FIRE PREDICTION FOR A NON-SANITARY LANDFILL "BUBANJ" IN SERBIA

by

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This paper reviews the state of the Bubanj landfill near the city of Nis, Serbia, which has been used for 47 years, and which is categorized as a non-sanitary landfill. We utilised the LandGEM 3.02 model, for estimating landfill gas emission rates, to calculate the amount of landfill gases. Additionally, we measured the amount and composition of landfill gas in section S4 of the landfill from July 2014 to June 2015. We utilised the ALOHA software to estimate the fire-vulnerable zone. The results of our analysis show that the measured average methane emission is higher than the calculated emission. The difference between the measured average emission and calculated emission of methane is logical, as the measurements were performed in an active section, where methane emission higher than in inactive sections is to be expected. Based on the measured methane emissions during one year, we conclude that the methane emission drops as the ambient temperature drops. This paper showcases the state of the Bubanj landfill, which is highly unsatisfactory in terms of environmental and fire protection because of landfill gas generation.

Key words: *landfill, landfill gas, modelling, methane, fire risk*

Introduction

Landfills are objects with a high risk of fire. The risk of fire is estimated by calculation indicators and actual indicators of landfill gas emissions, and by ambient temperature, and by modeling risk of fire at landfills. Fires are a frequent occurrence in landfills. The study was conducted in *Bubanj* landfill near the city of Nis, Serbia. In the region, the biggest landfill fire broke out in Sarajevo, Bosnia and Herzegovina, in September 1996, when there was an explosion of methane trapped in the landfill body, resulting in a landslide of ca. 500,000 m^3 of waste reaching a distance of 700 m [1]. To date, our media have reported on the following landfill fires:

- April 12, 2011, fire at the municipal landfill in Jagodina, Serbia,
- February 17, 2012, fire at the municipal landfill *Bubanj* near Nis, Serbia,
- September 5, 2012, fire at the municipal landfill *Bubanj* near Nis, Serbia,
- August 3, 2013, fire at the municipal landfill in Trebinje, Bosnia and Herzegovina,
- March 26, 2015, fire at the illegal dump near Kragujevac, Serbia, and
- June 26, 2015, fire at the municipal landfill in Paraćin, Serbia.

On June 6, 2015, there was another big fire at a landfill near Zagreb, Croatia.

Exploitation of the official landfill of the city of Nis in the part of town called *Bubanj* began in 1968. The landfill was built at the time when Serbia was yet to enact legislation regarding landfills [2-7]. Its original design did not include any modern technical systems, such as

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a suitable base, precipitation drainage ducts, a system for filtrate collection and evacuation, and a system for landfill gas collection and further treatment. The absence of these features caused landfill body destabilization, uncontrolled drainage of landfill leachate, uncontrolled landfill gas emissions, and occasional waste smouldering and burning. The most recent fire at the landfill broke out in 2012. The landfill is intended for municipal and other non-hazardous waste.

The municipal waste landfill *Bubanj* is located in the south-western area of the Nis valley, on the western slopes of Bubanj hill, about 150 m from the local road connecting Nis and the village of Doljevac. In relation to the city of Nis, it is located in its south-western part, directly below the city cemetery. It is about 5.2 km away from the city centre by road and about 4 km by air. It has an elongated shape stretching in the north-south direction (fig. 1).

The total area of the landfill is 31.07 ha. It comprises four sections: S1, S2, S3, and S4. Figure 2 shows the layout plan of the landfill with all four sections. Waste is currently deposited in section S4, whose area is ca. 2.5 ha, whereas sections S1, S2, and S3 are closed.

Section S4 is only allowed to receive non-hazardous wastes. This category includes the following waste types:
- municipal waste,
- inert industrial waste,
- public space waste, and
- waste from non-industrial-type companies, waste from shops, administrative buildings, *etc.*, and ash from household heating stoves.

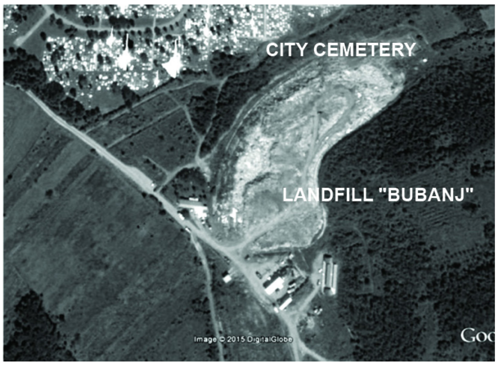

Figure 1. Location of *Bubanj* landfill

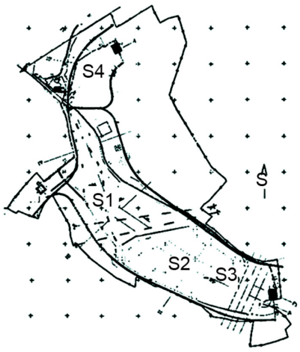

Figure 2. Layout plan of *Bubanj* landfill with sections S1, S2, S3, and S4

Most of the landfill body lies on clay soil that is categorized as coherent compact soil. Soil composition makes this location suitable for a landfill.

The landfill was supposed to be closed and reclaimed in 2000 at the elevation of 283.5 meters above sea level. However, the landfill is still in operation. Until 2005, it had no precipitation drainage ducts, a degassing system, or a system for leachate collection and treatment.

Today, the Nis landfill receives around 200 t of waste daily, which amounts to approximately 73,000 t annually.

Methodology

We calculated the amount of landfill gas using the LandGEM 3.02 model for landfill gas emission assessment, designed by the US Environmental Protection Agency [8]. LandGEM 3.02 is based on a first-order equation used to calculate the amount of methane generated from waste decomposition.

To calculate methane generation in section S4, we used the data on the number of people by the Statistical Office of the Republic of Serbia. According to the data, Nis had a population of 127,654 in 1971, and 260,237 in 2011, when the last census was conducted [9]. The data on the amount of waste that we used to calculate methane generation were taken from a study conducted by the Faculty of Technical Sciences, University of Novi Sad, Novi Sad, Serbia [10, 11].

Landfill gas is generated through bacterial activity. Increase of landfill gas amount is proportional to the increase of the amount of organic waste in the landfill [12].

In order to make a simulation with LandGEM 3.02, we used the following input parameters:

– landfill open year 1968
– landfill closure year (with 80-year limit) 2017
– methane generation rate, *k* 0.040 per year
– potential methane generation capacity, L_o 100 m^3Mg^{-1}
– non-methane organic compounds (NMOC) concentration, and 4,000 ppmv as hexane
– methane content 50% by volume

In addition to the calculations by means of LandGEM, we measured the amount and composition of landfill gas in section S4 of the landfill from July 2014 to June 2015.

We performed the measurements using the German MRU GmbH and the US Landtec gas analyzers, in accordance with the standard SRPS ISO 10780:2010. Stationary source emissions – Measurement of velocity and volume flow rate of gas flows in ducts according and standard DML 3.2:2010. Measurement of oxygen, CO_2, CO, nitrogen oxides (NO, NO_2, NO_x), SO_2, total hydrocarbons (CxHy), and hydrogen sulphide – Method based on the manufacturer instructions for automatic gas analyzer Vario Plus Industrial, Germany, and on EPA 3A:2008, EPA 10:2006, EPA 7E:2008, EPA 6C:2008, and EPA 25V:2000 [13, 14].

A total of 68 gas wells were installed at the Nis landfill from 2008 to 2010 [15].

Twenty-two gas wells were installed in section S4 in 2010 (fig. 3). We measured landfill gas emissions only in gas wells 9, 10, 12, 13, 15, 16, 18, 19, 21, and 22, as the other gas wells were inaccessible due to large amounts of waste covering them (fig. 4).

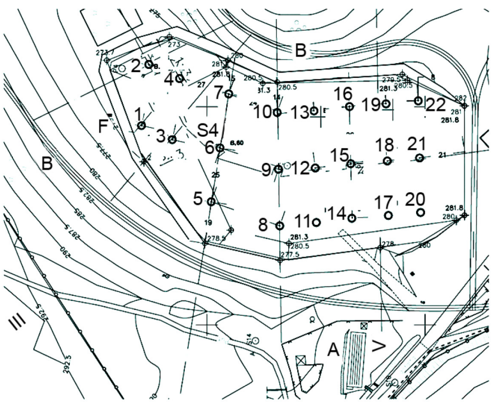

Figure 3. Layout of gas wells in the active section S4 of the *Bubanj* landfill

Figure 4. Measuring landfill gas emissions in the active section S4 of the *Bubanj* landfill

In addition, we used the ALOHA software to assess the vulnerable zone in case of a fire and for modelling [16].

Results and discussion

Table 1 provides emissions of landfill gas and methane from the *Bubanj* landfill from 1968 to 2108, calculated with LandGEM 3.02.

Table 1. Emission of landfill gas and methane from the *Bubanj* landfill by year

Year	Total landfill gas			Methane		
	[mg per year]	[m^3 per year]	[av. ft^{-3} min^{-1}]	[mg per year]	[m^3 per year]	[av. ft^{-3} min^{-1}]
1968	0	0	0	0	0	0
1973	1.456E+03	1.166E+06	7.833E+01	3.889E+02	5.829E+05	3.917E+01
1978	2.883E+03	2.308E+06	1.551E+02	7.700E+02	1.154E+06	7.755E+01
1983	4.266E+03	3.416E+06	2.295E+02	1.140E+03	1.708E+06	1.148E+02
1988	5.522E+03	4.422E+06	2.971E+02	1.475E+03	2.211E+06	1.486E+02
1993	6.641E+03	5.318E+06	3.573E+02	1.774E+03	2.659E+06	1.786E+02
1998	7.597E+03	6.083E+06	4.087E+02	2.029E+03	3.042E+06	2.044E+02
2003	8.395E+03	6.722E+06	4.516E+02	2.242E+03	3.361E+06	2.258E+02
2008	9.398E+03	7.525E+06	5.056E+02	2.510E+03	3.763E+06	2.528E+02
2013	1.076E+04	8.615E+06	5.788E+02	2.874E+03	4.307E+06	2.894E+02
2014	1.103E+04	8.835E+06	5.936E+02	2.947E+03	4.417E+06	2.968E+02
2015	1.130E+04	9.050E+06	6.080E+02	3.019E+03	4.525E+06	3.040E+02
2018	1.207E+04	9.662E+06	6.492E+02	3.223E+03	4.831E+06	3.246E+02
2023	9.878E+03	7.910E+06	5.315E+02	2.639E+03	3.955E+06	2.657E+02
2028	8.088E+03	6.476E+06	4.351E+02	2.160E+03	3.238E+06	2.176E+02
2033	6.622E+03	5.302E+06	3.563E+02	1.769E+03	2.651E+06	1.781E+02
2038	5.421E+03	4.341E+06	2.917E+02	1.448E+03	2.171E+06	1.458E+02
2043	4.439E+03	3.554E+06	2.388E+02	1.186E+03	1.777E+06	1.194E+02
2048	3.634E+03	2.910E+06	1.955E+02	9.707E+02	1.455E+06	9.776E+01
2053	2.975E+03	2.383E+06	1.601E+02	7.947E+02	1.191E+06	8.004E+01
2058	2.436E+03	1.951E+06	1.311E+02	6.507E+02	9.753E+05	6.553E+01
2063	1.994E+03	1.597E+06	1.073E+02	5.327E+02	7.985E+05	5.365E+01
2068	1.633E+03	1.308E+06	8.785E+01	4.362E+02	6.538E+05	4.393E+01
2073	1.337E+03	1.071E+06	7.193E+01	3.571E+02	5.353E+05	3.596E+01
2078	1.095E+03	8.765E+05	5.889E+01	2.924E+02	4.382E+05	2.945E+01
2083	8.962E+02	7.176E+05	4.822E+01	2.394E+02	3.588E+05	2.411E+01
2088	7.337E+02	5.875E+05	3.948E+01	1.960E+02	2.938E+05	1.974E+01
2093	6.007E+02	4.810E+05	3.232E+01	1.605E+02	2.405E+05	1.616E+01
2098	4.918E+02	3.938E+05	2.646E+01	1.314E+02	1.969E+05	1.323E+01
2103	4.027E+02	3.224E+05	2.166E+01	1.076E+02	1.612E+05	1.083E+01
2108	3.297E+02	2.640E+05	1.774E+01	8.806E+01	1.320E+05	8.869E+00

The data in tab. 1 reveal that landfill gases and methane will still be generated after section S4, the last active section of the landfill, has to be closed in 2017.

Figure 5 shows the total emission of landfill gas, methane, CO_2, and NMOC, obtained from a LandGEM 3.02 simulation. Increasing emissions of landfill gas, methane, and CO_2 are to be expected until 2018, after which their generation should decrease, assuming that the landfill has to be actually closed in 2017. This indicates the necessity of remediation and reclamation of the current landfill.

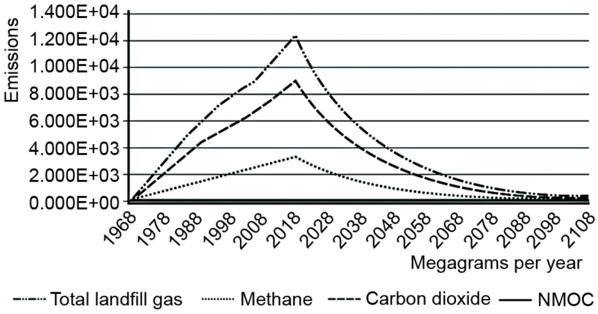

Figure 5. Total emission of landfill gas, methane, CO_2, and NMOC from the *Bubanj* landfill

Figure 6 shows methane emission obtained from a LandGEM 3.02 simulation. Increasing methane emission is to be expected until 2018, after which it will begin to decrease.

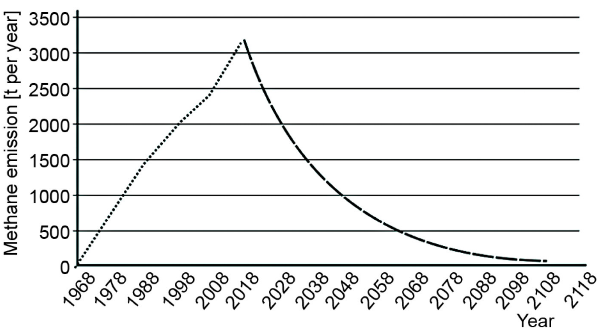

Figure 6. Methane emission from the *Bubanj* landfill

Table 2 provides the measured landfill gas emissions from section S4. We performed three measurements of landfill gas emission for each selected gas well, also tab. 2 shows the mean values of measured methane, CO_2, CO, and nitrogen oxide emissions.

Figure 7 shows the impact of ambient air on the amount of methane in landfill gas. We established the highest methane emission for gas well 21 and the lowest for gas well 16. Gas well 16 emits low amounts of methane due to:

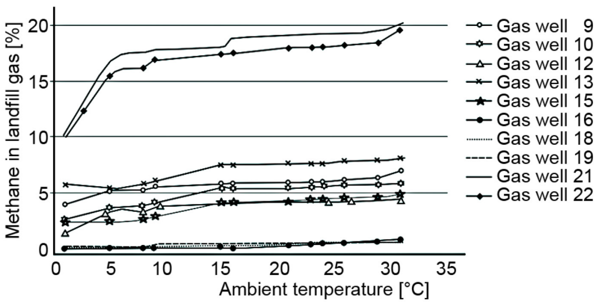

Figure 7. Impact of ambient temperature on methane emission in section S4 of the *Bubanj* landfill

– large amount of inert material underneath gas well 16,
– horizontal flow of methane to the nearest gas well along the path of least resistance, or
– inability of methane to leave the landfill body due to formation of clay pockets and clogging of the perforated gas well pipe.

The impact of ambient temperature on methane emission was analyzed by Vujić, *et al.* [17], and our research has only confirmed their results. Figure 7 reveals that the rise in ambient air temperature increases methane emission. This increase is especially pronounced in gas wells 21 and 22, whereas it is lower in other gas wells due to temperature stability in the landfill body, which is over 30 m deep.

We used the ALOHA software to assess the vulnerable zone in case of a fire. We ran the simulation according to the following scenario.

Table 2. Emission values of monitored parameters in the active section S4 of the *Bubanj* landfill

Gas well	Date of measurement/ Ambient temperature [°C]	Waste gas velocity [ms^{-1}]	CH_4 [%]	CO_2 [%]	CO [ppm]	NO [ppm]	Methane mass flow [kgh^{-1}]	Date of measurement/ Ambient temperature [°C]	Waste gas velocity [ms^{-1}]	CH_4 [%]	CO_2 [%]	CO [ppm]	NO [ppm]	Methane mass flow [kgh^{-1}]
9	July 2, 2014/ 24 °C	1.6	6.0	12.8	1	1	7.74	Jan. 29, 2015/ 1 °C	0.9	4.1	9.8	0	0	2.98
10		1.6	5.0	13.6	1	1	6.45		0.9	2.6	9.1	0	0	1.89
12		1.6	4.1	13.6	2	1	5.29		0.9	1.5	9.1	0	0	1.09
13		1.4	7.3	14.6	1	1	8.25		1.0	5.8	10.1	0	0	4.68
15		1.5	3.9	12.8	2	1	4.72		1.0	2.5	8.8	0	0	2.02
16		1.4	0.5	15.6	1	1	0.56		1.0	0	10.3	0	0	0
18		1.5	0.5	14.0	1	2	0.61		1.0	0	9.6	0	0	0
19		1.5	0.4	14.2	0	0	0.48		1.1	0	8.9	0	0	0
21		1.5	19.0	12.4	0	0	23.00		1.1	10.1	7.5	0	0	8.97
22		1.6	17.9	12.8	1	2	23.12		1.1	10.1	8.3	0	0	8.97
9	Aug. 28, 2014/ 26 °C	1.6	6.2	13.5	1	1	8.01	Feb. 22, 2015/ 16 °C	1.5	5.9	12.2	2	1	7.14
10		1.6	5.7	14.1	1	1	7.36		1.5	5.5	13.1	1	2	6.66
12		1.6	4.3	13.7	2	1	5.55		1.4	4.2	13.1	1	1	4.75
13		1.4	7.7	14.8	1	1	8.70		1.4	7.6	13.9	1	1	8.58
15		1.5	4.6	12.8	2	1	5.57		1.5	4.2	12	1	2	5.085
16		1.5	0.6	15.6	1	2	0.73		1.3	0.2	15.1	2	1	0.21
18		1.5	0.5	14.1	1	2	0.61		1.4	0.3	13.8	2	2	0.33
19		1.5	0.6	14.5	1	0	0.73		1.4	0.4	13.8	1	2	0.45
21		1.6	19.2	12.7	1	0	24.79		1.5	18.9	12.1	1	1	22.88
22		1.6	18.2	13.0	1	2	23.50		1.6	17.6	12.1	1	0	22.73
9	Sep. 10, 2014/ 21 °C	1.5	5.9	12.5	1	1	7.14	Mar. 15, 2015/ 8 °C	1.0	5.4	10.8	1	1	4.35
10		1.6	5.6	13.5	1	1	7.23		1.1	3.9	10.7	0	1	3.46
12		1.4	4.3	13.5	0	1	4.86		1.2	3.4	11.0	1	1	3.29
13		1.3	7.7	14.0	1	1	8.08		1.0	5.8	12.1	0	1	4.68
15		1.5	4.3	12.2	2	1	5.21		1.0	2.7	11.1	1	1	2.18
16		1.3	0.3	15.3	1	0	0.31		1.1	0.1	13.8	0	1	0.09
18		1.4	0.4	13.9	1	2	0.45		1.2	0.2	11.9	0	1	0.19
19		1.4	0.4	14.0	0	0	0.45		1.2	0.2	12.2	0	0	0.19
21		1.5	19.0	12.3	0	0	23.00		1.4	17.6	11.1	1	0	19.89

Table 2 (Continuation)

Gas well	Date of measurement/ Ambient temperature [°C]	Waste gas velocity [ms^{-1}]	CH_4 [%]	CO_2 [%]	CO [ppm]	NO [ppm]	Methane mass flow [kgh^{-1}]	Date of measurement/ Ambient temperature [°C]	Waste gas velocity [ms^{-1}]	CH_4 [%]	CO_2 [%]	CO [ppm]	NO [ppm]	Methane mass flow [kgh^{-1}]
22		1.5	18.0	12.5	1	1	21.79		1.3	16.2	10.7	1	0	16.99
9	Oct. 21, 2014/ 23 °C	1.5	6.0	12.8	1	1	7.26	Apr. 6, 2015/ 9 °C	1.1	5.6	11.1	0	1	4.97
10		1.6	5.6	13.6	1	1	7.23		1.2	4.1	10.9	0	1	3.97
12		1.5	4.3	13.6	1	1	5.20		1.2	3.8	11.2	1	1	3.68
13		1.3	7.7	14.5	1	1	8.08		1.1	6.1	13.2	0	0	5.42
15		1.5	4.4	12.6	2	1	5.32		1.1	2.9	11.3	0	1	2.57
16		1.3	0.5	15.3	1	0	0.52		1.2	0.1	14.1	0	1	0.09
18		1.4	0.5	14.0	1	2	0.56		1.2	0.2	12.2	0	1	0.19
19		1.4	0.5	14.1	0	0	0.56		1.4	0.3	12.7	1	0	0.34
21		1.5	19.2	12.3	0	0	23.24		1.5	17.8	11.3	1	0	21.55
22		1.5	18.0	12.8	1	2	21.79		1.4	16.9	10.9	1	0	19.09
9	Nov. 16, 2014/ 15 °C	1.5	5.8	12.0	2	1	7.021	May 7, 2015/ 31 °C	1.7	6.9	14.2	2	1	9.47
10		1.5	5.5	12.8	2	1	6.66		1.8	5.9	14.8	2	2	8.57
12		1.4	4.1	12.5	1	1	4.63		1.7	4.6	13.9	2	2	6.31
13		1.4	7.5	13.8	1	1	8.47		1.6	8.1	15.5	1	1	10.46
15		1.4	4.1	11.9	2	2	4.63		1.6	4.9	13.1	2	1	6.33
16		1.2	0.2	14.9	2	1	0.19		1.6	0.7	15.7	2	1	0.90
18		1.4	0.3	13.6	2	2	0.34		1.7	0.7	14.2	2	2	0.96
19		1.4	0.4	13.7	1	2	0.45		1.8	0.8	14.9	1	1	1.16
21		1.4	18.1	12.0	1	1	20.45		1.7	20.1	13.4	1	1	27.57
22		1.4	17.5	12.0	1	0	19.77		1.8	19.7	14.6	2	1	28.62
9	Dec. 9, 2014/ 5 °C	1.0	5.3	10.7	1	1	4.28	June 4, 2015/ 29 °C	1.6	6.4	13.6	1	2	8.26
10		1.1	3.6	10.7	0	0	3.19		1.7	5.8	14.5	1	1	7.96
12		1.1	3.3	10.8	0	0	2.93		1.7	4.5	13.8	2	2	6.17
13		1.0	5.5	11.7	0	1	4.44		1.5	7.9	14.9	1	1	9.56
15		1.0	2.4	10.1	1	1	1.94		1.6	4.7	12.9	2	1	6.07
16		1.1	0.1	12.1	0	1	0.09		1.5	0.6	15.7	1	2	0.73
18		1.2	0.2	10.5	0	1	0.19		1.6	0.6	14.2	2	2	0.77
19		1.2	0.2	11.1	0	0	0.19		1.6	0.7	14.6	1	0	0.90
21		1.2	16.8	10.0	1	0	16.27		1.7	19.5	13.0	1	0	26.75
22		1.3	15.8	10.0	1	0	16.58		1.7	18.5	13.8	2	0	25.38

One hundred kg of methane is trapped in the landfill body beneath gas well 16. Due to land subsidence or earthquakes, methane is released and it escapes the landfill:
(1) not causing a fire, and
(2) causing a fire due to the presence of an ignition source.

The scenario was constructed for atmospheric temperature of 30 °C, wind speed of 2 m/s, and air mass stability, *C*.

Figure 8 shows the toxic zone caused by sudden emission of 100 kg of methane in section S4.

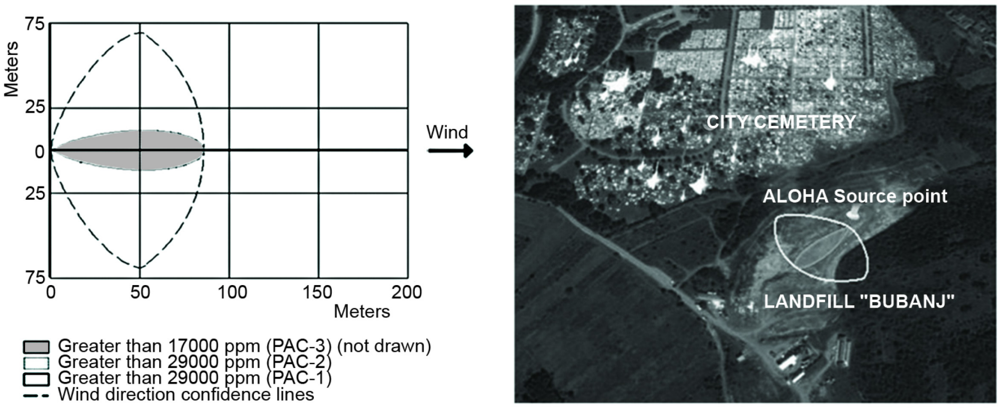

Figure 8. Toxic zone caused by sudden emission of 100 kg of methane in section S4

Figure 8 reveals that in the event of a 100 kg methane emission in section S4, the zone of toxic concentration of 2,999 ppm would spread windward over an 86 m diameter. The maximum allowed concentration for methane is 1,000 ppm, as it is for all alkanes up to C_4H_{10}. Concentration of 2,999 ppm can cause nausea, vomiting, headache, and dizziness in humans. Landfill employees and collectors of secondary raw materials can be found in this zone, as evidenced by about ten of them being present during every measurement we performed.

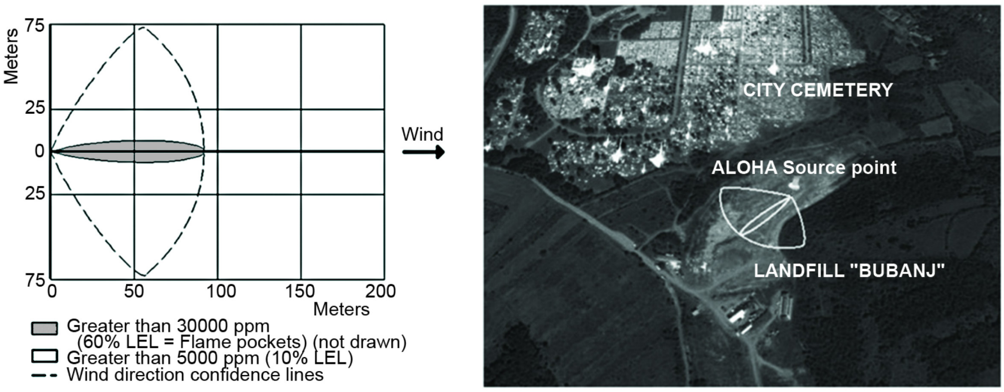

Figure 9. Fire risk zone due to sudden emission of 100 kg of methane in section S4

Figure 9 reveals that in the event of a 100 kg methane emission in section S4, the zone vulnerable to fire with an ignition source present (*e. g.* cigarette butts left by the collectors of secondary raw materials) would spread windward over a 92 m diameter.

Figure 10 shows the vulnerable zone after the ignition of 100 kg of methane in section S4.

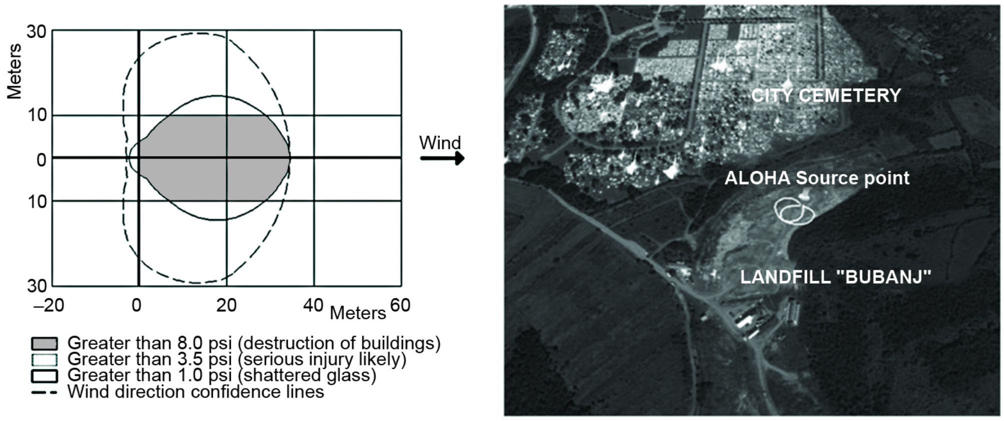

Figure 10. Vulnerable zone after the ignition of 100 kg of methane in section S4

Figure 10 reveals that a fire and explosion of 100 kg of released methane in section S4 could injure persons within a 35 m diameter.

Even though every individual vulnerable zone is within the landfill perimeter, the vulnerable zone in case of a fire would be far bigger due to the domino effect, *i. e.* the ignition of methane, whose concentration is within flammability limits, in other gas wells and the ignition of inflammable waste.

The effects of landfill fires are particularly detrimental to the environment due to emissions of gaseous combustion products. The effects of uncontrolled combustion of rubber in landfills are covered in Stefanov *et al.* [18].

According to the Regulation on the Content of Accident Prevention Policy and the Content and Methodology of Creating Safety Reports and Accident Protection Plans [19] and the results of our simulation:

– the probability of such an accident is considered to be low, and
– considering the width of vulnerable zones for cases with and without a fire, the probability of serious consequences is higher due to the expected number of six to fifteen injured people (resulting from the number of collectors of secondary raw materials present at the landfill).

The risk is thus categorized as a medium risk, which is fairly manageable.

Conclusions

The results revealed that the measured average methane emission form July 2014 to June 2015 was 7.22 kg/h per gas well. The LandGEM 3.02 model calculated methane emission for 2015 at 3,019 t, which equals 344.63 kg/h from the entire landfill. Since the landfill contains 68 gas wells, the average methane emission per gas well is 5.07 kg/h. The difference between the measured average emission and calculated emission of methane is logical, as the measurements were performed in an active section, where methane emission higher than in inactive sections is to be expected.

Based on the measured methane emissions during one year, we concluded that methane emission drops as the ambient temperature drops. The biggest drop in methane emission occurred when ambient air temperature went below 5 °C.

Based on fire simulation using the ALOHA software, we concluded that fire risk is present at the landfill. The latest major fire broke out in 2012, and despite a large number of smaller fires that occurred since then, they were all extinguished quickly thanks to 24-hour supervision by landfill employees and one fire fighting vehicle, which is always available at the landfill.

This paper showcased the state of the *Bubanj* landfill, which was revealed to be highly unsatisfactory in terms of environmental and fire protection because of landfill gas generation.

A potential solution to the problem of solid waste management is the construction of a regional sanitary landfill, recycling, and waste-to-energy through incineration. Waste-to-energy incineration has been covered by Brems *et al.* [20], who consider the possibility of plastic waste incineration, and Radovanović *et al.* [21], who address the possibility and justification of incinerating harmless municipal and industrial waste in Serbian thermal power stations, whereas Bošković *et al.* [22] provide a techno-economic analysis of cogeneration facility construction at landfills.

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