwater contamination (and human consumption)	The final top cover of landfill section III	€ 934,400 (total capital costs)
		Water treatment systems at the household level	Between € 50,000–240,000 (total cost of incentives)
		Awareness campaigns and related actions	€ 7520 (total costs)
Waste combustion	Injuries (including burning injuries) by formal waste workers	Implementation of a collection, transport and treatment system of biogas	€ 3,015,195 (total capital costs) € 211,063/year (operating and maintenance costs)
		Daily cover of waste	< € 49,928/year
		Implementation of safety and training programmes for waste workers	€ 4000/year
Waste combustion	Inhalation, ingestion and/or dermal contact with contaminants by inhabitants	Implementation of a collection, transport and treatment system of biogas	See above
		Daily cover of waste	See above
		Setting up a fast and efficient emergency population warning system	€ 10,000 (total costs)
Spread of contaminants in the air (excluding waste combustion)	Inhalation, ingestion and/or dermal contact with contaminants	Implementation of a collection, transport and treatment system of biogas	See above
		Daily cover of waste	See above
		Air filters at the household level	€ 189,200 (total cost of incentives)

to reduce them, along with cost estimates. This case study illustrated the utility of using SWSP approach for risk management.

When considering groundwater contamination of Aquifer I from leachate, which was the hazard identified to have very high risk, the contaminants' dilution resulted in almost negligible impact at 600 m from the source of release. We used Eq. (1) to achieve a conclusion with the previously shown values. However, as previously mentioned, we conservatively considered that the first-order degradation rate constant λ was equal to zero. It is an acceptable assumption in the absence of tests to assess site-specific biodegradation (Vaccari et al. 2018). Thus, given the almost negligible dilution obtained, we found that the groundwater quality of the first aquifer would be below the Serbian drinking water standards (Serbian Gazette 2019). Indeed, taking (Vaccari et al. 2018) as a reference, the influence of the Leaching Factor was limited. Such a result aligns with the findings from the study of Djogo et al. (2017), where the concentration of chemicals measured in the peripheral channels around the Novi Sad landfill was of the same magnitude measured in the groundwater below the landfill. Furthermore, developing Eq. (1) the DAF resulted in 1.01.

The average concentrations of Cd, Cr and Pb were estimated to be more than an order of magnitude above the WHO (2017) guidelines for drinking water quality, i.e. 0.003 mg/l, 0.05 mg/l, and 0.01 mg/l, respectively. The adverse health outcomes of Cd, Cr and Pb include neurodevelopmental effects and adverse birth outcomes (WHO 2017). Consequently, the severity was assumed as catastrophic, leading to a very high level of risk. However, even a major severity (that is of a lower level) would have led to a high-risk level. In both the cases, control measures should be implemented.

Another hazardous event considered was "waste combustion", taking into account the phenomena of self-combustion in the landfill. Large fires affected the landfill at least once per year, while small fires were more frequent. Both types of fires were mainly due to the biogas production in the landfill, which was not collected and adequately treated, making combustion more possible. Fire is one of the more severe risks a landfill faces (ISWA 2019). As noted by Tot et al. (2019) analysing landfills' status in Serbia and the risks of injuries and damage for waste workers, some fires might be characterised by a shallow collapse, where operators of heavy machinery (i.e., compactors and bulldozers) may fall.

For the hazard "inhalation, ingestion and/or dermal contact with contaminants by inhabitants" related to the event "(uncontrolled) waste combustion", detailed information about the concentration of pollutants in the air during open burning in Novi Sad was not available. Furthermore, epidemiological studies related to this threat were not found, neither in Novi Sad nor elsewhere. This limitation is probably because the open burning of waste is more common in developing countries or in contexts where collecting detailed information is not easy. It is perhaps also due to the illicit nature that often characterizes such a practice. However, studies concerning the concentration of pollutants generated during open burning of MSW have highlighted the elevated concentration of POPs (such as dioxins) and other toxic and carcinogenic compounds (Estrellan and Iino 2010; Zhang et al. 2011). Furthermore, the level of pollutants in flue gases from incineration plants is known, and many epidemiological and human biomonitoring studies have been conducted (Candela et al. 2013, 2015; Ghosh et al. 2019; Parkes et al. 2020; Xu et al. 2019a, 2019b). As a consequence, it was assumed that:

- The flow of contaminants related to big fires from the landfill of Novi Sad was not continuous but it lasts at least two days per year.
- Compounds that can bioaccumulate were spread in the surrounding environment.
- There was no treatment of flue gases. As a consequence, the flow was in any case higher than that from the incinerators.

As a result, a significant risk was assumed. Indeed, with a precautionary approach, for people who live closest to the landfill the event was considered unlikely (i.e., the current local context makes it possible at least once per year) but catastrophic (indeed it can be associated with cancer and birth defects).

The hazardous event “spread of contaminants in the air (excluding waste burning)” and the hazard “inhalation, ingestion and/or dermal contact with contaminants” represented the last risk discussed. Petrovic et al. (2018) measured the air concentration of organochlorine pesticides (OCPs), PCBs, and PAHs in the landfill of Novi Sad. Then, they conducted a health risk assessment using the methodology suggested by US EPA, founding no risks associated with these pollutants in the landfill (Petrovic et al. 2018). However, only the gaseous phase was analysed, while the particulate matter was not considered, leading to a possible underestimate of the overall risk. Simultaneously, as previously mentioned, residents complained about the bad smell from the landfill. As a result, the risk was analysed for residents living in the two areas, taking into account some epidemiological studies from similar contexts. In particular, in a cohort study, Mataloni et al. (2016) found a higher incidence of all respiratory diseases and acute respiratory infections in young people under 15 living close to sanitary landfills. Furthermore, investigating people living within 1.2 km of a landfill in a cross-sectional study, Heaney et al. (2011) found mucosal irritation and upper respiratory issues as symptoms associated with odour. As a consequence, with a precautionary approach, the risks for residents in the Klisa suburb and in the illegal houses north of the landfill, both about 600 m from the sites, were assumed as moderate in terms of severity (i.e., event potentially resulting in moderate temporary health effects, such as upper respiratory illness) and likely in terms of likelihood (i.e., the current local context makes it possible at least once per week). The risk resulted as high.

As noted, for the structure of the SWSP, both WSP and SSP were taken as a reference. However, an additional part was dedicated to the cost analysis. It represented a novelty that can help define the most appropriate interventions, giving an order of magnitude of their cost. A further crucial point consisted of the health risk assessment matrices. The SWSP should interest many stakeholders, such as inhabitants of the communities, local administrations, public or private companies that manage the solid waste sector, and NGOs that deal with MSW management. However, further research will be needed. Indeed, on the one hand, it emerged the need for more advanced studies regarding dumpsites, the uncontrolled combustion of waste and health risks (Vinti et al. 2021). Thus, conducting epidemiological studies to fill this gap would be useful. On the other hand, the structure of the risk matrix should be investigated further. Indeed, the matrix demonstrated that it is possible to compare dangerous events very different from each other through a standard scale of assigned values. Although it has been highlighted that it will also be up to the SWSP team members to establish the matrix's specific characteristics, a general structure should be agreed upon at the international level. It would allow adapting the matrix to the various case studies analysed. Noteworthy, applying the SWSP to other case studies should allow for refining its structure.

Until now, the health risk matrix based on a SWSP approach was employed only in one other research study. However, the context was quite different, and solid waste management practices in rural Ghana villages (Vinti et al. 2023) were considered. Nevertheless, the same scale was used in the semi-quantitative risk assessment matrix. Thus, although a comparative analysis could be misleading, it is noteworthy that in the disposal of solid waste in rural Ghana dumpsites, the hazardous event for the spread of contaminants in the air resulted in a high-risk level, as in the Serbia case study. Noteworthy, in Ghana, it had a high risk in only one village out of nine, corresponding to the biggest among the dumpsites investigated. However, in that study, in many cases, it was impossible to collect adequate information about the groundwater; therefore, the leaking of leachate into the groundwater represented a hazardous event that deserves further investigation. It must be highlighted that in Ghana and Serbia, it was possible to consider and compare different hazardous events using a common yardstick through the risk matrices.

In addition to the control measures identified to reduce the health risks, further benefits could be recognised when implementing the 3Rs concept (waste reduction, reusing and recycling). Indeed, this would avoid overloading the system regarding waste flow disposed of in the municipal landfill. Furthermore, the 3Rs approach can contribute in reducing greenhouse gas emissions and other environmental threats (Yang et al. 2023; Lee et al. 2016).

Limitations

This study has some limitations. For example, since the wells drawing water from Aquifer I are not officially monitored or registered, gathering detailed information regarding the per capita water usage or the number of inhabitants utilizing it was not possible. Additionally, although Aquifer II and Aquifer III were not considered for the health risk matrix, more detailed data about them was not available but would have been helpful. An additional gap that future authors should fill is the lack of information about groundwater quality upstream of the landfill. Thus, although our analysis and the available data led us to conclude that the landfill leachate is intensely polluting Aquifer I, data from wells or piezometers upstream of the landfill would be pivotal.

Furthermore, data about the wind direction and speed during the year were unavailable, but they would have helped increase the accuracy of the analysis. Additionally, more information about the waste workers' condition in the landfill will be necessary. The implementation of a national database would be helpful. The use of numerical models, for example, in assessing the spreading of pollutants in the air or, with more accuracy, the spreading of the contaminated plume in the groundwater, would help improve the accuracy of the health risk analysis. However, more detailed site-specific data will be needed.

The limitations discussed above, including the need for more quantitative data in some cases, may have influenced the results. However, we overtook these limitations through our methodology and a conservative approach. In the future, more accurate field assessments will be necessary; they should also allow for comparing and evaluating the accuracy achieved with the discussed procedure.

Conclusions

The case study of Novi Sad allowed us to present and discuss the proposed SWSP extensively. In addition to the control measures identified, the 3Rs concept could bring further benefits. The 3Rs concept should be assessed in more detail, and a value chain analysis should complement it. Indeed, the site-specific situation can strongly influence the techno-economic sustainability of any decision about waste reduction or recycling. Although the 3Rs and the value chain analysis represent critical aspects, they remained out of the scope of this work. Additionally, although the concept of an SWSP was recently introduced (Vinti et al. 2023), that work only focused on the health risk matrix. The current research represents the first publication in a scientific journal where the entire structure of the SWSP was discussed and applied to a real case. Considering the topic's breadth and novelty, this application of the safety plan focused on MSW. For the structure of the safety plan, both WSP and SSP were taken as a reference. However, an additional section was dedicated to the cost analysis. It represented a novelty that can help define the most appropriate interventions, giving an order of magnitude of their cost.

This research demonstrated the utility in developing an SWSP, and potential benefits. The application is possible, both in developing and industrialised countries. Although there is a greater need for such interventions in low-income settings where waste management presents other challenges (Villa et al. 2022; Velis and Cook 2021; Tesseme et al. 2022; Kaza et al. 2050), the MSW management can often be improved even in industrialised countries. Risk assessment matrices represent a crucial element of the safety plan that allows a comparison of dangerous events that are profoundly different from each other through a standard scale of assigned values.

While the scientific community has much to contribute to the development of effective SWSP strategies, it is also important to demonstrate that the SWSP approach can be applied outside the research context. Applying the SWSP to other case studies should allow for refining the structure of the SWSP.

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Declarations

Conflict of Interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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