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NATALIJA PETROVIĆ (ORCID: 0000-0002-3404-2626) [1]
DEJAN VASOVIĆ (ORCID: 0000-0003-4043-8093) [2]
BRATIMIR NEŠIĆ (ORCID: 0000-0002-5154-8792)[1]
NEMANJA PETROVIĆ (ORCID: 0000-0003-4010-2311)[1]

LANDFILL LEACHATE MIGRATION MODELING USING THE LANDSIM SOFTWARE. CASE STUDY OF GIGOŠ REGIONAL SANITARY LANDFILL

The paper aims to provide insight into data on leachate migration, composition, and migration time and to improve the engineered barrier system (EBS) importance through different pollutant concentrations in the landfill at the base of the unsaturated zone and off-site, for the real-case scenario with composite liners (EBS) and the worst-case scenario with no liners (NO EBS) using the LandSim software for 30, 100, 1000 and 20 000 years in 1000 iterations. Also, the paper aims to analyze the leachate leakage through the waste for different migration times and different internal layers to create a qualitative and quantitative basis for assessing leachate's impact on the environment. The results obtained by modeling the parameters of the real case at the Gigoš landfill showed that the leachate leakage amount is about 340 times lower when EBS is present and concentrations of nitrogen, chlorides, arsenic, lead, cyanides, and mercury in the worst-case scenario (NO EBS) exceed the permitted limits according to the laws of the Republic of Serbia.

1. INTRODUCTION

Every year in Serbia, there is an increase in the amount of waste deposited in sanitary landfills. Also, a large part of generated municipal waste is deposited in unsanitary landfills [1]. Mixed municipal waste is deposited in landfills without any prior treatment, and that is a key source of surface and groundwater pollution [2]. Sustainable waste management, which has a potential environmental impact, has become indispensable in the last few years.

[1] Academy of Technical and Preschool Studies Niš, Aleksandra Medvedeva 20, 18000 Niš, corresponding author N. Petrović, email address: natalija.petrovic@akademijanis.edu.rs
[2] University of Niš, Faculty of Occupational Safety in Niš.

Concerning environmental and water protection, a special problem has been tified in the form of contaminated water (leachate) generated within a landfill body as a product of the reaction between waste materials undergoing decomposition and infiltration [3]. Landfill leachate is a polluted liquid that passes through the landfill body, where it extracts soluble, colloidal, and suspended matter out of the deposited waste. It represents a complex and heterogeneous mixture with a highly variable composition, which mainly includes various organic and inorganic compounds as well as microorganisms, so landfill leachates are a significant source of surface and groundwater pollution [4].

The quantity and quality of leachate depends on several influencing factors (climate, amount and composition of waste, hydro-geological characteristics of the landfill site, municipal waste disposal technique, as well as the age of the landfill) [5]. During the working life of the landfill, including operational phases and phases after closure, it is necessary to control landfill leachate as well as surface flows near the landfill to monitor the migration of leachate and its impact on the immediate environment [6]. The negative impact of leachate was studied worldwide more than 20 years ago [7, 8], but in Serbia, the negative impact of leachate was studied only several years ago.

Waste material, depending on the type of material deposited, can be classified as rapidly degradable, whose decomposition takes from 3 months to 5 years, and slowly degradable material, whose decomposition takes 50 or more years [9, 10]. During the aging of the landfill, solid waste decomposes and changes under the influence of physical, chemical, and biological processes.

First, the physical changes take place, i.e., the waste is compressed, during the following years, it settles continuously, which is a consequence of consolidation and its biological decomposition. In this way, the height of the deposited layer can be reduced by about 30%. In the first layer of deposited waste, while there is still oxygen in the cavities, aerobic processes take place. Later, after the depletion of oxygen, the anaerobic decomposition of solid waste occurs due to biothermal decomposition, accompanied by leachate and gases, as a result of which the landfill settles. The chemical characteristics of the leachate are affected by the biological decomposition of biodegradable organic substances, chemical oxidation processes, and the dissolution of organic and inorganic substances within the waste [4]. The actual composition of leachate depends on a number of variable factors such as waste composition, temperature and moisture content, liquid pathways, landfill thickness, stages of waste decomposition, the ability of the intermediate layers to absorb and remove pollution, as well as the quality of the water that infiltrates the landfill.

The main source of landfill leachate is the atmospheric precipitation that falls on the surface of the landfill and is filtered through the landfill body. Depending on the time of year or meteorological parameters in general, the amount of precipitation may differ and thus have a different effect on the amount of water that will be filtered over a specific period [6]. Furthermore, water migration through the waste depends on the porosity of the waste, its humidity, thickness, as well as changes in the chemical and morphological composition of the waste in the internal layers of the landfill, which are caused by landfill aging [5].

Previous studies of leachate were based on examining the impact to the ecosystem and human health in a short period of time in different simulation models, with different pollutants and migration times, and at different landfills [11–13]. Long-term dynamics of leakage from landfill site and pollutant concentration were also studied in the past years [14–17].

The internal layers of the landfill are important because they can form impermeable barriers and accumulation zones in the waste [17]. Landfill internal liners are designed to create a barrier between the waste and the environment. The most important purpose of a liner system is to prevent leachate contaminants from reaching the environment and to prevent soil, surface, and groundwater contamination. Unsanitary landfills generally do not have any protective layer, so it is important to examine various scenarios of leachate flow through a composite system and without engineered barrier systems (EBS).

Several studies discussed the importance of different liner systems in the landfills [11, 17, 18]. This type of study is mostly conducted using various simulation models, such as hydraulic evaluation of landfill performance (HELP), the water balance method (WBM), LandSim, and several others. Software-assisted research helps fill the gaps in knowledge about long-term landfill leachate emissions and their potential adverse effects on environmental quality. In addition, the evaluation of performance degradation of the main landfill functional units can be established most precisely with the help of software packages such as those mentioned above.

The numerical model used for the present analysis of leachate leakage, concentration, and migration time is the LandSim simulation model, a probabilistic performance assessment model for predicting the impacts of landfill development on groundwater [19]. LandSim is used to predict concentrations and elevations of leachate during the operational phase of the landfill site, including changes in infiltration, declining source term within leachate, and deteriorating leachate control systems [13].

The first aim of this paper is to analyze the leakage of leachate through waste for different migration times and different internal layers at Gigoš landfill.

The second aim is to improve the importance of EBS in the landfill body through a case study of concentrations of different pollutants at the base of the unsaturated and saturated zones, with composite liners and no liners.

In general, this paper presents a comparative analysis of the Gigoš landfill real-case scenario (with composite EBS) and the potential worst-case scenario (no EBS), performed using the LandSim model, with leachate migration and concentration of pollutants at the base of the unsaturated zone and the saturated zone (off site) over a long period as the output, for the purpose of creating a qualitative and quantitative basis for assessing their environment impact in Serbia.

2. STUDY AREA: REGIONAL SANITARY LANDFILL GIGOŠ, JAGODINA, SERBIA

There are 11 sanitary landfills in Serbia, all of which are reaching the limits of their capacity. They do not operate fully in accordance with the conditions set out in the EU Landfill Directive. In addition to the 11 sanitary landfills, there are about 100 unsanitary municipal landfills and more than 3000 illegal dumpsites throughout Serbia [20].

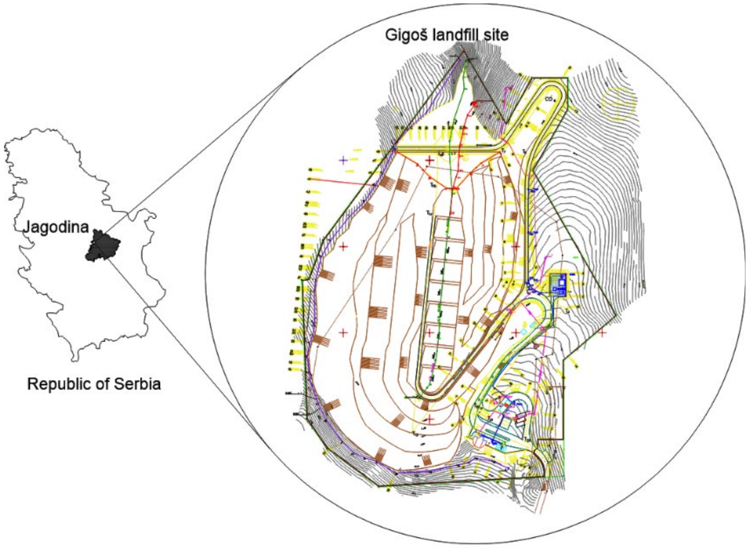

Fig. 1. Location and layout of the Gigoš regional sanitary landfill

Regional sanitary landfill Gigoš is located northwest of Jagodina in the mountainous area of the Jagodina Forestry at the Gigoš site (Fig. 1). The landfill is operated by PWW Deponija Jagodina LLC. It lies at latitude N43°59′ north and longitude E24°14′. The Velika Morava flows about 2 km away from the Gigoš landfill. The terrain is steep with slopes of up to 50%. The nearest settlements are Novo Lanište (about 2.5 km away) and Bagrdan (about 3 km away). Individual houses are at a distance greater than 500 m. The area *P* of the landfill complex is approximately 11.83 ha. The landfill was opened in 2010, and its capacity is 1 500 000 m^3, which corresponds to a disposal period of more than 25 years. The landfill complex fills the dredged space between two bank ridges, behind which the dredged morphological forms also extend.

Waste is weighed at the Waste Collection and Selection Center, which is located 13 km from the landfill. At this site, individual fractions of waste, mainly packaging waste (paper, plastic, metal, etc.) are separated, and the rest is deposited in the landfill. The landfill laboratory, where leachate samples are tested, is located at the Waste Collection and Selection Center. The daily amount of waste deposited in the landfill is

372 m^3/day in uncompacted state or 114 m^3/day in compacted state, which amounts to 150 t/day. The average morphological composition of municipal solid waste deposited in the Gigoš landfill is shown in Table 1.

Table 1

Average morphological composition
of municipal solid waste deposited in the Gigoš landfill [9]

Component	Share in total mass quantity [%]
Paper	10.8
Glass	6.78
Plastic	7.31
Tire	6.33
Waste from public areas	27.12
Textiles	4.3
Metal waste	0.45
Organic waste	21.96
Construction waste	5.92
Other	9.04

At the specified location, the ground is mainly composed of category III (sandy clay) and category V (crystalline shale) soil materials [9]. The soil is globally permeable to water, which is why measures have been taken to protect the soil and groundwater from pollution.

There are three different geological layers at the location:

- Layer 1. Clay – dusty sandy, brown in color with an average thickness of 1.0–1.5 m.
- Layer 2. Grus, with scaly decay of shale (mica schist) with an average thickness of 1.0–1.5 m.
- Layer 3. Crystalline shale, with higher crystallinity, zones of higher average mechanical damage – layer thickness of 7.50 m.

Five piezometers were installed at depths of 20–27 m in order to control groundwater pollution. Currently, 4 piezometers are in operation, one of which is used as a reference and remains outside the landfill’s influence in order to monitor the impact of the landfill's operation on groundwater.

3. METHODOLOGY

3.1. LEACHATE INVENTORY

The total surface area of the landfill for the operational period is 66.127 m^2. Waste disposal is planned in three phases. Currently, 1/3 of the total area is adopted as the relevant area for the leachate calculation, which is 22.042 m^2.

Determination of the amount of leachate is based on the following assumptions [9]:

- Sources of infiltration, i.e., seepage, are the precipitation that reaches the landfill body and the water that is produced as a product of chemical and biological reactions of solid waste decomposition.
- All surface contact of water from the terrain surrounding the landfill complex is drained away in a controlled manner through perimeter channels.
- Groundwater cannot infiltrate the landfill body either from the sides or from the bottom, i.e., the subsoil.
- The movement of water through the landfill body is directed vertically downward.

The average daily amount of leachate from the surface of the landfill body is calculated on the basis of annual precipitation in Jagodina and it amounts to 3.36 m^3/day. The maximum daily amount of leachate from the surface of the landfill body is calculated based on the maximum daily precipitation in Jagodina, which amounts to 36.6 m^3/day [9].

Leachate generation and quality at the site are controlled in the landfill laboratory. Leachate monitoring is performed on a representative number of samples at each point where the liquid is drained away from the site in a controlled manner. Leachate volume is measured monthly, while all other measurements are performed quarterly (*Regulation on Landfill Waste Disposal*, Official Gazette of the RS, No. 92/2010, and *Rulebook on the Method and Conditions for Measuring the Quantity and Testing the Quality of Waste Water and the Content of the Report on the Performed Measurements*, Official Gazette of the RS, No. 33/2016).

Table 2

Leachate components' concentration [mg/dm^3]
from the Gigoš landfill body in 2022 [21]

Component	Measured value	Emission limit in wastewater[1]	Emission limit in drinking water[2]
Nitrogen	295.9	70	0.5
Chlorides	3282.25	4,500	250
Cyanides	0.01	0.2	0.05
Arsenic	0.53	0.1	0.01
Lead	0.11	0.5	0.01
Mercury	0.0003	0.05	0.001
Phenols	0.001	50	0.001

[1]*Regulation on Limit Values of Emission of Polluting Substances into Water and Deadlines for Reaching Them*, Official Gazette of the RS, No. 67/2011, 48/2012 and 1/2016.

[2]*Rulebook on the Hygienic Safety of Drinking Water*, Official Gazette of the RS, No. 42/98 and 44/99, Official Gazette of the RS, No. 28/2019.

In the laboratory, leachate tests are performed quarterly through groups of parameters such as general parameters, nutrients, salinity, metals, and organic substances content. In this paper, the research was conducted based on 7 parameters: nitrogen, chlorides, cyanides, arsenic, lead, mercury, and phenols contents, owing to their frequent presence in leachate. The measured values of the parameters from the Gigoš landfill body in 2022 are shown in Table 2. The table shows that certain parameters exceed the permitted values, so the leachate is treated further and discharged into the landfill body as such. The paper aimed to show the potential amounts of these parameters in different EBS liners and their changes over different time intervals.

3.2. ENGINEERED BARRIER SYSTEM (EBS)

The engineered barrier system (EBS) is a containment structure designed and constructed to inhibit the migration of landfill leachate from operating or closed landfills. Within landfills, the engineered barrier may consist of membrane and/or clay-and-bentonite enriched sand layers, together with the drainage system to minimize the head of the leachate above the engineered barrier [19]. The membrane is a synthetic material (such as HDPE) manufactured and installed as a liner at the base of a landfill cell to reduce the rate of leachate egress (and groundwater ingress). The composite liner is a liner comprising two or more separate components usually including a mineral liner and a geotextile membrane liner. Different sites will use different barrier designs and some older sites may have no barrier at all. Because of the recognized limitations in engineered barrier system (EBS) technology, some leakage of leachate through the base of the landfill is inevitable [19]. The magnitude of this leakage depends on the head of the leachate, the characteristics of the liner system, and the hydraulic conductivity of the underlying material.

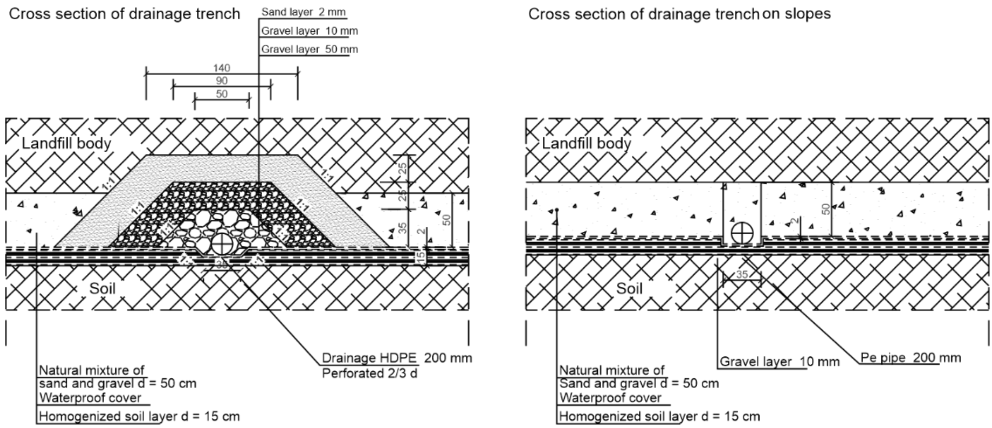

Fig. 2. Gigoš landfill composite lining: cross-section of drainage trench (left) and cross-section of drainage trench on a slope (right)

At the Gigoš landfill, as a solution for the controlled disposal of non-hazardous waste, so-called the sandwich system technology was adopted, i.e., layer by layer that eliminates the possibility of the final disposal of waste with maximum environmental protection measures. Isolation of the bottom and slopes of the landfill-formed body was carried out to prevent the penetration of landfill leachate and landfill gases into the soil and their uncontrolled leakage from the site, which would result in soil, groundwater, and surface water pollution.

The composite lining of the landfill body bottom (Fig. 2) contains the following layers:

- synthetic clay (bentonite) at the bottom and slopes of the landfill body,
- HDPE (high-density polyethylene) liner, rough on both sides,
- geotextile,
- a drainage of gravel.

Drainage material is placed above the second layer of geotextile as a filtering layer for leachate. The gravel protects the drainage pipes and the waterproofing base from machinery. Bentofix® layers are placed on the slopes of the body, and a layer of gravel is placed over it, which is supported by the placement of car tires. Waste is deposited over a layer of gravel. Waste disposal is carried out through surface disposal.

3.3. LANDSIM SIMULATION MODEL

The LandSim software model was developed for the Environmental Protection Agency to provide probabilistic quantitative risk assessments of the performance of specific landfill sites concerning groundwater protection [19]. It is a tool to evaluate the leakage rate of leachate from landfills, attenuation in the unsaturated zone, and dilution and contaminant transport in the saturated zone. LandSim also determines the environmental performance of different liners (e.g., compacted clay versus HDPE/clay) [11, 18, 22]. The model uses the Monte Carlo simulation technique to select from predefined various input values to create parameters for use in the calculations of the model.

Few prominent researches have been conducted using the LandSim simulation model. In 2007, Slack et al. [23], examined the dependence of leachate amount on the infiltration amount to the open waste and examined the occurrence of contaminants at the base of the clay liner, the base of the unsaturated zone, and at the compliance point. Mishra et al. [16, 17] examined the impact of leachate on human health depending on different EBS, and Sun et al. [13] investigated the effects of geomembrane degradation and landfill defects on long-term leachate leakage and groundwater quality.

Where no engineered barrier is in place, as is the case in many older landfills, LandSim calculates the leakage by using Darcy's Law [19]

$$Q = KiA \tag{1}$$

where: Q is leachate flow rate per cell, m^3/s, K hydraulic conductivity of the unsaturated zone material directly beneath the waste, m/s, i average vertical hydraulic gradient, A cross-sectional area of the cell, m^2.

The choice of hydraulic conductivity for the unsaturated zone is not straightforward, because it depends on the moisture content. This will change significantly as the underlying material of the site progressively moistens. The hydraulic conductivity of composite liners is controlled by the quality of the welds between individual sheets and by what happens after the liner has been placed. Based on the results of both analytical and experimental work, the following equation is proposed for leachate leakage through composite liners:

$$q = C_d i_{av} h^{0.9} a^{0.1} K^{0.74} \tag{2}$$

where: q is leachate flow rate per defect, m^3/s, C_d constant describing the quality of contact between membrane and underlying strata, i_{av} average vertical hydraulic gradient, h head of leachate on the defect, m, a area of the defect, m^2, K hydraulic conductivity of the unsaturated material directly beneath the membrane, m/s.

LandSim is designed to simulate variable source dispersion in a manner that conserves mass, mimics reality, and allows the assessment of retarded species. Longitudinal dispersion is modeled in all pathways, and retardation and biodegradation are also included. LandSim uses the Laplace transform technique to solve the advection-diffusion equation that describes contaminant transport.

Of no less importance is the fact that nitrogen is the component of landfill leachate that is usually used to determine the residual potential of leachate as a pollutant, i.e., the period after the closure of the landfill during which leachate should be monitored. The concentration of ammonium nitrogen, in addition to chloride concentration, is a parameter that changes little or not at all over time from the moment of disposal. Further, ammonium ions and chloride ions are components of leachate that are not susceptible to biodegradation, nor do they participate in various physical and chemical processes during which the substances present are decomposed, and generally leave the solid phase easily. Phenols are organic substances subject to biodegradable processes. Their degradation takes place in aerobic and anaerobic respiration, whereas they are absent in oxidation and co-oxidation processes. In water and soil, cyanides take the form of free cyanides, but much more likely is the form of cyanide complexes, given the unique property of cyanides – that they easily form complexes with a large number of metals. Although many of these complexes can be considered relatively stable and therefore less toxic, they still pose an environmental threat due to their ability to release toxic ions under uncontrolled conditions. Heavy metals as pollutants in the environment are a serious health and environmental problem because they are toxic, non-biodegradable, and have a very long half-life in the soil. Considering these facts, it is much easier and more reliable to model expected concentrations using the LandSim software.

3.4. INPUT PARAMETERS

Various parameters are combined to model the amount of produced leachate, the concentration of selected pollutants in the leachate, migration within the landfill, the probability of leakage through the existing barrier, and transport within the underground layer to the aquifer. The input parameters for the Gigoš landfill obtained based on the research submitted to [9] and laboratory measurements at the Waste Collection and Selection Center Jagodina [21] are shown in Table 3.

Table 3

Input parameters for LandSim

Parameter	Value			Justification
Infiltration				
To open waste, mm/year	600			[9]
Through the cap, mm/year	50			[19]
Cell geometry				[9]
Cell length at base, m	170			
Cell width at base, m	180			
Base area, ha	3.06			
Top area, ha	3.72			
Final waste thickness, m	single 30			
Leachate inventory	Log triangular			
	Minimum	Likely	Maximum	
Ammonium N, mg/dm^3	39.6	295.9	410	[21]
Chlorides, mg/dm^3	2481	3282.25	5318	
Cyanides, mg/dm^3	0.01	0.01	0.01	
Arsenic, mg/dm^3	0.39	0.53	0.92	
Lead, mg/dm^3	0.03	0.11	0.28	
Mercury, mg/dm^3	0.0001	0.0003	0.0005	
Phenols, mg/dm^3	0.001	0.001	0.001	
Drainage blanket				[9]
Conductivity, m/s	log uniform (0.0003, 0.003)			
Thickness, m	0.5			
Engineered barrier	composite EBS (HDPE)			
Design thickness of mineral liner, m	log uniform (1, 1.5)			[9]
Hydraulic conductivity, m/s	single 2×10^{-11}			*LandSim Manual*
Longitudinal dispersivity, m	single 0.1			10% of thickness *LandSim Manual*
Unsaturated pathway	sediment			
Pathway length, m	log uniform (8, 10)			[9]
Hydraulic conductivity, m/s	log uniform (1×10^{-11}, 1×10^{-8})			*LandSim Manual*
Aquifer pathway				
Hydraulic conductivity, m/s	log triangular (0.0002, 0.002, 0.02)			*LandSim Manual*

The time slices chosen in the simulator are 30, 100, 1000, and 20 000 years for 1000 iterations. In the first case scenario, i.e., the real case, the landfill has a composite liner with a HDPE capping system. The worst-case scenario was assumed to be the one with no EBS.

4. RESULTS AND DISCUSSION

LandSim estimates the possible pollutant concentrations at different levels that may reach a given point on the ground over a long time. The results obtained with the LandSim simulator show the difference in the leakage rate, pollutant concentrations in the unsaturated zone and off-site point (5 m down hydraulic gradient) for a composite liner (real-case study) and no EBS (worst-case study). The time for unsaturated pathway migration plot shows the predicted time, in years, for leachate to migrate from the base of the EBS to the water table.

4.1. REAL-CASE STUDY

LandSim simulations revealed that after a thirty-year management period, the leachate head on the composite barrier system increased from 0.6 m, since the landfill began its operation, to 3 m over the 20 000-year period that was modeled. According to the model, the maximum leachate head of 3 m occurs between 22 and 29 years, which coincides with the period of surface breakout of the leachate. The leakage rates from the composite liner were also calculated using multiple LandSim simulations and the plot shows that the minimum amount of leakage was 20 dm^3/day until 20 years into the post-closure period and started to increase to reach its maximum amount of 70 dm^3/day after 150 years, due to EBS lifespan [24]. The present study shows the pollutant concentrations at the source, at the base of the unsaturated zone, and off-site. The initial concentrations of chosen pollutants (nitrogen, arsenic, chlorides, cyanides, mercury, lead, and phenols) were estimated at the landfill laboratory in Jagodina, and further concentrations were simulated and predicted for a longer time.

Pollutants obtained in the model show that there are no significant concentrations for the first 170–200 years, which coincides with the lifespan of the clay layer mentioned in a prominent study [17]. After that, they reach their peak concentrations in the period between 300 and 500 years after the landfill closure. The model shows that nitrogen, chlorine, and phenols are not evident after a long time due to their fast decomposition properties. Cyanides, arsenic, lead, and mercury are present at low concentrations even after 20 000 years because these pollutants share the properties of long estimated half-lives and high retardation factors [23].

Nitrogen, phenols, and chlorine concentrations peak at the base of the unsaturated zone in the amount of 190, 0.00002, and 2550 mg/dm^3, respectively. After 700 years, pollutants show a decreasing trend and they are not evident at the base of the unsaturated zone over a long time.

After 300 years, cyanides, arsenic, lead, and mercury reach their maximum concentrations at the base of the unsaturated zone in the amount of 0.025, 0.55, 0.125, and 0.0003 mg/dm^3, respectively. All these pollutants are present at negligible concentrations for up to 20 000 years.

The presence of pollutants off-site was not evident for the first 250 years after the landfill closure, and then the concentrations of all pollutants increased to their maximum. Concentrations of nitrogen, phenols, and chlorine were 0.02, $1.6 \cdot 10^{-9}$, and 0.25 mg/dm^3, respectively, and after 500–800 years they were at zero level. Cyanides, arsenic, lead, and mercury have concentrations of $2 \cdot 10^{-5}$, $6 \cdot 10^{-4}$, $1 \cdot 10^{-4}$, and $3 \cdot 10^{-7}$ mg/dm^3, respectively, and these pollutants are evident over a long time of 20 000 years. All pollutant concentrations are within the limit values according to any legislation.

4.2. WORST-CASE SCENARIO

The minimum amount of leakage with no EBS was 5000 dm^3/day until 1000 years into the post-closure period and started to increase to its maximum amount of 24 000 dm^3/day, which also coincides with the period of surface breakout of the leachate. Unlike the real-case scenario, in the worst-case scenario, pollutant concentrations reach their maximum values much faster, mostly 5–10 years into the post-closure management period. After 3–5 years, nitrogen, phenols, and chlorine concentrations peak at the base of the unsaturated zone in the amount of 270, 0.0006, and 3700 mg/dm^3, respectively. After 300 years, they show a decreasing to zero level over a long time. Cyanides, arsenic, lead, and mercury reach their maximum concentrations at the base of the unsaturated zone after 5–10 years in the amount of 0.04, 0.7, 0.17, and 0.0004 mg/dm^3, respectively. These pollutants are present in minimal amounts for up to 20 000 years.

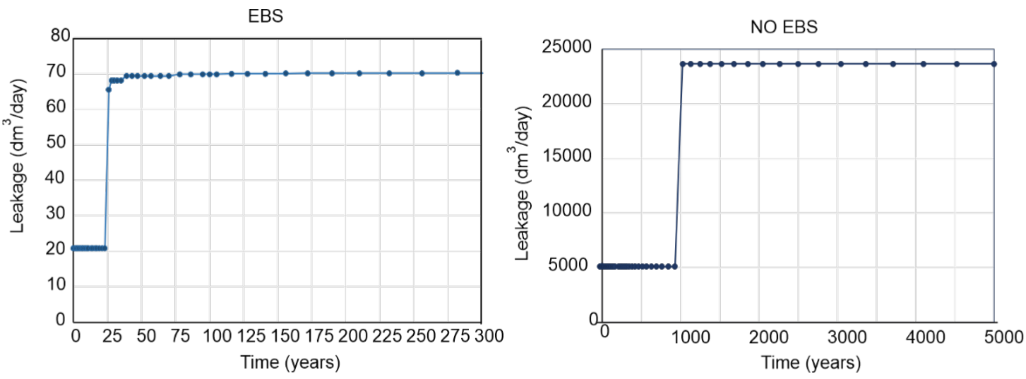

Fig. 3. Leakage rate over a long time: real-case scenario (left), worst-case scenario (right)

Outside the landfill, all pollutant concentrations reach their maximum values in 5–10 years. Concentrations of nitrogen, phenols, and chlorine were 5.82, 0.000025, and 71 mg/dm^3, respectively, and after 150 years they were not evident off-site. Cyanides, arsenic, lead, and mercury concentrations have the values $4.45 \cdot 10^{-3}$, 0.0135, 0.0034, and $1.04 \cdot 10^{-5}$ mg/dm^3, respectively, and all these pollutants are evident over a long period of 20 000 years. During the landfill's initial stage, the concentration of leachate and its components gradually increases to the maximum, after which the concentration of the leachate decreases and stabilizes at a specific constant value, which coincides with the results of previous studies [13, 17].

Figure 3 simulates the leakage rate over a long time and shows time dependences of the cumulative frequency distribution of the leakage rate. The increase in the leakage rate is not obvious in the short-term period (up to 10 years), while in the medium-term period (20–30 years), the increase in the leakage rate is nearly double that of the short-term (Fig. 3 left). It increases more clearly after 100 years, almost four times faster than the short term, and almost two times faster than the medium term. A significant increase in leakage usually occurs when control management ceases, which is why there is a sharp increase in leakage after 30 years, which is also studied in the literature [13].

On the other hand, in the worst-case scenario (Fig. 3 left), an initial constant leakage of 5000 dm^3/day corresponds to the measured values of the average daily amount of leachate at the landfill measured in the laboratory. After a certain time, there is a sudden increase in leakage in the amount of 24 000 dm^3/day due to cap and soil degradation, which also coincides with the measured maximum amount of leachate from the landfill body.

Figure 4 clearly shows the huge difference between the pollutant concentrations in the real case and the worst-case scenario. This is a representation of the potential state of sanitary and non-sanitary landfills over a longer time.

In the worst-case scenario, all pollutant concentrations visibly increase after 5 years and reach their maximum values by 10 years. The reason for this is the absence of protective layers and rapid leachate absorption through waste and soil. All concentrations show a decreasing trend after 350 years, possibly as a consequence of the landfill's end of life [24]. Differences in the length of presence depend on the type of pollutants; for example, heavy metals remain until the end of the predicted period as heavy metals are particularly known to be highly persistent, while other pollutants are not present until the end of the predicted period due to their fast decomposition [25]. In the real-case scenario, the concentration growth is visible after 170 years, which coincides with the service life of the liners beneath the landfill body, as mentioned in the literature [17].

In both cases, nitrogen, phenol, and chlorine simultaneously show a decrease in concentration and disappear over time but concentrations in the worst case are approximately 45% higher than those in the real-case scenario. The difference is that in the worst case, the maximum concentrations are much higher and persist in the unsaturated layer much longer, approximately 200 years longer than in the real case, which can result in much higher environmental pollution if the landfill does not have protective layers.

Lead and arsenic are more persistent in the unsaturated zone than the previously mentioned pollutants, but they still disappear over a long time, while mercury and cyanides remain in the unsaturated zone with noticeable concentrations even after 20 000 years. Lead, arsenic, and mercury concentrations are 36, 27, and 33%, respectively, higher than their concentrations in the real-case scenario, while cyanides show the highest concentration difference in the two scenarios, as much as 52%.

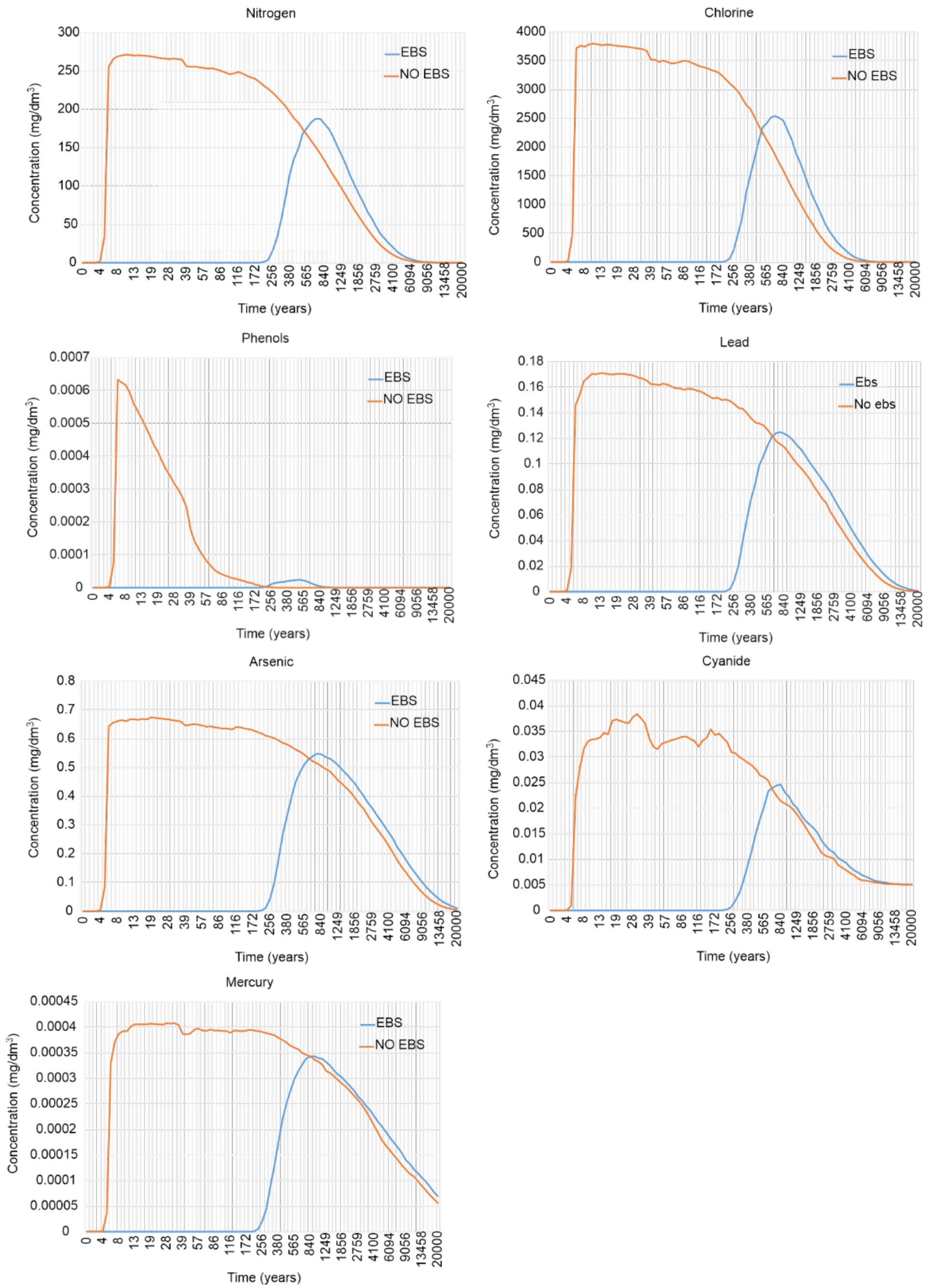

Fig. 4. Pollutant concentrations in the unsaturated zone base
in real-case (EBS) and worst-case scenarios (NO EBS)

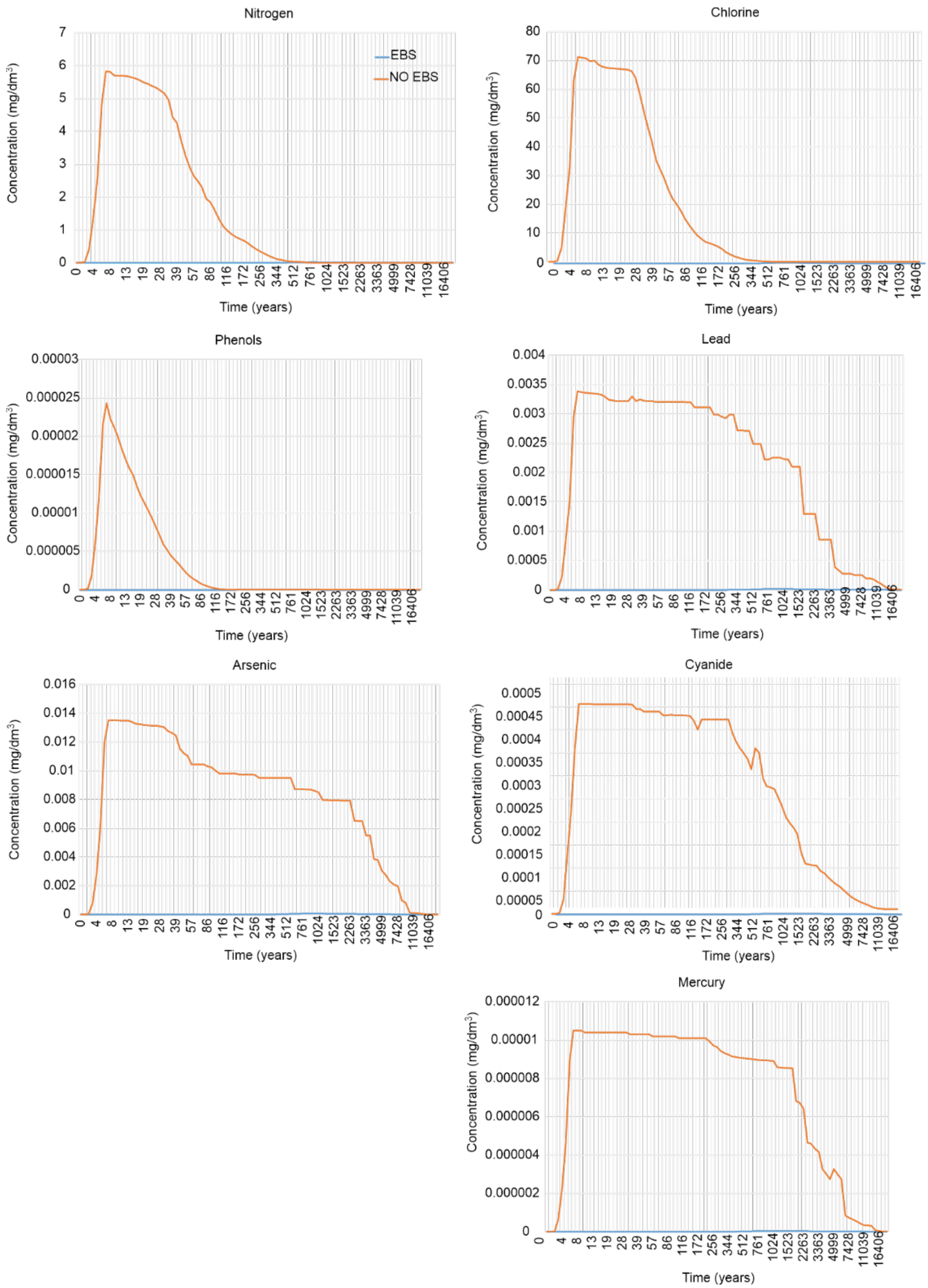

Fig. 5. Off-site pollutant concentrations in real-case (EBS) and worst-case scenarios (NO EBS)

According to the changes in pollutant concentrations in the landfill body, present research shows that the lifetime of the landfill lasts between 300 and 700 years, depending on the type of pollutants, which coincides with the period of increasing pollutant concentrations in a predicted lifespan for the duration from the operation of waste landfills to their end of life mentioned in the literature [24].

From approximately 8 to 100 years, the pollutant concentrations remained relatively stable. During this period, the aging of the landfill had not yet begun, and the leakage rate was relatively constant. Pollutant concentrations initially decreased very slowly and were close to a constant value. After 100 years, the dynamic equilibrium of pollutant transport was broken with an increase in the leakage rate due to the aging of the landfill.

The greatest importance of protective layers results from the comparison of the plots of pollutant concentrations outside the landfill body shown in Fig. 5. Output values obtained through statistical data by the LandSim software in time slices of 30, 100, 300, 1000, and 20 000 years indicate different changes in pollutant concentrations in the real-case and the worst-case scenario.

Statistical data in the real-case scenario indicate zero concentration values in time intervals of up to 1–30 and 30–100 years. The biggest changes in pollutant concentrations occur in the period between 300 and 1,000 years. From 300 to 700 years, nitrogen concentration increased 17 times, and chlorine 35 times. Phenols show a 28-fold increase from 250 to 500 years when they reach their maximum concentration. Arsenic, cyanides, lead, and mercury show very similar trends of concentration changes from 300 to 1,000 years. Namely, their increase after 300 years is 21 times, 26 times, 20 times, and 22 times higher, respectively, than in the previous period, until 950 years, when they reach their maximum concentrations.

Statistical data in the worst-case scenario show somewhat different trends in pollutant concentrations. The biggest changes occur in the time slices 1–30 years and 30–100 years. After that, pollutant concentrations decrease sharply. From 5 to 10 years, the concentration of nitrogen, chlorine, and phenol increases by 65, 66, and 58 times, respectively. After 30 years, pollutant concentrations are in constant decrease, and after 300 years for nitrogen and chlorides and 100 years for phenols, they are negligible. Arsenic, cyanides, lead, and mercury have different changes in concentrations over time. In the time interval of 5–10 years, they have a sudden increase in concentration, 65, 90, 63, and 68 times, respectively. In the 10th year, they reach maximum values, followed by a minimal drop in concentrations until 1000 years. After that, they remain present in minimum concentrations even up to 20 000 years.

In the real-case scenario, there is no negative impact of any pollutants on the Gigoš landfill. Pollutant concentrations in the surrounding area do not exceed the limit values prescribed by any law. On the other hand, the worst-case scenario shows much higher concentrations over a much longer time. Pollutant concentrations do not exceed the maximum permitted concentrations consistent with applicable regulations, which refer to wastewater; however, some of them exceed the permitted concentrations for surface water, groundwater, and drinking water. Table 4 shows the summary of LandSim result outputs and limit values according to legal regulations in Serbia and in the EU.

Table 4

Summary of LandSim results and legal regulations [mg/dm^3]

Pollutant	LandSim output	Wastewater[1]	Surface water[2, 3]	Groundwater[2]	EU water standard[4]
Nitrogen	5.82	70	1	no data	0.5
Chlorides	71	4500	50	no data	250
Phenols	0.000025	50	0.001	no data	no data
Arsenic	0.0135	0.1	0.005	0	0.01
Lead	0.0034	0.5	0.0014	0	0.01
Cyanides	0.0045	0.2	no data	0	0.05
Mercury	0.000014	0.05	0.00007	0	0.001

[1]*Regulation on Limit Values of Emission of Polluting Substances into Water and Deadlines for Reaching Them*, Official Gazette of the RS, No. 67/2011, 48/2012, and 1/2016.

[2]*Regulation on the Limit Values of Pollutants in Surface Water and Groundwater and Sediment and Deadlines for Achieving Them*, Official Gazette of the RS, No. 50/2012.

[3]*Regulation on the Limit Values of Priority and Priority Hazardous Substances that Pollute Surface Water and Deadlines for Achieving Them*, Official Gazette of the RS, No. 24/2014.

[4]Council Directive 98/83/EC on the Quality of Water Intended for Human Consumption.

Table 4 shows that most off-site pollutants exceed the values of the maximum allowed concentrations. Phenols are the only ones that do not exceed the limit values prescribed by any legal act. The reason for this is that phenol decomposition rates are higher than those of other pollutants and therefore they do not pose a threat to the environment. On the other hand, arsenic to the greatest extent exceeds the permitted limit values for both surface and groundwater. In a previous study [25], the results also showed that arsenic exceeded the permitted limits and proved to be a high-risk pollutant. According to the regulations (Table 4), nitrogen, chlorides, arsenic, and lead exceed the permissible values in surface water by 5.8, 1.4, 2.7, and 2.5 times, respectively. Also, according to this regulation, the direct and indirect release of arsenic, lead, cyanidess, and mercury into groundwater is prohibited. According to Directive 98/83/EC, nitrogen and arsenic exceed the permitted values by 11.6 and 1.35 times, respectively.

This research showed the prediction of the real case of the Gigoš landfill, which is relatively young and of good quality, and the potentially worst case that would occur at an unsanitary landfill or Gigoš landfill, if it somehow, under extraordinary circumstances (earthquake, fire, landfill gas explosion, bombing, acts of terrorism, flood, etc.), became unsanitary. There are many unsanitary landfills in Serbia, which are old and would potentially show even greater deviations from the permitted values than in this research. Therefore, it is very important to continue with the prediction of events at unsanitary landfills.

5. CONCLUSION

It is very difficult to predict the actual composition of leachate; however, with the help of adequate software, more reliable data on leachate migration, pollutant concentrations, migration time, etc., can be provided. LandSim software provides options for predicting events at both sanitary and non-sanitary municipal waste landfills. In the LandSim software, data on leachate for 30, 100, 300, and 1000 years were obtained, and these periods were chosen precisely because of the potential insight into the landfill condition, while monitoring is still carried out, but also after the landfill monitoring period.

LandSim models contaminant transport from initial leachate concentrations entered into the program: the concentrations can be assumed to be present in the leachate at the base of the landfill. Hence, surface seepage of leachate from the landfill is likely to contain some contaminants, potentially initiating pollution incidents in surface water bodies and affecting land use in the vicinity of the landfill. When the materials failed, the leachate with high concentrations of persistent pollutants continued to leak, resulting in pollutant concentration in the surrounding groundwater exceeding the acceptable concentration.

Using LandSim modeling, it was determined that the leachate amount is about 340 times lower when EBS is present (real-case scenario) and the increase in the amount of leachate in a landfill with EBS occurs when the landfill is still being monitored (in the first 20 years). In the case where the landfill does not have EBS (worst-case scenario), the leakage increases for up to 1000 years, after which it remains constant.

Furthermore, LandSim output shows that at the landfill with EBS, not a single pollutant exceeds the permitted limits prescribed by either Serbian or EU. On the other hand, the situation is different at the landfill without EBS. Concentrations of nitrogen, chlorides, arsenic, lead, cyanides, and mercury exceed the permitted limits according to Serbian regulations. According to Council Directive 98/83/EC, concentrations of nitrogen and arsenic exceed the permitted values.

The obtained data on future potential events at the landfill can provide the operator with an insight into which steps should be taken, for example, field interventions or elaborations, to reduce the risk of the negative environmental impact of leachate. The establishment of a generic landfill in the worst-case scenario provides a basic pattern of geochemistry and behavior of the leachate plume.

This research will continue in the direction of comparing the pollutant concentrations in leachate with the limit values defined by European standards and directives and harmonizing them with documents such as BREF for Waste Treatment and Monitoring of Emissions to Air and Water.

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